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# THE CREATION OF THE LIGHT ELEMENTS – COSMIC RAYS AND COSMOLOGY

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# THE CREATION OF THE LIGHT ELEMENTS-
# COSMIC RAYS AND COSMOLOGY

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CONTENTS

## 1. INTRODUCTION

Since the pioneering and persuasive work of Burbidge, Burbidge, Fowler and Hoyle (1957) it has been clear that most of the elements are created by nuclear reactions in the centers of stars. Some of these elements, including those most abundant, are produced during the long quiescent periods of hydrogen and helium burning which occupy most of a star's life. Others are produced much more quickly, on time scales of seconds or fractions of seconds during the supernovae which terminate the lives of sufficiently massive stars. These same supernovae return the products of stellar evolution to the interstellar medium, where they may be incorporated into newly condensing stars.

The "light elements" with $A < 12$ do not share this stellar origin. That they do not is based on a simple and compelling argument. Namely, they are too fragile, in the sense of having short lifetimes against destruction by proton induced reactions, especially $(p,\alpha)$ reactions, at the temperatures and densities of stellar interiors. In the sun, for example, $^2H$ is continuously created by the $p+p \rightarrow {}^2H+e^+ +\nu$ reaction, but is immediately destroyed by the faster reaction $p+d \rightarrow {}^3He + \gamma$, with the result that the number ratio of $^2H$ to $^1H$, denoted $^2H/^1H$,[†] is small. At equilibrium, $^2H/^1H \lesssim 10^{-17}$ (Clayton 1968), some twelve orders of magnitude less than the observed abundance. Similar arguments apply to the other light elements, excluding only $^4He$. Other places, cooler and/or less dense, must then be found for their creation so that their destruction does not immediately follow. The nuclide $^4He$ is produced during stellar hydrogen burning, but is not made in its observed abundance ($^4He/^1H \simeq 0.1$) and another site must be found.

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† The reader's attention is drawn to the glossary which appears at the end of this article.

An elucidation of the processes responsible for creation of the light elements is the subject of this review. One had hoped that these processes, occurring outside of stars, might somehow shed light on more fundamental phenomena in the galaxy or the Universe. In recent years a "standard model" has emerged which explains the synthesis of the light elements in a natural, straightforward and economical fashion. The hope that fundamental results would follow has been more than justified.

In this standard model of light element creation certain isotopes are made by spallation reactions in the cosmic rays, and the magnitude and time dependence of their abundances may allow one to place constraints on the infall of primitive material into the galaxy and on the power contained in (so far unobservable) low energy cosmic rays. Other isotopes are the ashes of the primeval hot big bang explosion which began the Universe. It is from their abundances that the most important deductions seem possible. One can estimate the mean universal density of hadronic matter and thereby conclude that the Universe is open and that the present expansion will continue forever (at least if the neutrinos have sufficiently small masses). Other deductions, reflecting the interaction of particle physics and cosmology (particle astrophysics), include strong limits on the number of lepton-neutrino pairs and on the masses of neutrinos.

At this point it may be useful or at least, wise, to recall a comment of Mark Twain [†] made in *Life on the Mississippi* : "There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact." As I will point out, a substantial "investment of fact" has been made in this problem, but the deductions are of sufficient importance that a word of warning is in order. It is clear, that

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[†] I am grateful to W.A. Fowler for using this quotation (Fowler, Caughlan and Zimmerman, 1975) and hence calling it again to my attention.



given the small number of observables, 8 isotopic abundances, and the nature of the physics involved, all the deductions above must be model dependent. For example, the deductions of the universal density and the neutrino number depend on the so-called standard big bang of Wagoner (1973), which contains a number of ad hoc assumptions. Nevertheless, the standard model of light element creation is certainly the simplest model which explains the facts, and its substantial predictive power -- it contains, in principle, no free parameters -- makes it an ideal starting point for more elaborate theories.

I will begin with a brief survey of the relevant observables : the elemental and isotopic abundances. (This section is necessarily more technical and detailed than what follows; the uninterested reader can skip all but the introduction and summary). Then will follow a history of early attempts to understand the origin of the light elements, leading up to the suggestion of Reeves, Fowler and Hoyle (1970), that they were formed by spallation of the interstellar gas by the galactic cosmic rays (GCR). At this point I will break the narrative to outline the ingredients of the GCR creation mechanism in some detail. Particular attention will be paid to inputs from nuclear physics ; techniques for measuring the pertinent spallation cross sections will be described and the results of these measurements will be summarized. Given this cross section information, observed cosmic ray fluxes and known interstellar abundances, cosmic ray transport calculations then yield estimates of light isotope production in the GCR. One finds that this mechanism is adequate for $^6Li$, $^9Be$, $^{10}B$ and possibly $^{11}B$, but not for the other light isotopes. Next follows a discussion of the hot big bang origin of the Universe and the nucleosynthesis which inevitably accompanies it. The synthesized abundances depend only on the mean universal density, and while this dependence is different for different isotopes, all those remaining : $^2H$, $^{3,4}He$ and $^7Li$ are reproduced at a common value of the density. Moreover, this density is quite reasonable from an astrophysical point of view. Having achieved an understanding of the creation of the light elements, we then turn to the implications of our understanding of their synthesis for other areas of physics. As mentioned previously, these are considerable.

The aim of this article is frankly pedagogic. As such the stress is on the basic physics of the subject. This I have tried to treat in a short and self contained fashion, while including sufficient detail to give a feeling for the subject : for what is likely to survive in the long term ; for what will probably be changed, in detail, with new experimental work ; for what is frankly speculative. I have stressed the links that connect particle physics and cosmology and the observable reflecting these links , nucleosynthesis, because I think future developments of greatest interest lie there.

Having taken this broad brush point of view it is clear that I cannot discuss the details so as to satisfy the reader who needs a truly deep insight into the field. For him I list in the relevant sections, a series of more detailed review articles to which he can refer. Finally, I ignore, except in passing, what one can learn about the chemical and dynamical evolution of galaxies from the constraints imposed by the abundances of the light elements. For a discussion of this interesting but complex topic I refer the reader to a recent text : Audouze and Vauclair (1980) and to recent reviews : Tinsley (1980), Vigroux (1979) and Audouze and Tinsley (1976).

## 2. ABUNDANCES OF THE LIGHT ELEMENTS

The general trend of elemental abundances with atomic weight is shown in Fig. 2.1. Most of these abundances were obtained from meteorites (the carbonaceous chondrites) and are presumably representative of the solar neighborhood some $5 \times 10^9$ years ago, but it is none the less common to refer to them as the standard, universal or, even, cosmic abundances. As Trimble (1975) has pointed out, what is perhaps "the most surprising thing, is that such a compilation



can be made at all". As examples of apparent difficulties : $^2H/^1H \simeq 1.5 \times 10^{-4}$ † in terrestrial water, while this same ratio in the center of the galaxy is $< 10^{-5}$ ; and the lithium observed on the solar surface is $10^{-2}$ that shown in Fig.2.1, as are the abundances of all the heavy elements in some old (population II) stars.

One finds, however, that in these and in the great majority of other cases, secondary effects account for the differences from an apparently universal value. There is an overabundance of $^2H$ in terrestrial water because chemical processes happen in this case (Geiss and Reeves 1980) to favor the formation of $^2H_2O$ over $^1H_2O$, while, in the active central region of the galaxy, deuterium is destroyed by stellar processing. The lithium in the sun is destroyed when convection carries it to hotter regions below the solar surface. Finally, the metal poor stars are believed to have condensed from the interstellar medium prior to its enrichment by stellar synthesis. This represents a more apparent difference, but it is found that the *relative* abundances for $A \geq 12$ differ little from the solar system values. It has then been fruitful to regard Fig. 2.1 as representing the standard abundances and to discuss deviations from it in terms of secondary processes.

The dominant property of the abundance curve is a strong decrease with increasing mass, amounting to some ten orders of magnitude between $^1H$ and $^{208}Pb$. Superimposed on this general trend are local maxima reflecting the special stability of alpha particle, iron peak and closed neutron-shell nuclei. One also sees the deep valley reflecting the special fragility of the light elements, with Li, Be and B having abundances comparable to those of the heaviest elements.

† The symbol $Isotope_i/Isotope_j$ or $Element_i/Element_j$ means the ratios by number. The symbol X(isotope) or X(element) means the fraction of that isotope or element by mass.

To obtain a quantitatively reliable estimate of element abundances is in some sense a black art, involving, for example, an understanding of chemical fractionation in meteorites and condensation into interstellar grains, or alternately the assumption that these processes are negligible. One of the most problematic abundances has unfortunately been that of B where values differing by a factor of 100 appear in the recent literature. Fortunately, much new information has become available and the light element abundances are now sufficiently well known for our purposes. A large part of this advance can be traced to the Copernicus satellite which has made possible the observation of ultraviolet transitions not accessible to ground-based astronomy.

A detailed discussion is not within the scope of this article, so I will rely upon recent reviews, updating them only when qualitatively significant new work has become available or when work in progress has been published.

### 2.1. Abundance of $^2H$

Many observations in the past eight years have shown that the ratio $^2H/^1H$ is an order of magnitude smaller in the interstellar medium than in terrestrial matter. The most reliable information follows from observations of Lyman series absorption (by atomic hydrogen and deuterium) of light from hot OB stars near the sun. A recent review of this work (Laurent, Vidal-Madjar and York, 1979) is shown in Fig. 2.2. Early results were consistent, within their uncertainties, with $^2H/^1H = 1.8 \times 10^{-5}$, but there are recent results in the range of $(0.25-4)\times 10^{-5}$, significantly above and below this value. These observations are consistent with a universal abundance only if there are local mechanisms which can produce such variations from the assumed universal value. Laurent et al. (1979) suggest several processes which might create or destroy $^2H$, but perhaps more likely is the suggestion of Bruston et al.(1980) that radiation pressure effects selectively deplete atomic deuterium. One would expect that the universal value then lies near the upper end of the observed range, close to $^2H/^1H = 2.25 \times 10^{-5}$.



Estimates of $^2H/^1H$ obtained from observation of molecules in the solar system have been reviewed by Laurent et al. (1978). Fractionation effects, favoring the formation of deuterium containing molecules, are expected and are usually assumed to account for the generally high values ($^2H/^1H=(1-6)\times 10^{-5}$) obtained from these measurements. A recent measurement which attempts to control such effects (Combes, Encranez and Owen 1978) yields $^2H/^1H = (2.3 \pm 1.1) \times 10^{-5}$ on Jupiter.

Observation of the ratio $^3He/^4He$ in the solar wind provides another estimate. Assuming that part of the $^3He$ results from conversion of primeval $^2H$ by the $^2H(p,\gamma)^3He$ reaction during the formation of the sun, one has (Geiss and Reeves 1972 ; Reeves 1974):

$$\left(\frac{^2H}{^1H}\right) = \left(\frac{^4He}{^1H}\right)_\odot \left[\left(\frac{^3He}{^4He}\right)_{\text{solar wind}} - \left(\frac{^3He}{^4He}\right)_\odot\right]. \qquad (2.1)$$

Following Geiss and Reeves (1972), we take $\left(\frac{^3He}{^4He}\right)_{\text{solar wind}} = 4.0 \times 10^{-4}$.

From measurements on gas rich meteorites (Black 1973) the isotopic ratio at the formation of the solar system is $(^3He/^4He)_\odot = (1.5 \pm 0.5) \times 10^{-4}$. I find (section 2.4), that $(^4He/^1H)_\odot = 0.095 \pm 0.013$ yielding finally :

$$(^2H/^1H) = (2.4 \pm 1.0) \times 10^{-5}. \qquad (2.2)$$

The results summarized in Table 2.1 are in some sense in remarkable agreement within rather large uncertainties. But is also clear that any universal abundance is not yet well determined. I adopt

$$\frac{^2H}{^1H} = (1.6 \pm 1.0) \times 10^{-5} \qquad (2.3)$$

which encompases the central values of all but the two extreme measurements in the interstellar medium (ISM).

Table 2.1. Abundance of $^{2}H$

| Source | $^{2}H/^{1}H$ |
|---|---|
| Interstellar (atomic) | $(0.25-4)\times10^{-5}$ |
| Solar system (molecules) | $(1 - 6) \times 10^{-5}$ |
| Solar wind | $(2.4 \pm 1.0) \times 10^{-5}$ |
| Adopted galactic value | $(1.6 \pm 1.0) \times 10^{-5}$ |

Abundances in the ISM have also been observed for a number of deuterated molecules. All these show strong fractionation effects, yielding large apparent ratios $^{2}H/^{1}H$. Perhaps the most useful result, from our point of view, is that $^{2}HCN$ is strongly depleted near the galactic center (Penzias et al. 1977) indicating that intense stellar processing leads to a net destruction of deuterium.

## 2.2 Abundance of $^{3}He$

Of all the light element abundances, that of $^{3}He$ is least well known. One can use Eqs. 2.1.,2.3 and $(^{3}He/^{4}He)_{solar\ wind}$ to obtain $(^{3}He/^{4}He)_{\odot}=(2.2\pm1.2)\times10^{-5}$. It is difficult to observe $^{3}He$ in the ISM and the single (probable) observation (Rood, Wilson and Steigman 1979) of $^{3}He/^{1}H = (4 \pm 1) \times 10^{-5}$ is, because of possible systematic effects, apparently regarded by the authors as a conservative upper limit. Finally there is the meteoric result (Black 1973 and references therein) previously discussed. These results are summarized in Table 2.2. I adopt

$$^{3}He/^{1}H = (1.5 \pm 1.2) \times 10^{-5}. \qquad (2.4)$$



This result apparently precludes the substantial production of $^{3}He$ in low mass stars proposed by Rood, Steigman and Tinsley (1976).

Table 2.2 Abundance of $^{3}He$

| Source | $(^{3}He/^{1}H)$ |
|---|---|
| Solar wind $(^{3}He/^{4}He) = (4.0) \times 10^{-4}$ (Geiss and Reeves 1972) | $(2.2 \pm 1.2)\times10^{-5}$ |
| Interstellar medium (Rood, Wilson and Steigman 1979) | $(4 \pm 1) \times 10^{-5}$ or $<5 \times 10^{-5}$ |
| Meteorites $(^{3}He/^{4}He)_{o} = (1.5 \pm 0.5)\ 10^{-4}$ (Black 1973) | $(1.4 \pm 0.6) \times 10^{-5}$ |
| Adopted galactic value | $(1.8 \pm 1.2) \times 10^{-5}$ |

## 2.3 Abundance of $^{4}He$.

It is generally agreed that the abundance of $^{4}He$ is universal in nature, except for production in hydrogen burning stars. There are a number of reviews, which are themselves reviewed by Trimble (1975) and Schramm and Wagoner (1977). Recently Yang et al. (1979) have surveyed information on helium abundance in stars and have concluded that the fraction of helium by mass $X(^{4}He) \simeq 0.20 - 0.25$ with a firm upper limit of $X(^{4}He) \lesssim 0.25$. However, these estimates often involve detailed and complex stellar models and one can clearly question the precision, or, at least, the accuracy of individual results. Indeed, abundances well outside the quoted range often occur, although the largest deviations are commonly for rather complex evolved objects (e.g. Cepheids and other variable stars). It is the ensemble of results that is, *perhaps*, convincing.

Fortunately, information on the composition of gaseous nebulae (HII regions) both in and outside our galaxy has become available in the past few years. Many of these objects have a very low abundance of heavy elements and presumably provide a reliable estimate of the primeval helium abundance. Furthermore, it seems possible to establish a correlation between the enrichment of metals† (Z by mass) and the helium abundance, which then permits an extrapolation to Z = 0. An example of such data is shown in Fig. 2.3 which is taken from Lequeux et al. (1979). This data and the earlier data for $Z < 0.01$ (see for example Peimbert (1975); Peimbert, Torres-Peimbert and Rayo (1978) and Churchwell et al. (1978) ) generally lie in the range Z = 0.22 - 0.26, although there are a few exceptions. From the data of Fig. 2.3 one obtains $Y(Z=0) = 0.228 \pm 0.014$. The value of the slope, $\Delta Y/\Delta Z$, depends on the details of the analysis and on further assumptions (Peimbert 1975) ; an estimate more accurate than $\Delta Y/\Delta Z = 2\pm1$ is probably not warranted. The radiotelescope data of Churchwell et al. (1979) show a variation of the apparent abundance (that of $He^+$) of helium with distance $D_G$ from the galactic center. They argue that the measured value at large $D_G$, $Y = 0.218 \pm 0.020$ represents the primordial abundance. There are plausible mechanisms to account for the observed variation with $D_G$.

I take for the primordial abundance :

$$\left.\begin{aligned} Y &= 0.23 \pm 0.02 \\ {}^4He/{}^1H &= 0.075 \pm 0.009 \end{aligned}\right\} \text{primordial} \qquad (2.5)$$

$$\Delta Y/\Delta Z = 2 \pm 1 .$$

At the time of the formation of the solar system with Z = 0.019 these numbers become

† In common astronomical parlance "metals" are elements with A > 4. Because Li, Be and B are so rare, this term means effectively everything except the light elements with which we are concerned. Thus $Z = X(A \geq 12)$. For brevity we also use $Y \equiv X(^4He)$.



$$\left.\begin{aligned} Y_\odot &= 0.27 \pm 0.03 \\ ({}^4He/{}^1He)_\odot &= 0.095 \pm 0.013. \end{aligned}\right\} \text{solar system} \qquad (2.6)$$

## 2.4. Abundances of Li, Be and B

The abundances of these elements have been reviewed by several authors (Boesgaard 1976 ; Reeves and Meyer 1978; Meyer 1978). Meyer's results augmented by a recent measurement of B in the interstellar medium (Meneguzzi and York 1980) are shown in Table 2.3.

Table 2.3 Abundances of Li, Be, B and adopted galactic abundances a)

| Source | $(Li/H)\times10^{12}$ | $(Be/H)\times10^{12}$ | $(B/H)\times10^{12}$ |
|---|---|---|---|
| Meteorites C1, C2 | 2200 ± 400 | 36 ± 13 | 1400 (2.3)[b] |
| Meteorites E4 | 1900 ± 800 | 14 (?) | 500 (?) |
| Solar | 10 ± 3 | 14 (1.6) | 200 (2) |
| Stellar | 1000 (2) | 13 (1.6) | 150 (2) |
| Interstellar medium | > 500 | | 150 (2) |
| Adopted Galactic | 1000 (2) | 14 (1.6) | 150 (2) |

a) Error factors are given in parentheses. X(2) means the value is X within a factor of two. Thus $300(2) = 300^{+300}_{-150}$

b) See text for a discussion of recent meteoritic results for B.

Very few measurements of interstellar abundances are available and furthermore it seems likely, at least for Li and Be, that some of the atoms are not observed because they are preferentially locked up in the interstellar grains so that observed values must be treated as lower limits. Meneguzzi and York (1980) argue that B is unlikely to have condensed onto grains ; the value shown is based on this assumption.

More detailed information is available for the abundances in stellar photospheres, with twenty or more measurements for each element. One sometimes encounters cases where the abundances have been modified by evolutionary processes. The sun is such a star : its Li abundance has been depleted by a factor of 100 (by convective mixing into hotter regions) as is typical for stars of its class, while its Be and B abundances are unaffected, also as expected (Reeves and Meyer 1978). Since these processes are in general well understood (Boesgaard and Chesley 1976), stars which show their effects can be avoided. Consistent results are then obtained as is shown in Fig. 2.4. One therefore expects stellar photospheric abundances to reliably reflect the mean galactic abundances.

It is then a surprise that the meteorites appear to be enriched, compared to the photospheric abundances. Recent measurements (Curtis, Gladney and Jurney 1980) on a group of chondritic meteorites (types C, H, L) give a boron abundance $^{11}B/H = (360 \pm 230) \times 10^{-2}$. These authors argue that the much larger results obtained previously arose from contamination of various sorts. Accepting their result, the meteoritic abundances of Li, Be, B are still higher than the photospheric abundances by a factor of two or three. It is not clear that these differences are real, being comparable to the uncertainties, but in any case, following Meyer (1978), I have chosen the photospheric abundance as the best estimate of the galactic abundance, arguing that meteorites are complex objects which have undergone complex chemical and physical changes during their condensation from the protosolar cloud. By contrast, stellar surfaces seem simple and well understood.

Finally, the isotopic ratios (Meyer 1978)

$$^{7}Li/^{6}Li = 12.6 \pm 0.2$$
$$^{11}B/^{10}B = 4.05 \pm 0.10$$



are taken from terrestrial and meteoritic data since spectral lines for two isotopes of the same element cannot usually be resolved in stars. As is clear from the assigned errors these ratios are straightforward to measure and generally consistent from sample to sample.

### 2.5 Summary and Comments

In table 2.4 we summarize the abundance data which are the input for the considerations of the rest of this paper. It is perhaps surprising that we can present such a summary, a single number for each nuclide, since creation and destruction processes would be expected, in the absence of fortuitous compensation, to yield time dependent abundances. Unfortunately, in most cases the time interval sampled is $\leqslant 5 \times 10^9$ years, and the uncertainties in the results preclude a slope measurement. A possible exception occurs for $^{9}Be$; I will return to this case later.

Table 2,4 Abundances of the light elements

| Nuclide | $N/{}^1H$ a) | $X_i$ (fraction by mass) a) b) |
|---|---|---|
| $^1H$ | 1,00 | 0.75 |
| $^2H$ | $(1,6\pm1.0)\times10^{-5}$ | $(2.5\pm1.5)\times10^{-5}$ |
| $^3He$ | $(1.8\pm1.2)\times10^{-5}$ | $(4.2\pm2.8)\times10^{-5}$ |
| $^4He$ | $0.075\pm0.009$ | $0.23\pm0.02$ (primordial) |
| | $0.095\pm0.013$ | $0.27\pm0.03$ (solar system) |
| $^6Li$ | $70(2)\times10^{-12}$ | $300(2)\times10^{-12}$ |
| $^7Li$ | $900(2)\times10^{-12}$ | $4600(2)\times10^{-12}$ |
| $^9Be$ | $14(1.6)\times10^{-12}$ | $90(1.6)\times10^{-12}$ |
| $^{10}B$ | $30(2)\times10^{-12}$ | $200(1.6)\times10^{-12}$ |
| $^{11}B$ | $120(2)\times10^{-12}$ | $900(2)\times10^{-12}$ |

$^7Li/^6Li = 12.6 \pm 0.2$

$^{11}B/^{10}B = 4.05 \pm 0.10$

a) Error factors are given in parentheses. X(2) means the value is X within a factor of 2.

b) For $A \leq 3$ these are primordial mass fractions ($X(A > 12) = 0$ ; $X(^4He) = 0.23$) and for $A \geq 4$ they are solar system values ($X(A \geq 12) = 0.019$ ; $X(^4He) = 0.27$).

## 3. CREATION PROCESSES

One might think it simple to find sources for nuclear species as rare as the light elements but this view does not survive a detailed examination of the possibilities. Indeed, it is only in the past ten years that viable sources for most of the light elements have been found and some aspects of the subject are still controversial.

In their survey Burbidge et al. (1957) pointed out that $^2H$ and the isotopes of LiBeB[†,††] had to be produced by an unknown x process in regions of low temperature and density, for example, in stellar atmospheres or gaseous nebulae. They speculated that neutrons from (p,n) reactions might be captured by protons to form $^2H$ and that high energy protons (> 100 MeV) might break up (or spall) abundant nuclei to form LiBeB. Production of LiBeB in spallation reactions had been suggested earlier (Fowler et al. 1955 ; Hayakawa 1955) and has been used (Bonsak and Greenstein 1960) to account for observations of Li in stars. It was assumed that early in a star's life (T Tauri phase) intense electromagnetic activity produced energetic flare particles which irradiated the surrounding material. In one detailed model of the solar system (Fowler, Greenstein and Hoyle 1962) it was assumed that the irradiated material was in small "icy planetesimals" surrounding the sun; in another model (Bernas et al. 1967) it was the stellar atmosphere itself. These particular models were subject to detailed criticism, but any autogenic model (in which each star makes its own LiBeB) encounters two major difficulties.

First, it seems unlikely that autogenic production in different stars

† It was then thought that $^3He$ and $^4He$ were produced in stars during hydrogen burning.

†† When referring collectively to a group of light elements we shall use the following abbreviations : LiBeB ≡ $^{6,7}Li$, $^9Be$, $^{10,11}B$ ; CNO ≡ $^{12}C$, $^{14}N$, $^{16}O$

will lead to the uniform abundances one finds for these elements. Second, the production of the high energy particles apparently requires, at least in some cases, more energy than the total available to the star ( Ryter et al.1970)[†] This state of affairs led Reeves, Fowler and Hoyle (1970) to suggest that nucleosynthesis by the galactic cosmic rays (GCR)) could produce $^{6}Li$, $^{9}Be$ and $^{10,11}B$ in their observed abundances. This idea has survived and elaborations of it will be described below. But first I mention the concurrent developments in cosmological nucleosynthesis.

Although the idea of element creation in a cosmological setting goes back at least to the 19th century (Trimble 1975) the modern viewpoint dates to the recognition of Hoyle and Tayler (1964) that the observed amount of $^{4}He$ could not have been made in stars and their demonstration that it could have been made in a primeval big bang explosion. Following closely upon this result, the discovery (Penzias and Wilson 1965) of the universal microwave radiation and the explanation of its 3° blackbody spectrum as a remnant of a hot dense phase in the early universe led to a series of improved calculations. These showed that not only $^{4}He$ was a product of big bang nucleosynthesis, but also $^{2}H$ and $^{3}He$ (Peebles 1966 a, b) and even $^{7}Li$ (Wagoner, Fowler and Hoyle 1967).

At this point plausible mechanisms for making all the light elements were in hand. In what follows below I will describe the current picture of cosmic ray and big bang nucleosynthesis in some detail. Further reference to past work can found in the reviews by Reeves (1974), Audouze and Tinsley (1974), Trimble (1975) Schramm and Wagoner (1977) and Austin (1977).

† Recently Canal et al. (1975) have shown that the energy requirements are less severe if one considers nucleosynthesis by α+α reactions, but they are still formidable.



## 4. NUCLEOSYNTHESIS IN THE GALACTIC COSMIC RAYS

A clue to an important creation mechanism can be found in Fig. 4.1 . Namely that the relative abundance of LiBeB is much greater in the cosmic rays than in the remainder of the solar system. It is possible to ascribe this difference to LiBeB creation by reactions of the more abundant cosmic ray nuclides, e.g. $^{12}C$, $^{14}N$, $^{16}O$, with nuclei in the interstellar medium. Models incorporating this mechanism reproduce the observed cosmic ray abundances in some detail, including the filling of the LiBeB valley and the similar valley lying below the iron peak in the abundance curve.

Since some of the LiBeB so created will thermalize and become part of the interstellar medium, eventually to be incorporated into stars, this process clearly contributes to the light element abundances. One must, of course, demonstrate that it is *quantitatively* effective. Fortunately this demonstration rests on very simple arguments which we present as a prelude to a more detailed discussion.

### 4.1. A simple model.

In the simplest possible model, the yield per unit time of a nuclide "i" is :

$$\frac{dN_i}{dt} = \sum_{\substack{proj.\\tar.}} N_T \int_0^\infty \phi_P(E)\sigma^i_{PT}(E)\,dE \qquad (4.1)$$

where $\phi_P$ is the flux of the cosmic ray projectile P, $N_T$ is the number density of the interstellar target T and $\sigma^i_{PT}$ is the cross section for formation of a nuclide i in a collision of P and T. The important reactions are those for which the product $N_T\ \phi_P$ is large. In Fig. 4.1 one sees that these are for p or α on (p, α , $^{12}C$, $^{14}N$, $^{16}O$, $^{20}Ne$, $^{28}Si$, $^{32}S$, Fe) with p + CNO dominant (except possibly for α + α in the creation of $^{6,7}Li$).

One then has the two main classes of reactions shown in Fig. 4.2. A collision between a GCR proton and a CNO target in the interstellar medium yields low energy LiBeB with a high probability of thermalization. On the other hand, products of reactions induced by CNO projectiles have velocities near the projectile velocity and are likely to be destroyed by further reactions or to escape from the galaxy before slowing to thermal velocities. In our simple model we account for this by limiting the summation of Eq. 4.1 to proton or alpha particle projectiles and to heavier targets. It is adequate for a rough estimate to consider only protons striking CO, since these are the most abundant targets in the interstellar medium.

The particle spectrum emitted by the cosmic ray sources is well described by a power law spectrum

$$\phi_p(E) \sim (E+E_o)^{-2.6} \text{ cm}^{-2} \text{ sec}^{-1} \text{ MeV}^{-1} \qquad (4.2)$$

with E and $E_o$ in MeV/nucleon. Most of the calculations we shall discuss set $E_o = m_p c^2$, i.e. they are power laws in total energy. For such a spectrum most of the particles have energies between 100 and 3000 MeV. If the cross sections do not depend strongly on energy and we shall see later that they do not, the nuclear reactions will be concentrated in this same region. This is shown in more detail in Fig. 4.3. Schematic approximations to the factors in the integrand of Eq. 4.1 are given as a function of energy along with the resulting rate of production in various energy intervals. One notes that about 80 % of cosmic ray production occurs for energies between 100 and 3000 MeV.

Since the cross section is essentially constant in the region of nucleosynthesis we remove it from the integral to obtain

$$\frac{dN_i}{dt} \simeq (N_C \sigma^i_{pC} + N_O \sigma^i_{pO}) \phi_p(E > 30 \text{ MeV}) \text{ sec}^{-1} \text{ cm}^{-3} \qquad (4.3)$$

where $\phi_p(E > 30 \text{ MeV})$ is the total flux above the reaction threshold near 30 MeV. Finally, assuming that the production rate is constant from the birth



of the galaxy (at $t_{galaxy}$) to that of the sun (at $t_{sun}$) and dividing by the density of hydrogen H yields

$$\frac{N_i}{H} = (\frac{N_C}{H} \sigma^i_{pC} + \frac{N_O}{H} \sigma^i_{pO}) \phi_p (E>30 \text{ MeV}) [t_{galaxy} - t_{sun}]. \qquad (4.4)$$

For the best available estimates of the parameters I obtain the results of Table 4. 1. Except for $^7$Li the predictions agree within the uncertainties with the observed abundances of Li, Be and B. A detailed treatment of the cosmic ray transport process (Meneguzzi, Andouze and Reeves (1971) changes these results only in detail, increasing the predictions by 20-40 %. Given these strong indications that, excepting $^7$Li, the elements LiBeB are made in the galactic cosmic rays, we undertake a more detailed review begining with a discussion of the relevant spallation cross sections and techniques for their measurement.

Table 4.1. Simple estimate of Li Be B production by the galactic cosmic rays

| Nuclide | $\sigma^{i\,(a)}_{pC}$ (mb) | $\sigma^{i\,(a)}_{pO}$ | $(N_i/H)^{(b)}_{theory}$ | $(N_i/H)^{(c)}_{expt}$ | Theory/Expt |
|---|---|---|---|---|---|
| $^6$Li | 14.8 | 13.9 | $45 \times 10^{-12}$ | $70 \times 10^{-12}$ | 0.64 (0.90)$^{(d)}$ |
| $^7$Li | 20.5 | 21.2 | $66 \times 10^{-12}$ | $900 \times 10^{-12}$ | 0.07 |
| $^9$Be | 6.2 | 4.4 | $16 \times 10^{-12}$ | $14 \times 10^{-12}$ | 1.13 |
| $^{10}$B | 22.7 | 12.7 | $51 \times 10^{-12}$ | $30 \times 10^{-12}$ | 1.71 |
| $^{11}$B | 57.0 | 26.5 | $118 \times 10^{-12}$ | $120 \times 10^{-12}$ | 0.98 |

a) Cross sections from Lindstrom et al. (1975) at 2.1 GeV.

b) From Eq. 4.4 with σ's from columns 2 and 3 ; $N_C/H = 480\times10^{-6}$ and $N_O/H=850\times10^{-6}$ from Meyer (1978); $\phi_p(E>30) = 8.3 \text{ cm}^2 \text{ sec}^{-1}$ from Meneguzzi, Audouze and Reeves (1971); and $t_{galaxy} - t_{sun} = 9\times10^9$ yr.

c) From Table 2.4.

d) Number in parentheses includes rough estimate of contribution from $\alpha+\alpha \rightarrow {}^6\text{Li}+np$.

### 4.2. Important nuclear cross sections

It is useful to begin by specifying in detail the experimental information and theoretical understanding required by the problem at hand. Since total production cross sections enter Eq. 4.1 one need not measure angular distributions. Nor does one need to measure the energy distribution of the reaction products, since their energy affects only the probability of thermalization and detailed information is not necessary. Finally, since there is, at most, one stable nuclide for each mass and the other isobars decay to it in times short compared to astrophysical time scales, one needs only the sum of cross sections for a given mass.† Thus $^{11}C$, with its 20 min half life, is equivalent to $^{11}B$ for all astrophysical purposes.

As a consequence, only grossly inclusive measurements are required, but they nevertheless present certain difficulties. These are made clear by the data for p +$^{12}C$ at 2.1 GeV shown in Fig. 4.4. The point is that the reaction products all have rather low energy. For Li, about 50 % lie below 5 MeV and the fraction is larger for heavier elements. (For these estimates I assumed exponentially decreasing spectra, a good approximation in the observed region). Thus one needs to identify reaction products down to rather low energies, a difficult task with the usual techniques. For example, the $\Delta E$-E (energy loss, total energy) telescope used for the data of Fig. 4.4 provides only element, not mass, identification and that only above about 0.6 MeV per nucleon. It is then incapable of providing the cross section information necessary for astrophysics. I will discuss below the techniques that have been used to surmount

† In considering the cosmic ray propagation problem two exceptions to this rule must be considered : $^{10}Be$, whose intrinsic half life ($(1.6\pm0.2)\times10^6$ yrs) is comparable to the flight time of cosmic rays to earth, and $^{7}Be$ which decays by capturing a K electron and hence is stable at high energies because it is stripped of these electrons. These exceptions are unimportant for the creation of the rare light elements, where the products have long since been thermalized and have become part of the interstellar medium.



these difficulties.

These techniques must be adequate over a wide range of energies. As indicated in Fig. 4.3 projectiles with energies between perhaps 50 and 10,000 MeV contribute to production by the observed galactic cosmic rays. Evaluation of contributions from a possible flux of low energy cosmic rays and from stellar flare particles requires data in the range from threshold (≈3 to ≈ 30 MeV) to 100 MeV.

The most important reactions, assuming equal cross sections for a given product, are those for which $N_T\ \phi_P$ is large. These products are summarized in Fig. 4.5. One sees that the p+CNO reactions are expected to dominate element production except for $^{2}H$ and $^{6,7}Li$ where the reactions p+$^{4}He$ and $\alpha$+$^{4}He$, respectively, will be important. Anticipating the results of cross section measurements, Fig. 4.5 shows also the products $N_T\phi_P\sigma_{PT}$ where the cross section $\sigma_{PT}$ for producing mass 7($^{7}Li$+$^{7}Be$) is taken mainly from Raisbeck and Yiou (1976 a). For p+$^{4}He$ and $\alpha$+$^{4}He$ the cross sections leading to $^{2}H$(Meyer 1974) and $^{6}Li$ (Meneguzzi, Andouze and Reeves 1971), respectively, are utilized. All these cross sections were evaluated at energies appropriate to the galactic cosmic ray production process (600-700 MeV/nucleon). Several conclusions are clear. Production estimates will be accurate within 10 % if one includes only the p+CNO and $\alpha$+CNO reactions, except that $\alpha$+$^{4}He$ is important for $^{6}Li$. Crude estimates of other cross sections are adequate. Including only p+CO reactions, as in the simple model described earlier, will yield a result low by 30 or 40 %. It also seems unlikely that production of $^{2}H$ by the p+$^{4}He$ reaction can explain the observed abundance of $^{2}H$. From the ratios of $N\phi\sigma$ products in Fig. 4.5, one deduces that the cosmic rays will make 100 times as much $^{2}H$ as $^{7}Li$, while the ratio of abundances $^{2}H/^{7}Li$ is about $10.^4$

It is sometimes necessary to consider the contributions of secondary nuclei, presumably not present in the cosmic ray sources. For example, $^{11}B$ is relatively abundant in the cosmic rays($^{11}B$:$^{12}C$ ≈ 1:4) and its reactions are not negligible, especially for nuclides such as $^{10}Be$, produced from it with unusually large cross sections. However, because it is a "heavy" cosmic ray (Fig. 4.2) it will not contribute greatly to the overall mass-10 production.

### 4.3. Techniques for cross section measurements

Because one needs the yield for stable as well as radioactive nuclei, the measurement of radioactivity following bombardment of a target, while simple, is sufficient or useful only in a few special cases (e.g. production of $^{10}Be$ for use as a clock for cosmic ray age, or $^{7}Be$ for use as an absolute standard in the mass-spectrometric measurements described below). A number of experiments have employed nuclear emulsions as targets. But because of difficulties in identifying the target species and because reactions yielding neutral particles may go undetected the results obtained have often disagreed with those from established procedures. I therefore discuss these no further.

As I have mentioned, straightforward measurements of the double differential cross section $\frac{d^2\sigma}{dEd\Omega}$ using standard $\Delta E$-E telescopes for particle identification are also not generally applicable. The bulk of the yield often lies at such low energies that either the particle does not penetrate the $\Delta E$ detector or the $\Delta E$-E information is insufficient by itself to identify the particle uniquely. A combination of the $\Delta E$-E technique (with thin gaseous $\Delta E$ detectors) and the time-of-flight technique described below may be the method of choice for these measurements.

#### *4.3.1. Mass spectrometry.*

This technique is extremely straightforward in principle. A target of highly purified material is bombarded by a large integrated flux of projectiles (protons or alpha particles). The small quantity ($10^{-9}$-$10^{-12}$g) of product nuclide is separated from the target and the relative yields are measured in a mass spectrometer. Isotope dilution procedures or known radioactive cross sections



are then used to determine the absolute yields. Such measurements at Orsay (Bernas et al. 1965; Yiou 1968) yielded the first values of cross sections for the stable elements. While the technique is applicable at all energies and to all targets, it is painstaking and difficult. For example, one needs to develop a new procedure for each target-product combination. Nevertheless, most p+CO and $\alpha$+CO cross sections at energies above 100 MeV have been measured in this way as described in Fontes et al. (1971), Lestringuez et al. (1971), Raisbeck, Lestringuez and Yiou (1972) ; Yiou et al. (1973); Raisbeck, Lestringuez an Yiou (1975) ; Fontes (1975) ; Raisbeck and Yiou (1975; 1976 a; b; c); Raisbeck and Yiou (1977 a; b) and Fontes (1977).

#### *4.3.2. Relativistic heavy ions*

In the inverse of the usual procedure one accelerates heavy ions such as C, N or O to high energies and allows them to strike targets of H or He. (Heckman et al. 1972). The light elements produced emerge with rather small transverse momenta and almost the same velocity as the beam. They are therefore tightly collimated in the forward direction and are relatively simple to detect and identify from their magnetic rigidity and energy loss in thin detectors. This technique is of great generality, being applicable to any target-projectile combination once the heavy ion beam is developed. Its major limitation appears to be a restricted energy range, the lower energy limit being set by the finite transverse momenta which eventually make separation of adjoining isotopes difficult, and the upper limit by the available energy of heavy ion beams (presently $\leqslant$ 2.1 GeV per nucleon). The only available results are for $^{12}C$+p at 1.05 and 2.1 GeV per nucleon and $^{16}O$ + p at 2.1 GeV per nucleon. (Greiner et al. 1975 ; Lindstrom et al. 1975).

#### *4.3.3. Time of flight*

A pulsed beam of protons or alpha particles strikes a target and the reaction products are detected by measuring both their kinetic energy E and their time of flight from the target t. One then calculates the product $Et^2$ which (non-relativistically) is independent of the velocity of the reaction product but is proportional to its mass. Because only a single detector is involved, the low energy cut-off can be 0.5 MeV or less, thus including the great bulk of the energy spectrum. The only serious experimental complication is that rather specialized gas cells (Laumer et al. 1974 b) are required for gaseous targets. Having measured the double differential cross section, $\frac{d^2\sigma}{dEd\Omega}$, the total yield is obtained by integration over energy and angle. This technique is applicable in principle to all projectiles and targets and has been used extensively at bombarding energies of 100 MeV and below. Only the *mass* of the product particle can be determined, but since only a single isotope of a given mass is stable, this is not often a limitation. More serious, in principle, is that $^9Li$, $^9C$ and $^{11}Li$ are detected, but on astrophysical time scales, have a substantial probability (35 %, 100 % and $\geqslant$ 61 %, respectively) of $\beta$ decaying to particle unstable final states. Fortunately, these nuclides are produced with small cross sections (Lindstrom et al. 1975) and introduce an uncertainly less than about 10 %.

Such time-of-flight measurements were first carried out at Michigan State University (Davids, Laumer and Austin 1969) and more recently at the University of Washington (Jacobs et al. 1974) and Maryland (Roche et al. 1976). Other measurements by these techniques are described in Davids, Laumer and Austin (1970), Rudy et al. (1972) ; Laumer et al. (1973) ; Laumer, Austin and Panggabean (1974 a) ; Panggabean, Austin and Laumer (1974), Oberg et al. (1975) Moyle et al. (1979) and Gökmen, et al. (1980). Present results are confined to energies below about 100 MeV by the availability of pulsed accelerator beams. However, continuous beams can be used, provided a sufficiently thin detector can be placed near the target to provide a reference time for the measurement of reaction product velocity. Thin foil secondary emission detectors employing channel plate detectors are now available and are adequate for this purpose,



providing time resolution in the 200-300 psec range. Some of the Maryland measurements (Moyle et al. 1979) were carried out with such a device.

To summarize this section, it appears that the time-of-flight method, possibly combined with $\Delta E$-E techniques using thin gaseous $\Delta E$ detectors, is, because of its generality, the method of choice for measurements of spallation cross sections. However, when heavy ion beams are available the ease of particle identification may make more accurate results possible, especially at high energies.

### 4.4. Characteristics of the cross sections

Cross sections measured by a combination of all the techniques described above are shown in Fig. 4.6 for protons bombarding the most important targets : $^{12}C$ and $^{16}O$. Several properties are striking. The cross sections reach an asymptotic value for energies above 500 MeV and are not far from this asymptotia at 100 MeV. Furthermore, $^{12}C$ and $^{16}O$ targets have very similar cross sections, except near threshold and for products close to the target mass. These properties are often taken to reflect the high energy concepts of limiting fragmentation and factorization as applied to the peripheral grazing collisions which dominate the cross sections of interest, but they are also obtained from simple Glauber or cascade model approaches. (Goldhaber and Heckman (1978) review these matters). Alternatively, in the picturesque phenomenology of heavy ion physics (think here of a $^{12}C$ beam bombarding a proton target), one imagines that a slice is cut from the projectile during the collision process. Since the nature of the slice is geometrically determined and since one finds empirically that the excitation of the observed projectile fragment is constant for bombarding energies above 20 MeV per nucleon (Scott 1978) the observed results follow.

While it appears from Fig. 4.6 that the p+CO data are adequate, much less is known about the other relevant reactions. Only low energy data is published for $^{14}N$+p (Laumer et al. 1973) although an abstract (Lindstrom et al. 1977) reports that measurements have been made at relativistic energies. Rather complete data will be available soon for $\alpha$ + CNONe up to 40 MeV/nucleon (Gökmen et al. 1980) and a few high energy measurements are available for $\alpha$+CO (see the papers by Fontes (1975), Raisbeck and Yiou (1975; 1977 a), and the review by Yiou and Raisbeck (1976 a)). These establish that the ratio of alpha and proton induced cross sections $\sigma_{\alpha T}/\sigma_{pT} = 2.2 \pm 0.7$ above 200 MeV/nucleon and $1.6 \pm 0.2$ above 1.0 GeV/nucleon. An adequate recipe would be to set $\sigma_{\alpha T}/\sigma_{pT} = 2.2$ for $E_\alpha < 1$ GeV/nucleon and 1.6 at higher energies. Given the expected contribution of the $\alpha$+CO reactions, (Fig. 4.5) this procedure should introduce an uncertainty of less than 5 % in the predicted abundances.

Since some of the cross sections are unknown it seems useful to discuss how one might make a priori estimates of them. The concept of factorization mentioned above implies that the cross section $\sigma^i_{PT}$ can be written as the product of a factor $\gamma_T$ dependent only on the target and another factor dependent on the projectile and the product: $\sigma^i_{PT} = \gamma_T \gamma^i_P$. For light projectiles, $\gamma_T \alpha A^{1/4}$, allowing one to predict that the ratios of cross sections for $^{12}C$+p and $^{12}C+\alpha$ reactions are $(M_\alpha/M_p)^{1/4} \simeq 1.4$. In fact, the ratio is somewhat larger than this (Raisbeck and Yiou 1975 ; 1977 a) presumably reflecting the known failure of factorization for such light targets (Goldhaber and Heckman 1978).

Perhaps the most widely used estimates for the purposes discussed here are those from the semi-empirical formulae developed by Silberberg and Tsao (1973) and by Tsao and Silberberg (1979) Recently these authors (Silberberg and Tsao 1977) have compared the Monte-Carlo and semi-empirical methods for predicting spallation cross sections. For the nuclei which concern us, and at energies above 60 MeV, they conclude that the semi-empirical method is better, predicting proton induced cross sections within a standard deviation of perhaps 30 %. At lower energies, the Monte Carlo predictions are better and provide reasonable results down to perhaps 20 MeV. At still lower energies nuclear structure effects (resonances) can be important and there is no real substitute for measurement. Such a situation is shown for the important $\alpha+\alpha$ reaction in Fig. 4.7.



Fortunately, for our evaluation of the galactic cosmic ray mechanism, this discussion need not concern us in detail, since most of the important cross sections have been measured and estimates need be made only for reactions which contribute at the 10 or 20 % level. The $\alpha+\alpha$ reaction is a possible exception to this statement. Cross sections are now available up to 40 MeV/nucleon (King et al. 1975 ; King et al. 1977 ; Glagola et al. 1978 ; Alard et al. 1979 for $^{6,7}Li$ and $^7Be$ and up to 1 GeV for $^7Be$. (Yiou and Raisbeck 1977). It is now clear that this reaction is unimportant for production of $^7Li$ in the galactic cosmic rays and the present data is adequate for low energy sources. But the $\alpha+\alpha$ reaction may still play a dominant role in the production of $^6Li$ and further measurements of $^6Li$ cross sections are important. Moreover, there is an inconsistency in the cross section for $^6Li$ measured by Alard et al. (1979) at 103 MeV and the results (Glagola et al. 1978) at lower and higher energies.

I have not attempted an exhaustive review here, but I hope all data important for the present application have been mentioned. For a detailed review of the high energy data, the reader is referred to Raisbeck and Yiou (1976 a) and some later results discussed in Raisbeck and Yiou (1977; a;b) and Fontes (1975; 1977). The paper listed in section 4.3.3 provide an adequate bibliography for the low energy data ; that available at the time was reviewed by Bodansky et al. (1975). A review of all the pertinent cross sections is now underway at Maryland (Viola 1980).

Figures 4.6 and 4.7 summarize the data in the most useful fashion for our purpose. The p+CO data describe the bulk of the proton induced reactions and can with adequate accuracy be presumed also to describe the (marginally important) $p+^{14}N$ cross sections at high energy. One obtains the $\alpha$+CO cross sections by assuming that they are 2.2±0.7 (1.6±0.2) times those for protons for $E_\alpha < 1.0$ GeV/nucleon ($E_\alpha > 1.0$ GeV/nucleon) as discussed previously.

Finally it is necessary to extrapolate the $\alpha+\alpha\rightarrow{}^{6}Li+pn$ cross section to high energy in a more or less arbitrary fashion.

### 4.5 Detailed cosmic ray transport calculations

Up to now we have based our discussion on the zero-order model embodied in Eq. 4.1, which is similar in spirit and level of detail to the initial cosmic ray production model of Reeves, Fowler and Hoyle (1970). Following this seminal paper several more detailed calculations appeared ( Meneguzzi, Audouze and Reeves, (1971, hereafter MAR) discussed light element nucleosynthesis in the context of a detailed cosmic ray transport calculation ; Mitler (1970, 1972) and Truran and Cameron (1971) considered also the effects of galactic evolution ; Meneguzzi and Reeves (1975, hereafter MR ) examined possible contributions of low energy particles; and Reeves and Meyer (1978) applied these phenomena to a study of infall of primeval material into the galaxy. Unfortunately the last detailed transport calculations were those of MR and significantly more cross section information is now available. Nevertheless, one does not anticipate major changes in these results. In what follows I will show that rather good estimates of changes in light element production arising from changes in cross sections can be made almost independently of the detailed cosmic ray propagation model.

This "model independence" is fortunate, since our understanding of cosmic rays is far from complete. For example, we do not know the nature of the sources of the cosmic rays, nor the mechanisms that accelerate them and confine them to a poorly defined region of the galaxy. For a discussion of these matters the reader is referred to reviews by Cesarsky (1980), Raisbeck (1979) and Waddington (1977). Fortunately, this level of detail is not necessary for our purposes and one can rely rather directly on the observed properties of the cosmic rays.



We know that the cosmic rays are nearly isotropic, that the spectrum at the cosmic ray sources is well described by a power law in the energy or rigidity and that the source composition does not differ greatly (less than about an order of magnitude for any isotope) from that of the solar system. To produce the abundant LiBeB in the cosmic rays from a source in which they are rare requires that the cosmic rays pass through an average of 5-7 $g/cm^2$ of material on their way to the earth. For an average interstellar gas density of $\lesssim 0.5$ $atom/cm^3$, the average path to the earth is substantially greater than a typical dimension of the galaxy. It is clear that the cosmic rays have wandered for a long time ($\gtrsim 10^7$ y) in a diffusion like fashion in the galaxy, and for many purposes it is possible to employ a homogeneous model, the "leaky box" model (Cesarsky 1980). In this model one replaces the finite galaxy and the point cosmic ray sources by an infinite, homogeneous system in which the sources are distributed uniformly and the spectrum of cosmic rays is everywhere the same. The loss of particles from the system is accounted for by associating with each particle a mean path for excape $\Lambda_e \sim$ 5-7 $g/cm^2$, assumed to be the same for all particles, but possibly dependent on rigidity or energy. For this simple model the distribution of path lengths $\ell$ a cosmic ray has travelled before reaching the earth, is $P(\ell) = \Lambda^{-1}e^{-\ell/\Lambda}$. Here $\Lambda$ describes also the effect of destruction by decay and nuclear interactions and hence $\Lambda<\Lambda_e$ (MAR 1971).

To apply the model one proceeds as follows. Assuming a source composition and spectrum one solves the transport equations which account for transformations of the cosmic rays by nuclear interactions with the interstellar particles; energy loss by collisions with electrons; and catastrophic loss by escape from the galaxy ($\Lambda_e$), decay or a nuclear interaction. The transported spectrum will differ from the source spectrum both in its energy distribution, containing fewer low energy particles, and its particle content, containing, for example, LiBeB which are absent from the source. The abundances of these light elements compared to those of CNO, are used to fix $\Lambda_e$ by insisting that LiBeB/CNO agree with that observed in the cosmic rays at high energies where energy loss and solar modulation effects are unimportant. If necessary one may also adjust the source abundances or the source spectrum shape to improve agreement with observation. By these techniques MAR (1971), for example, established that $\Lambda_e \approx 6.3$ g/cm$^2$. Later MR(1975) showed that the production of thermalized LiBeB was essentially independent of $\Lambda_e$ as long as it was greater than 3.0 g/cm$^2$.

For such a model the production of the light elements is given by :

$$\frac{\partial N_i}{\partial t} = \sum_T N_T \int_0^\infty \left[\phi_p \sigma^i_{pT} + \phi_\alpha \sigma^i_{\alpha T}\right] dE + \langle I_{M_P} \rangle . \qquad (4.5)$$

Contributions to production of i by the cosmic ray protons and alpha particles are described by the first term. Its form is so simple, because as shown in in Fig. 4.2 the products of such collisions have rather low energies, and hence ranges << $\Lambda_e$, so that almost all of them survive to become part of the interstellar medium. Note that $\phi_p$ and $\phi_\alpha$ are transported spectra.

Contributions from heavy cosmic rays are indicated schematically by the last term. At first glance, one might except this term to dominate since $N_T\phi_P$ happens to be larger by a factor of about 3.5 (see for example MAR (1971), Table 2). However, these products are formed at approximately the beam velocity and are likely to escape from the galaxy or to be destroyed by interactions with protons and alphas in the interstellar medium before slowing down. For example, $^9$Be ions with a range $\approx \Lambda_e = 6.3$ g/cm$^2$ have an energy $\approx$ 180 MeV/nucleon, so that only heavy cosmic rays with energy less than this will contribute substantially to the light element yield. Only about 15 % of the transported spectrum lies below 180 MeV/nucleon and taking into account the destruction by nuclear reactions and the exponential path length distributions of the leaky box model only about 50 % of the products of these low energy reactions will be stopped. Considering the intrinsic advantage of 3.5 mentioned above we find that heavy cosmic rays contribute 0.15×0.50×3.5=0.26 as much as protons and alphas. A detailed calculation (MR 1975) yields 0.19 for this fraction. One



expects the corresponding fraction to be slightly smaller for $^{6,7}$Li since the ranges are longer for given energy/nucleon, and conversely to be larger for $^{10,11}$B.

As a result of the small contribution from the heavy cosmic rays, rather accurate estimates of galactic cosmic ray production can be made without detailed transport calculations. It is only necessary to evaluate the first term in Eq. 4.5 (this corresponds to the simple model of Eq.4.1) and to add perhaps 20 % for the contribution of heavy cosmic rays. The $\alpha+\alpha$ reaction is slightly more difficult, lying intermediate between the two extremes of Fig. 4.2 and must be treated with more care.

The calculations of MR(1975) yield the production rates for the light isotopes based on the present cosmic ray flux. To convert this rate to an abundance we need to multiply by the production interval and the ratio of the average flux to that at present. This subject has been reviewed recently by Forman and Schaeffer (1979) who conclude that the average flux has changed by at most a factor two over the past $10^9$ yr. There is some evidence of recent short term variations (100 yr - $10^5$ yr) at the 20 % level and that the flux averaged over the past $4\times10^5$ yr is 50 % higher than that averaged over the last $8\times10^8$ yr. These seems to be no experimental evidence concerning longer time scales, and different models of galactic evolution give different predictions (see Audouze and Tinsley (1974, 1976), Tinsley (1980)). In this circumstance the present flux seems the most reasonable choice. For an irradiation time it is common to choose $10^{10}$ yr as a reasonable round number. One is then considering production into the period following the birth of the sun to which *most* of the abundance determinations of Table 2.4 apply. The results thus obtained are shown in Fig. 4.8 and Table 4.2.

I have presented in Fig. 4.8 the results of MR(1975) because theirs are the most recent of the detailed cosmic ray transport calculations. As is clear from Table 4.2, they are in remarkably good agreement with other predictions, especially if one normalizes to the observed $^{9}Be$. Mitler (1970 ; 1972) obtained somewhat larger abundances of $^{6,7}Li$ than MR, mainly because he used larger estimates for the (then unknown) high energy $\alpha+\alpha$ cross sections. The estimates of MR are now known to be the more accurate for $\alpha+\alpha\rightarrow{}^{7}Li+p$ and probably, though not certainly, for $\alpha+\alpha\rightarrow{}^{6}Li+pn$. Is is not understood why the *absolute* abundances obtained by Moyle et al. (1979) are almost twice as high as the others. These authors use more up to date cross sections but also a source (rather than transported) cosmic ray spectrum and will presumably obtain too much low energy production. It does not seem that either of these effects should make quite such a large change.

There is an important uncertainty in these predictions because of the uncertainty in the cosmic ray spectrum at $E < 1$ GeV, where it is modulated by the effects of electromagnetic fields in the solar system. It may be (Meyer 1980) that $E_o$ in Eq. 4.2 should lie between 200 and 500 MeV, much less than the value of 931 MeV used by MR, corresponding to an increase in the flux of low energy particles. Calculations by MAR (1971) and Moyle et al. (1979) show that while smaller values of $E_o$ increase the overall production rate as expected, the relative rates are little changed. Presumably this reflects the fact that the cross sections *and their ratios* have nearly reached their asymptotic values at 100 MeV. In this fortunate circumstance one can remove most sensitivity to modulation effects by renormalizing the results so as to produce the correct amount of any one isotope.

It is then clear that the galactic cosmic ray source is capable of producing the observed abundances of $^{6}Li$, $^{9}Be$, $^{10}B$ and $^{11}B$ within their uncertainies, but that it does not produce enough $^{7}Li$ (by a factor of 10), or $^{2}H$, $^{3}He$ and $^{4}He$ (by much larger factors). If one accepts the galactic cosmic rays as the source for $^{6}Li$, $^{9}Be$, $^{10,11}B$, one can remove the uncertainties concerning the time variation of the cosmic ray flux and solar system modulation, by normalizing the production to the best known of these abundances , that for $^{9}Be$, as is done on the right hand ordinate in Fig. 4.8



The abundance ratios for the isotopic pairs $^{6,7}Li$, $^{10,11}B$ are especially well known, because chemical fractionation effects are small, and it is hence disappointing and somewhat disquieting that neither of these ratios is well reproduced by the galactic cosmic ray source. While the difference for B is small, less than a factor of two, it seems larger than the uncertainties in the relevant cross sections and in the calculation itself. This conclusion is bolstered by the fact that the $^{11}B/^{10}B$ ratio observed in the galactic cosmic rays, where the same processes operate, is very similar to the calculated value. For example, in the range from 30-1400 MeV/nucleon, measured values of $^{11}B/(^{10}B+^{10}Be)$ lie between 1.2 and 3.1 (much of the relevant data has been summarized by Westergaard (1979)).

The other "inevitable mechanism", the primeval big bang, can produce sufficient $^7Li$ to explain the Li ratio, but produces very little boron. It is then important for the credibility of the overall picture of light element creation that one find a plausible explanation for the boron isotopic ratio that does not destroy the overall agreement for $^6Li$, $^9Be$, $^{10,11}B$ shown in Fig. 4.8. In principle, either destruction of $^{10}B$ or creation of $^{11}B$ could remove the discrepancy and the results of Fig. 4.8 do not give us definite guidance on this point. But possible destruction by n capture seems sufficiently improbable, that recent discussions have chosen the route of creation, motivated by a plausible source of $^{11}B$ in spallation by particles with energies of a few to a few tens of MeV/nucleon. This possibility is examined next.

## 4.6 Nucleosynthesis by low energy particles.

It has been recognized for some time (Bernas et al. 1967) that a flux of sufficiently low energy particles will produce large $^{11}B/^{10}B$ ratios. This follows simply from the Q value for the $^{14}N(p,\alpha)^{11}C$ reaction (Q = −2.92 MeV, less negative than any other reaction) and its consequence that at low energy $^{11}B$ is the only important product of proton induced reactions. Contributions from α induced reactions will reduce the effect, especially if MeV/nucleon is the relevant energy parameter, since, as shown in Fig. 4.9, many of these reactions have Q-values in the −2 to −10 MeV/nucleon range. Nevertheless, detailed calculations by Bodansky et al. (1975) find $^{11}B/^{10}B > 4$ for energies below 15 MeV/nucleon.

Several authors (e.g. Reeves, Fowler and Hoyle 1970) have used this fact to put limits on the low energy cosmic ray flux by requiring that $^{11}B$ not be overproduced. Others (first MAR 1971) suggested that adding such a flux to the inevitable high energy galactic cosmic ray flux might allow one to explain the Li and B isotopic ratios. Reeves and Meyer (1978) review the

Table 4.2. Light element production in the galactic cosmic rays. All abundance ratios with respect to $^1H$ have been multiplied by $10^{12}$

| Isotope Ratios | $E_{xpt}$ (a) | MR 1975 (b) obs | MR 1975 (b) norm | Mitler (1970,1972) (b) abs. | Mitler (1970,1972) (b) norm. | Moyle et al (1979) (b) abs. | Moyle et al (1979) (b) norm. | Meyer (1977) (b) abs. |
|---|---|---|---|---|---|---|---|---|
| $^2H/^1H$ | $(1.6\pm1)\times10^7$ | | | | | | | $(1-3)\times10^4$ |
| $^3H/^1H$ | $(1.8\pm1.2)\times10^7$ | | | | | | | $(1-3)\times10^4$ |
| $^6Li/^1H$ | 70(2) | 70 | 49 | 140 | 87 | 154 | 57 | |
| $^7Li/^1H$ | 900(2) | 128 | 90 | 281 | 174 | 204 | 76 | |
| $^9Be/^1H$ | 14(1.6) | 20 | <u>14</u> | 22.6 | 14 | 37.7 | 14 | |
| $^{10}B/^1H$ | 30(2) | 82 | 57 | 80.4 | 50 | 186 | 69 | |
| $^{11}B/^1H$ | 120(2) | 198 | 139 | 221 | 137 | 374 | 139 | |
| $^7Li/^6Li$ | 12.6±0.2 | 1.8 | | 2.0 | | 1.3 | | |
| $^{11}B/^{10}B$ | 4.5±0.1 | 2.4 | | 2.7 | | 2.0 | | |

a) Taken from Table 2.4 The quantities in parenthesis are error factors. Thus X(2) means the value is X within a factor of 2 either way.

b) The column labelled "abs"(for absolute) is obtained by multiplying the predicted production rate by $10^{10}$ yr. That labeled "norm" is obtained from the relative production rates normalized to reproduce $^9Be$.

work on this subject and argue that it is best to adjust the low energy flux to fit the $^{11}B/^{10}B$ ratio since it is difficult to make $^{11}B$ in other ways, while the big bang makes $^{7}Li$. One then checks whether the flux obtained is consistent with known constraints and determines whether the generally satisfactory description of the abundances shown in Table 4.2 is maintained. The motivation for this approach is the observation of low energy (5-50 MeV) particles in solar flares and in some cosmic ray experiments (see Reeves and Meyer (1978) for discussion). Hence the low energy spectra have usually been written in the form $\phi(E)\alpha E^{-\gamma}$ with $\gamma = 3$-$5^{\dagger}$ as is observed in flare spectra.

Results from Reeves and Meyer for $\gamma = 5$ are shown in Fig. 4.8. Reasonable fits to the abundances are maintained for either value of $\gamma$, assuming that one normalizes to the $^{9}Be$ abundance. If one compares absolute abundances, the predicted values are rather high, especially for $\gamma$=3. For $\gamma$=3 the low energy flux dominates the production of $^{6,7}Li$ as well as that of $^{11}B$.

A similar calculation by Moyle et al. (1979) yields somewhat different results, especially for the ratio $^{7}Li/^{6}Li$ which does not much exceed 3.1 compared to the values near 6.0 obtained by Reeves and Meyer. Since Moyle et al. had more recent cross section information at their disposal, it seems probable that this latter estimate is more reliable, but one should bear in mind that the important $\alpha$+CNO cross sections are poorly known ; these differences may then reflect the different extrapolations (or guesses) involved in estimating unmeasured cross sections. In either case, while the absolute abundances of $^{6,7}Li$ are reproduced within their rather large uncertainties, one cannot reproduce the well known ratio : $^{7}Li/^{6}Li = 12.6 \pm 0.2$.

In summary, the inclusion of a judically chosen low energy flux can re-

† In the low energy region (<100 MeV/nucleon) where ionization losses are important, a source spectrum $q(E)\alpha E^{-(\gamma+2)}$ corresponds to a transported spectrum $\phi(E)\alpha E^{-\gamma}$



produce the $^{11}B/^{10}B$ ratio without seriously disturbing the conclusions drawn from galactic cosmic ray production, but cannot simultaneously explain $^{7}Li/^{6}Li$; this awaits the discussion of the next section. The flux required to fit the $^{11}B/^{10}B$ ratio does not violate known limits on ionization or heating of the interstellar medium(MAR 1971 ; Reeves and Meyer 1978), especially as these fluxes may be confined to the neighborhood of their sources. But in the absence of independent estimates of flux strength, the whole procedure is at present rather ad hoc in nature, and its justification is its plausibility. One hopes that future information on the intensity of low energy fluxes and their spectra will eliminate some of the present ambiguities.

In any case, calculations with more reliable $\alpha$+CNO cross sections are necessary before even the above model conclusions are secure. Measurements have just been completed for $\alpha$+CNONe between 48 and 160 MeV (A. Gökmen et al. 1980) and will improve this situation. Preliminary evaluations of this data (V. Viola 1980) yield $^{7}Li/^{6}Li$ production ratios less than 2, consistent with the low estimates for this ratio mentioned above.

For the present, in any case, I take as a working hypothesis that $^{6}Li$, $^{9}Be$ and $^{10,11}B$ are produced in the galactic cosmic rays, supplemented for $^{11}B$ by a flux of low energy particles, and turn next to a discussion of the other "inevitable" mechanism: the primeval big bang.

## 5. NUCLEOSYNTHESIS IN THE PRIMEVAL BIG BANG

There is now convincing evidence that the Universe began in a primeval big bang and that light element nucleosynthesis almost inevitably accompanies this event. Several reviews of this subject have been published recently (Schramm and Wagoner 1977, Weinberg 1977, Tinsley 1977 and Tayler 1980) and I mention here only those aspects which are particularly pertinent to the creation of the light elements.

Theories of the hot big bang require, in addition to the validity of the equivalence principle, that universal temperatures once exceeded about $10^{11}$ K(kT ≈ 10 MeV), sufficient to disrupt all nuclei and to insure that the weak interactions are in equilibrium. The relative abundance of neutrons and protons is then fixed by equilibrium reactions such as

$$p + e^- \rightleftarrows n + \nu_e . \qquad (5.1)$$

In certain other applications involving equilibrium among heavier elementary particles (Steigman 1979) one must insist on much higher initial temperatures. In any case, it is assumed that these temperatures occur early in the expansion of the Universe from an initial hot dense singularity. Expansion from this initial state is continuing today, as indicated by the observed recession of all distant galaxies. The most convincing evidence for the hot big bang is the record of the hot dense initial state found in the background microwave radiation, which is nearly isotropic and has a spectrum close to that of a black body at T ≈ 2.8 K (Woody and Richards 1979).

### 5.1. The standard big bang.

If one makes , in addition to those mentioned earlier, the further assumptions that :

*(1)* general relativity is the correct theory of gravity ;

*(2)* the Universe is homogeneous and isotropic ;

*(3)* only the presently known particles were present during nucleosynthesis ;

*(4)* the baryon number of the Universe is positive ; and ,

*(5)* the lepton number† is less than the density of photons (i.e. the leptons are non-degenerate),

† The muon lepton number is defined as $L_\mu = n(\mu^-) - n(\mu^+) + n(\nu_\mu) - n(\bar{\nu}_\mu)$ and the electron lepton number $L_e$ in analogous fashion. The n's are number densities.



then one obtains the so-called "standard" big bang model of the Universe for which most calculations have been made.

One must determine the nature of this universe from experiments. If, as is commonly done, it is assumed that the cosmological constant $\Lambda$ is 0, then given T ≈ 2.8 K, the nature of the possible solutions depends only on the mean density of the Universe. It is useful to define a critical density

$$\rho_c \equiv \frac{3H_o^2}{8\,G} = 5.7 \times 10^{-30} \left(\frac{H_o}{55}\right)^2 \text{ g/cm}^3 \qquad (5.2)$$

where the Hubble constant $H_o$ (usually expressed in units of km sec$^{-1}$ Mpc$^{-1}$) relates the observed recessional velocity v of a distant galaxy to its distance R according to $v = H_o R$. Then the solutions can be classified by the value of the dimensionless density $\Omega \equiv \rho/\rho_c$ as shown in Fig. 5.1. In the low density case ($\Omega \lessapprox 1$) the Universe is open, has the escape velocity and will continue to expand forever, while in the high density case ($\Omega > 1$) the Universe is closed and will eventually collapse again to a hot dense singularity. The value of $H_o$ is still somewhat uncertain with values between about 55 and 110 km sec$^{-1}$ Mpc$^{-1}$ appearing in the recent literature (Peebles 1978). These correspond to $\rho_c = 5.7 \times 10^{-30}$ and $22.8 \times 10^{-30}$ g/cm$^3$, respectively.

Besides a gravitional theory, one needs the rates for the rather large number of reactions which synthesize the light nuclei from protons and neutrons. Thses rates, shown in Fig. 5.2, are relatively well known for $A \lesssim 7$ (with one exception, that which dominates the synthesis of $^6$Li) and permit calculation of nucleosynthetic yields to within a few percent for $^4$He and in general to better than a factor of two (again excepting $^6$Li). Detailed calculations of the standard big bang carried out by Wagoner (1973) and Beaudet and Yahil (1977) show that nucleosynthesis takes place 100-500 sec after the begining of the expansion when the temperature is near $10^9$K and the baryon density near 0.01 mg/cm$^3$. The mass fraction $X_i$ of a given isotope i produced during the big bang depends only upon $\rho_B$, the *present* average universal density† of baryons (neutrons and protons, including those bound into nuclei), as is shown in Fig. 5.3. Only $^2H$, $^{3,4}He$ and $^7Li$, *precisely those elements not made in the cosmic rays*, are made in significant quantities.

I have shown the results of Wagoner (1973); these are in generally good agreement with those of Beaudet and Yahil (1977) except that the latter predict a $^7Li$ abundance higher by about a factor of two over part of the mass range (see Fig. 5.4), apparently because different (more recent) reaction rates were employed.

Given the strong dependence of abundance on $\rho_B$ shown in Fig. 5.3, one needs a reliable estimate of the density before reliable predictions of nucleosynthesis can be made. However, density estimates are a matter of some controversy and only broad limits can be stated with certainty. For our purposes it is adequate to quote the (probably) conservative estimate of Gott et al. (1974),

$$0.04 \lesssim \Omega \lesssim 4, \qquad (5.3)$$

where the lower limit is obtained from an estimate of the mass associated with clusters of galaxies and the upper limit from limits on the deceleration of the expansion rate of the Universe. Given the uncertainties in $H_o$, this corresponds to

$$2 \times 10^{-31} \leqslant \rho \leqslant 9 \times 10^{-29}. \qquad (5.4)$$

Since one expects the baryon density to form most of the total density (but see section 7.2) the same limits apply to $\rho_B$.

† It is perhaps surprising that the abundances can be written in terms of the *present* baryon density, rather than that during the era of nucleosynthesis. The connection is provided by the ratio of the temperature during nucleosynthesis and that at present (≈ 2.8 K) which fixes the corresponding ratio of densities.



It is one of the triumphs of the hot big bang model that the observed abundance of $^4He$ is approximately reproduced over the allowed range of densities and is in agreement within the rather small uncertainties for $\rho_B < 2 \times 10^{-30}$ g/cm$^3$. Indeed, the $^4He$ abundance serves as a stringent test of the assumptions of the standard big bang, since deviations from them seriously change the predicted abundance† (Schramm and Wagoner 1977).

## 5.2. A concordant estimate of the universal density

Since the predicted abundance depends strongly on $\rho_B$, which is not accurately determined by astrophysical measurements, one cannot make a priori predictions of nucleosynthesis in the big bang. Rather, one must invert the process (Reeves 1974). Assuming that a nuclide is produced in the big bang, one determines the value of $\rho_B$ required to reproduce the observed abundance of each nuclide. If the picture is valid, the resulting densities should be consistent within their uncertainties.

Figure 5.4 shows the results of this procedure based on the calculations of Wagoner (1973), for $^2H$, $^{3,4}He$ and those of Beaudet and Yahil (1977) for $^7Li$. The sides of the rectangles show the range of abundance $X_i$ for a given isotope from Table 2.4 and the top and bottom, the range of densities $\rho_B$ needed to reproduce these $X_i$ in a big bang expansion. Thus for $^2H$, the sides reach from $X(^2H)=1.0\times10^{-5}$ to $4.0\times10^{-5}$ and the top and bottom from $\rho_B = 3.7\times10^{-31}$ g/cm$^3$ to $7.8 \times 10^{-31}$ g/cm$^3$, the densities which reproduce these abundances. A concordance of masses exists near $5.4\times10^{-31}$ g/cm$^3$. This value of $\rho_B$ corresponds to $\Omega_B = 0.09$ for a Hubble constant of 55 km sec$^{-1}$ Mpc$^{-1}$ (near the lower

† Beaudet and Yahil (1977) have shown that proper separate choices of the lepton numbers for muons and electrons allow one to compensate for these changes so that the tests are not entirely convincing. There seem, however, to be some particle physics arguments, based on grand unification theories, which perhaps make it unlikely that the lepton numbers will be sufficiently large to cause such effects (See section 7.2).

end of the allowed range) and is consistent with the values of $0.05 < \Omega < 0.2$ found by Gott (1979) in a review of density determinations from studies of galaxy clustering[†]. Determinations of $\rho_B$ based on the abundances of $^2H$ and $^7Li$ have been used previously to argue that, since $\Omega_B < 1$, the Universe is open and will continue to expand forever. I will return to this subject in a later section, but remark now that this limit refers only to the *baryon* density and not the total density of matter.

I turn now to the question of whether $^6Li$ might also be produced in the big bang. The results shown in Fig. 5.3 indicate that at the concordant density at most a few percent of the $^6Li$ could be made in this process, but one must remember that the relevant reaction rate (for $\alpha+d\rightarrow{}^6Li+\gamma$) is based on a purely theoretical estimate whose uncertainty is not known. Recently, however, cross sections for this reaction have been measured at center-of-mass energies between 1.5 and 8 MeV by Robertson et al. (1978). Analysis of these data in the framework of a direct-capture model indicates that the actual rate is substantially less than the estimate used by Wagoner (1973). Production of $^6Li$ in the big bang thus appears to be completely negligible in comparison to its production in the cosmic rays.

To summarize, it appears that the light elements *can* be synthetized as a byproduct of well known phenomena : $^2H$, $^{3,4}He$ and $^7Li$ in the primeval big bang and $^6Li$, $^9Be$, $^{10}B$ and $^{11}B$ (partially) in the galactic cosmic rays. An additional mechanism, plausibly a flux of low energy protons and alpha particles, must be invoked to produce additional $^{11}B$ and yield the correct ratio of $^{11}B$ to $^{10}B$.

Having presented such a simple picture it is necessary now to consider

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† With $H_o$ = 110 km sec$^{-1}$ Mpc$^{-1}$, one obtains $\Omega_B = 0.02$ which is uncomfortably small. It then seems difficult to reconcile such large values of $H_o$ with the predictions of big bang nucleosynthesis.



the "complications" of the real Universe and to determine whether this simple description remains viable.

## 6. COMPLICATIONS

When one examines possible elaborations of the simple theory just described, one finds that the situation is indeed complicated. Rather few definite statements can be made, but it seems that the overall effects may be sufficiently small that the simple description survives, although with perhaps a caveat or two attached. Here I will describe the general situation, reserving more detailed comments for the discussion of applications in the next section.

Two broad sorts of problems arise. First of all, one must consider possible sources of the light elements other than the cosmic rays and the big bang. Since abundances are known only within about a factor of two, it is not simple to rule out a possible source of the same strength as those already discussed. And second, one must be concerned with the effects of galactic evolution. One might reasonably imagine that the rate of supernova explosions and hence the cosmic ray flux (if they are associated-this is not yet settled) were greater when the galaxy was young. It follows that the production rate of $^6Li$, $^9Be$ and $^{10,11}B$ was greater then, than at present, unless the density of interstellar targets was substantially smaller. One might imagine also that there is a slow influx of more primitive material into the galactic plane. The origin of this material might be primordial matter swept out of intergalactic space by the motion of the galaxy, or infall of somewhat evolved material from the surrounding galactic halo. I shall refer to this material as infall, regardless of its possible source, and shall assume that it contains significant amounts only of those isotopes made in the big bang. Such infall would tend to dilute the interstellar medium (ISM) in the sense of reducing the concentration of recently born nuclides relative to the $^{1,2}H$, $^{3,4}He$ and $^7Li$ present in the ashes of the primeval big bang. One knows also that interstellar gas can be astrated: that is, incorporated into stars and later returned to the ISM. Some nuclides, e.g. $^{2}H$ and $^{6}Li$, are likely to be totally consumed by this process. Others, including $^{4}He$, are produced by it.

It is possible to incorporate these facts and possibilities into a detailed theory and much work has been done along these lines. (See the reviews of Audouze and Vauclair (1980), Tinsley (1980) and Audouze and Tinsley (1974; 1976). Unfortunately, the experimental information is presently inadequate to constrain these theories and they give only a broad outline of the possibilities consistent with the data, rather than a detailed unambiguous prediction.

### 6.1. Other sources of the light elements.

Reviews of other sources of the light elements have been made by Reeves, et al. (1973), Reeves (1974) and Reeves and Meyer (1978). Possible sources and the isotopes they may produce are : shock waves in supernovae ($^{2}H$, $^{7}Li$, $^{11}B$) ; post-shock nucleosynthesis at the boundaries of supernovae ($^{7}Li$, $^{11}B$); production by neutrinos from collapsing stellar cores ($^{2}H$, $^{7}Li$, $^{11}B$); nova explosions ($^{7}Li$); explosions of supermassive stars ($^{7}Li$); red giant flashes ($^{3}He$, $^{7}Li$) ; $\alpha + \alpha$ reactions near young pulsars ($^{7}Li$); main sequence stars ($^{3}He$, $^{4}He$) ; cosmological cosmic rays ($^{6,7}Li$); spallation in quasars or active galactic nuclei ($^{2}H$, $^{6,7}Li$); and low energy spallation reactions in stellar surfaces or elsewhere (all). Many of these sources are plausible in the sense that they could be effective given certain conditions or properties of the physical system involved. But in most cases detailed a priori calculations have not been done, so one does not know whether the required conditions actually occur in real systems with the necessary probability. Furthermore, in the absence of detailed theories of mass loss during quiescent burning stages, and of supernova, one cannot say with certainty whether an isotope, even if formed, would be likely to survive the processes necessary to transfer



it to the interstellar medium.

These sources are then neither *necessary*, since adequate sources of the light elements are known (except possibly for $^{11}B$), nor are they *inevitable*, since one cannot usually establish with high probability that they contribute significantly. Nevertheless, we must keep them in mind, especially if we draw important inferences from our model of light element creation. In what follows I show by example the methods one can sometimes apply in evaluating the likely importance of a given source.

For reasons which will later become clear the most crucial nuclei in this regard are $^{2}H$ and $^{4}He$. The "primordial" results in Table 2.4 for $^{4}He$ refer, in effect, to systems with $X(A \gtrsim 12) = 0$ (no constituents heavier than $^{4}He$) ; hence they include no contributions from synthesis in normal stars or in any other systems which produce normal amounts of CNO along with $^{4}He$. This fact and the uniformity of $^{4}He$ abundance from galaxy to galaxy (Lequeux et al. 1979) also seem to rule out substantial contributions from explosions of super-massive objects ("little bangs" - Wagoner, Fowler and Hoyle 1967) prior to galaxy formation.

Deuterium is relatively abundant, yet extremely fragile and hence is not simple to produce in its observed abundance. However, Hoyle and Fowler (1973) and Colgate (1973) have suggested that it might be made by shockwaves in Type II supernovae. If shock energies of several MeV per nucleon are reached, spallation reactions can break $^{4}He$ into protons and neutrons. If the post-shock temperature is not too high, then the deuterons formed by proton capture of the free neutrons will not be destroyed by further interactions. It is apparently not established that suitable shock waves form in supernovae and energy requirements seem high (Reeves 1974). But perhaps the most convincing arguments are based on the fact that processes which produce substantial $^{2}H$, tend to overproduce $^{7}Li$, $^{11}B$ or gamma rays. Only rather exotic (and therefore unlikely ?)

sites are possible. For example, production by spallation reactions in quasar-like objects very early in the history of the Universe (Epstein 1977, Eichler 1979, and references therein) cannot be ruled out completely, but certainly seems improbable when compared to the production which occurs naturally during a big bang explosion. One could take the result of Penzias et al.(1977) that deuterium containing compounds are depleted towards the galactic center where stellar processing is intense, as evidence both that astration destroys deuterium and that stellar sources of deuterium are unimportant. But this conclusion is weakened by the possibility of large fractionation effects.

Other isotopes for which additional processes seem rather unlikely are $^6Li$, $^9Be$ and $^{10}B$. It is less simple to make any definite statements about $^7Li$ and $^{11}B$ simply because there are a large number of possibilities, even though any one of them may seem more or less improbable (Reeves et al. 1973 ; Reeves 1974). Of course, it is assumed here that the $^{11}B$ required to reproduce the $^{11}B/^{10}B$ ratio is made by a flux of low energy particles. Should this flux be described by $E^{-\gamma}$ with $\gamma \lesssim 3$, substantial amounts of all the LiBeB isotopes will be produced along with the $^{11}B$ (Reeves and Meyer 1978). Finally, two mechanisms are likely to add to the primeval abundance of $^3He$ : (1) astration will convert primeval (big bang produced) deuterium to $^3He$, some unknown fraction of which will be returned to the ISM ; and (2) low mass stars generate $^3He$ during the normal course of hydrogen burning ; later, convection may carry some of it to the stellar surface where mass loss processes inject it into the ISM.

### 6.2. Effects of galactic evolution : astration, infall and all that.

That light elements formed by other mechanisms are later processed in stars is certain. What is uncertain is the net effect of the processing. Let us suppose that a fraction $f \simeq 0.8$ of the gas *initially* in the ISM has at some time been incorporated into a star. Since $^2H$ is destroyed in stars, one



might naively assume that the effects of astration change $^2H/^1H$ by a factor of 5. The actual effect is less than this, however, because a large, though poorly known, part of the gas forms stars lighter than the sun ($M<M_\odot$). Such stars have lifetimes at least comparable to the age of the galaxy and in effect lock up their gas indefinitely. To fix our ideas, assume that 25 % of the gas which has ever been in stars is now in the ISM. Then for f = 0.8, 20 % of the gas has never been processed and 0.8 × 25 % = 20 % has been processed and returned to the ISM. Then half the present interstellar gas has been processed and half has not. In this case the observed value of $^2H/^1H$ is a factor of two smaller than its primeval value.

The effects of astration also depend on the fragility of the nuclides involved : $^2H$, $^{6,7}Li$, $^9Be$, $^{10,11}B$ and $^3He$ have increasing probability of survival. It is usually assumed (Audouze and Tinsley 1974) that $^2H$ and $^{6,7}Li$ are destroyed by astration and that various fractions of the others survive.

It seems possible that these fractions are always rather small. For example, Bosegaard (1976) quotes estimates for one solar mass stars which indicate that they preserve $^7Li$, $^9Be$, $^{10}B$ and $^{11}B$ only in the outer 2.5 %, 4.8 %, 18.8 % and 17.8 % of their mass, respectively.

If there is infall of primeval material its effects depend on whether the nuclide of interest is also primeval or is instead produced in the galactic cosmic rays. In the former case infall will tend to restore the initial value, offsetting any effects of astration. On the other hand, dilution by infall will further reduce the apparent abundance of nuclides produced in the cosmic rays, adding to the effects of astration.

Given these possible and actual complications one is tempted to conclude that one can learn nothing from nucleosynthesis of the light elements. But it appears to me that one should resist this temptation, recalling that the abundances of all eight light isotopes are reproduced with what is essentially a theory with two parameters : the mean baryon density of the Universe and the intensity of a flux of low energy particles. Moreover, the two mechanisms involved are in some sense inevitable : we know there are cosmic rays and we are pretty sure there was a hot big bang ; only rather natural and straightforward applications of these mechanisms have been made.

The success of the standard model leads one to assume that the net affect of the "complications" is somehow small, perhaps similar to the uncertainties in the abundances themselves. In the case of the big bang produced nuclides $^{2}H$, $^{3,4}He$, $^{7}Li$ this might be because astration is not too large and is to some extent cancelled by infall. In the case of the cosmic ray nuclides $^{6}Li$, $^{9}Be$, $^{10,11}B$ it might be because (Reeves 1974): (a)"more stellar activity implies more GCR and hence more nuclide formation, but simultaneously more astration and stellar destruction, the net effect being an increase of the nuclide content and (b) more infall means dilution...". A proper balance of (a) and (b) could then yield a small effect. Furthermore, if astration destroys all cosmic ray nuclides equally (or almost completely) then normalisation to any one of them ( I have earlier chosen $^{9}Be$) automatically compensates, at the cost of an additional third parameter, for the effects of astration as well as for dilution by infall and a variable cosmic ray flux. It is encouraging that this normalization factor differs from one by less than 50 %.

It then seems most fruitful to take the standard model as a working hypothesis and to see what can be learned from it. Initially the "complications" are assumed to be unimportant but where appropriate, their effects are examined, following hints from models of galactic evaluation.

## 7. IMPLICATIONS OF LIGHT ELEMENT CREATION

The implications of the standard model for astrophysics, cosmology and particles physics are many, including determinations of: the age of the



Universe; the value of the Hubble constant; the rate of change of the gravitional constant G with time ; the allowable masses of neutrinos; fluxes of low energy particles in the galaxy; rates of infall of primeval material into the galactic disk; a limit on the allowed number of neutrinos and hence on the number of quark flavors; and the mean density of the Universe and whether the Universe will continue to expand forever. The last three of these will be discussed in more detail below both because they are of particular interest and because they well illustrate the strengths and weaknesses of this approach. For details on the others see Steigman (1979), Yang et al. (1979), Reeves and Meyer (1978), Schramm and Wagoner (1977) and Olive et al. (1980).

Many of the applications mentioned above are somewhat controversial, perhaps because such important conclusions apparently result from a "trifling investment of fact". However, these results rest on rather straightforward applications of the standard model developed above, and certainly cannot be dismissed out of hand. We are not being asked to "believe impossible things".†

### 7.1. Infall of primitive material into the galactic disk.

Whether there is an infall of primitive material into the galactic plane at a rate comparable to the star formation rate (a few percent of the total mass per $10^{9}$ yr) is still controversial ( Reeves and Meyer 1978 ; Audouze and Tinsley 1974). Recently Reeves and Meyer (1978) noted that the abundance of $^{9}Be$ was, within uncertainties, independent of time over the past $5\text{-}10 \times 10^{9}$ yr (Dravins and Hultqvist 1977) while a roughly constant cosmic ray flux would cause the observed abundances to grow linearly with time. They reconciled these two observations by assuming that the $^{9}Be$ was diluted by the infall of material free of $^{9}Be$ and placed limits on the rate of infall by

† Lewis Carroll, *Alice in Wonderland*.

requiring the predicted rate of change of $^{9}Be$ to be consistent with the observed value of zero to within the uncertainties.†

Unfortunately, uncertainties in the time dependence of the cosmic ray flux and in solar system demodulation corrections combine with uncertainties in the abundances themselves to limit the precision of such estimates. Indeed, Reeves and Meyer (1980) believe that evidence we are presently in a region of high cosmic ray activity (Cassé 1979) makes their earlier results unconvincing. But it seems likely that this approach will be valuable in the future as abundances become better known and as methods for unfolding solar system modulation from the observed cosmic ray fluxes become more reliable.

7.2. The mean baryon density and whether the Universe will expand forever.

Having established that certain of the light isotopes *can* be made in a primeval hot big bang, given a proper value of the baryon density $\rho_B$, it is a short and tempting step to invert this process. Assuming that they *are* made in the big bang, one uses the observed abundances to fix $\rho_B$. It was noted earlier that this implied $\Omega_B \simeq 0.09$, which in the simplest cosmological models corresponds to a Universe that will continue to expand forever. Here, after presenting a roughly historical account of such attempts, I will discuss the possibilities of escaping this conclusion.

Wagoner, Fowler and Hoyle (1967) first noted that the abundances of $^{2}H$ and of other isotopes produced in the big bang could be used to estimate the universal density, although these conclusions were based on larger values of $X(^{2}H)$ than those presently accepted. When the new (lower) estimates of the deuterium abundance appeared a number of authors (Black 1971; Geiss and Reeves 1972) reviewed these arguments. The case for an open Universe was put most

† Of course astration effects are in the same direction ; the authors corrected for their contribution.



convincingly by Gott et al. (1974) who combined limits set by big bang $^{2}H$ nucleosynthesis with other information to place limits on both $\Omega$ and $H_o$. Other reviews of these arguments can be found in Reeves (1974), Schramm and Wagoner (1977) and Yang et al. (1979). In the present approach ($H_o$=55 km sec$^{-1}$ Mpc$^{-1}$ and the results of Fig. 5.4 and Table 2.4) we obtain from $^{2}H$ a best value of $\Omega_B = 0.09$ and a one standard deviation upper limit of $\Omega_B \leq 0.14$. Most of these studies have been primarily based on the abundance of $^{2}H$, because its rapid dependence on $\rho_B$ reduces the importance of abundance uncertainties and corrections for astration and infall. The case for an open Universe has then been strengthened by the failure to find a likely alternative source of deuterium. Experimental evidence that there is a substantial spread in deuterium abundances near the sun (see section 2.1) is somewhat disquieting, calling into doubt that $^{2}H$ was formed by a universal source. However, recent theoretical work of Bruston et al.(1980) identifies effects that lead to a depletion of atomic $^{2}H$ with respect to $^{1}H$, perhaps explaining the observed spread of values and indicating that the higher observed values near $^{2}H/^{1}H = 2.25\times10^{-5}$ are primeval. In sum, the case for big bang creation of $^{2}H$ seems strong.

Because of its relatively large and well known abundance, attempts were also made to use $^{7}Li$ to fix $\rho_B$, but it proved too difficult to estimate contributions from other sources for this approach to be practical. However, Austin and King (1977) pointed out that since the abundance of $^{7}Li$ produced in a big bang increases with increasing $\rho_B$, one can obtain an *upper limit* on $\rho_B$ by requiring that the big bang not make *more* than the observed abundance. This yields (see Fig. 5.4) $\rho_B \lesssim 9\times10^{-31}$ g/cm$^3$, corresponding to $\Omega_B \lesssim 0.16$ for $H_o$=55 km sec$^{-1}$ Mpc$^{-1}$, again corresponding to an open Universe. This limit will be *strengthened* if other sources of $^{7}Li$ are found. For example, if the contribution of low energy particles really generates 50 % of the $^{7}Li$ (Reeves and Meyer 1978), $\Omega_B \lesssim 0.11$. All the values given for $^{7}Li$ are one standard deviation upper limits.

Finally, the accurate estimates of $X(^4He)$ now available imply (Yang et al. 1979) $\rho_B \lesssim 1.2 \times 10^{-30}$ g/cm$^3$ ($\Omega_B \lesssim 0.2$ for $H_o$=55). This limit somewhat weaker than that for $^2H$ or $^7Li$, but by the nature of the abundance determination, it is insensitive to possible effects of astration and infall. It does not appear that $^3He$ provides a convincing constraint since it can be made both in stars and by astration of primeval $^2H$.

The standard model then testifies rather strongly for a low density open Universe, but it must still be cross examined, sharply, to see what loopholes exist in the case. We have already presented reasons for believing that other sources of $^2H$ and $^4He$ are unimportant and the limit for $^7Li$ does not depend on this assumption. It remains to deal with the effects of astration and infall. Based on results from galactic evolution models it has been common to assume (Gott et al. 1974) that the net effect of astration plus infall has reduced the primeval values by a factor of two ; i.e. that the big bang had to make perhaps twice as much $^2H$ and $^7Li$ as are presently observed. Indeed, the correction cannot have been much more than this, or the density deduced would be less than that known to be present in galaxies.† The effect of this correction is to reduce the density deduced from $^2H$ and to weaken the upper limit from $^7Li$ to $\Omega_B \lesssim 0.3$. Mathews and Viola (1979) have pointed out that a comparison of the measured and predicted values of the ratio $X(^2H)/X(^7Li)$ provides an estimate of $\rho_B$ which is independent of astration, since both these nuclides are entirely destroyed by that process. They obtain results consistent with those presented here.

Another possibility is that the big bang expansion does not satisfy the standard assumptions. Schramm and Wagoner (1977) review a number of such

† This argument is especially strong if one accepts the arguments of Bruston et al.(1980) that the primeval value of $^2H/^1H$ is $2.25 \times 10^{-5}$ ($X(^2H) = 3.4 \times 10^{-5}$) which corresponds to $\Omega_B = 0.08$ for $H_o = 55$ km sec$^{-1}$ Mpc$^{-1}$. Another factor of two astration then seems improbable.



possibilities and show that in most cases, the requirement that one reproduce the $^4He$ abundance constrains the model to be close to standard (see also Tayler 1980). However, if one changes the muon and electron lepton numbers ($L_\mu$ and $L_e$) independently (Beaudet and Yahil 1977) one can change the light element production to an almost arbitrary degree. Indeed, David and Reeves (1980) have shown that one can then reproduce the light element abundances even for $\Omega_B \gtrsim 1$. Thus, if arbitrary lepton numbers are allowed, the light element abundances do not seriously constrain the universal density. However, Schramm and Steigman (1979) point out that the lepton numbers necessary to affect nucleosynthesis are large, comparable to the number of photons, and seem highly improbable. For example, if one attributes the observed baryon asymmetry (i.e. that no primeval antimatter has been observed) to the baryon number violating interactions of the grand unification theories (Gaillard 1980), one might expect the lepton numbers to be similar to the baryon number and hence smaller by a factor of $10^{9\pm1}$ than the number of photons.† Such small lepton numbers have negligible effects. Of course, this argument is only attractive, not obligatory, since there is as yet no convincing evidence for the grand unified theories. Observation of a half life for the proton near $10^{31}$ yr would probably constitute such evidence. For further details see Linde (1979), Steigman (1979) and Turner and Schramm (1979).

Another, perhaps more intriguing possibility is that the mass of the baryons does not presently dominate the mass of the Universe as predicted by the standard model. To put this possibility in perspective, we note (see Steigman 1979 and Tayler 1980 for a review of papers on this subject) that

† It is easy to understand qualitatively why the baryon number is not absolutely conserved in the grand unified theories, since quarks and leptons are treated as equals and transformations from one to the other are allowed. In a wide class of these theories, the difference of the baryon and lepton numbers B-L is conserved (Weinberg, 1979 ; Wilczek and Zee, 1979) so that each change of baryon number is accompanied by an equal change of lepton number and the result quoted above follows.

the number of light neutrinos is approximately the same as the number of photons and that if any one of the neutrino types had a mass of 50 eV, the neutrino mass density would (for $H_o = 55$) exceed the upper limit of Eq. 5.3. One must give careful consideration to this possibility in light of the recent evidence for non-zero neutrino masses based on possible observations of neutrino oscillations and on β-decay end points (Reines, Sobel and Pasierb 1980; Lyubimov et al. 1980). In any case, this limit on the mass of stable neutrinos is by far the best available for the muon (Daum et al. 1979) and tau neutrinos (assuming the latter exists and is light, $m_\nu \lesssim 1$ MeV).

It seems difficult to escape the conclusion that the density of baryons is insufficient to close the Universe and that if the baryon density dominates the total density, it is likely that the Universe will continue to expand forever.† If any of the neutrinos have substantial mass ($\gtrsim 1$ eV) their contribution to the cosmological mass density will be important. It seems that if one establishes $\Omega > 0.2$ from measurements of galactic correlations or dynamics, or by other means, it is probable that the density of the Universe is indeed *not* dominated by baryons.

### 7.3 The number of neutrinos and the number of quarks.

The mutual interconnections of cosmology and particle physics, the study of the very large and the very small, have proven more fruitful of results than one might have imagined. I have mentioned the possible impact of the grand unification theories in accounting for the initial baryon asymmetry, and on the other hand, the limits on neutrino masses which follow from those on the cosmological deceleration parameter. This section describes deductions on the number of stable light neutrinos which can be drawn from the abundance of $^4$He. For details the reader is referred to the reviews of Tayler (1980), Steigman

† We assume here that the cosmological constant $\Lambda=0$. See Tinsley (1977) for further discussion of this point.



(1979) and Schramm and Wagoner (1977).

The basic arguments involved are quite simple. Early in the big bang expansion, the energy density is dominated by radiation, i.e. by the contributions of massless (or relativistic) particles. Additional massless particles lead to a greater energy density which in turn increases the rate of the universal expansion since it is proportion to $\rho^{1/2}$. Among the effects of an increased expansion rate is an increase in the neutron to proton ratio n/p,† and since most of the neutrons are eventually incorporated into helium, an increase in the amount of $^4$He synthesized. One then has the connection :

(MORE neutrino species) → (larger ρ) → (faster expansion) → (higher n/p) → (MORE $^4$He)

Quantitatively an additional neutrino species changes $X(^4He)$ by roughly + 0.014.

Steigman, Schramm and Gunn (1977) first applied this relationship to place limits on the number of neutrinos by requiring that the big bang not synthesize too much $^4$He. Results from a detailed reassessment of the problem by Yang et al. (1979) are shown in Fig. 7.1. Detailed big bang calculations yield the curves shown for the standard model with e and μ neutrinos only and for models with up to five additional neutrino species. Assuming $X(^4He) \lesssim 0.25$, in good agreement with our upper limit, and a density consistent with the standard model concordant value of $5.4 \times 10^{-31}$ g/cm$^3$, Yang et al. found that only one additional stable neutrino could be tolerated, presumably that associated with the τ meson.

† This increase can be simply understood. The temperature, density, expansion rate and interaction rates all decrease with time but not equally fast. As long as the weak interaction rate is larger than the expansion rate, interactions such as $p+e^- \rightleftarrows n+\nu_e$ keep $n/p = \exp(-\Delta Mc^2/kT)$ where $\Delta M$ is the neutron-proton mass difference. At some temperature $T_*$, the interaction rate becomes too small to sustain equilibrium and the abundances freeze out at $n/p)_{T*}$. A larger expansion rate means that the freeze out occurs at a larger $T_*$ when $n/p)_{T*}$ is larger. Furthermore, fewer of the neutrinos decay prior to nucleosynthesis if the expansion is rapid.

If one accepts the validity of these constraints, then all the leptons have been discovered ; accepting further the relationship of lepton and quark generations, then only the "top" quark remains to be found. It is also possible, by similar arguments, to place (weaker) limits on the number of superweakly interacting particles (Olive, Schramm and Steigman, 1980). Many interesting possibilities exist if some of the neutrinos are massive. Such neutrinos may be associated with clusters of galaxies and account for the so-called missing mass. If neutrinos can decay by emitting photons, these photons would tend to distort the cosmic microwave spectrum and one can place limits on their flux. For references and some discussion, again see Tayler (1980) and Steigman (1979).

These are far reaching conclusions and one must certainly examine the assumptions which underlie them. One of these, the possible, if perhaps unlikely effect of large lepton numbers has been discussed above. Another sort of objection has been raised Stecker (1980) who suggests that the standard model is inconsistent with the ensemble of the available data. His conclusion is based on the implications of the observed deviation of the background microwave radiation from a black body distribution and (mainly) on inconsistencies in the production of $^4He$. It is clear that the situation is delicate. Stecker bases his conclusion that the big bang overproduces $^4He$ on an upper limit to the $^4He$ abundance of 0.23. In my opinion, the abundance data cannot sustain such a low upper limit, but what seems more relevant is to note that the presence or absence of consistency is based on a difference of 0.02 in $X(^4He)$. At this level one must certainly be concerned with the accuracy of the input data for the calculations. For example, the presumably equivalent calculations of Wagoner (1973) and Beaudet and Yahil (1977) differ by 0.004 in $X(^4He)$, Wagoner's value being larger. Perhaps more important is the possibility that the value of 10.7 min used by Wagoner for the neutron half life may be incorrect. A recent measurement by Bondarenko et al. (1978) yields $\tau_{1/2}=10.13\pm0.09$ min implying that the weak interaction is stronger than had been assumed.



Accepting this result means that the weak interactions freeze out at a lower temperature $T_*$ and less $^4He$ is produced. Quantitatively, this half life change reduces $X(^4He)$ by a bit more than 0.01 (Tayler, 1979), roughly allowing another neutrino to be "squeezed in". However another measurement just published (Byrne et al. 1980) yields $10.8 \pm 0.2$ min, in good agreement with earlier results.

It seems reasonable then to conclude that the standard big bang is at least marginally consistent with present data and that the limit on the number of neutrinos (and quarks ?) must be taken seriously. But if another one or two heavy leptons, presumably associated with long lived light neutrinos, are discovered ; or if the upper limit on the $^4He$ abundance is lowered ; or if the neutron half life is found to be substantially larger than presently thought, then a detailed reexamination of the standard big bang origin of $^4He$ will be required. For a discussion of other possibilities, see Tayler (1980) and Schramm and Wagoner (1977).

## 8. AN AGENDA

Having described our present understanding of the creation of the light elements, it seems worthwhile to mention those areas where progress seems most likely to affect this understanding and to suggest experimental and theoretical work.

Advances in the area of particle physics are probably most crucial. Further developments of the grand unification theories will presumably determine whether processes which generate a baryon asymmetry and small lepton numbers become a priori inputs of big bang cosmologies. A measurement of the proton half-life, or at least an improved limit on it, should be available in the next few years and will constrain the unification theories. Searches for additional heavy leptons are closely coupled to the viability of the standard big bang. Discovery of one or two more of them would certainly call this picture into doubt, but one should perhaps not be surprised if such discoveries are not forthcoming. And, of course, one requires confirmation of the evidence that neutrinos have mass (Reines et al. 1980, Lyubimov et al. 1980).

In the more classical areas of astrophysics, a reduction of the factor of two uncertainties in the Hubble constant would have a great impact. Although we have not stressed this fact, it is rather difficult to accomodate the larger values of $H_o$ ($\approx$ 110 km $sec^{-1}$ $Mpc^{-1}$) within the standard model (Gott, et al. 1974). For the values of $\rho_B$ determined from big bang nucleosynthesis, such large values of $H_o$ imply $\Omega_B$ so small that they conflict with estimates of $\Omega$ obtained from galactic dynamics and the clustering of galaxies. A narrowing of the allowed range of $\Omega$ obtained from such galactic studies would also be valuable. Combining these $\Omega$ and $\Omega_B$ obtained from nucleosynthesis would allow one to estimate the contribution to the masses of galactic clusters of (for example) neutrinos with non-zero mass.

Of the more detailed information needed to strengthen the estimates of the standard model, improved abundance data for $^2H$ and $^4He$ are perhaps most important. If the large variations presently observed for $^2H$ persist, and if models such as those proposed by Bruston et al. (1980) are finally insufficient to explain them, then the picture of universal $^2H$ production and with it the standard model itself face major difficulties. Assuming these questions are resolved, the $^2H$ abundance remains the best estimator of $\rho_B$ and most useful in placing limits on the net effects of astration and infall. Both experimental and theoretical efforts appear to be warranted. And of course, the $^4He$ abundance is crucial in so many contexts that further high precision measurements of $X(^4He)$ and its correlation with heavy element abundances seem almost mandatory.

In the domain of cosmic ray physics, the most critical unknowns, or poorly knowns, are the variation with time of the proton and alpha particle fluxes and the correction for modulation by electromagnetic fields in the solar system. Gamma ray studies, especially the observation of gamma lines from



possible cosmic ray sources (e.g. Cassé and Paul 1980) could improve our understanding of these sources and their time variation, while an improved theory of the modulation of electrons could be applied to better fix the incident hadronic spectra. Given such spectra it is possible to estimate light element production to good accuracy without detailed cosmic ray transport calculations, a great boon to those experimentalists interested in the effects of their new results on calculated abundances. It would be valuable, nevertheless, if a detailed transport calculation were done as a benchmark taking into account the cross sections that have become available since 1974.

Turning finally to nuclear physics, the following measurements seems of most importance: (a) a reliable value of the neutron halflife, which affects nucleosynthesis in the big bang, (b) cross sections for the $\alpha+\alpha\to{}^6Li+np$ reaction at $E_\alpha>200$ MeV, which are needed to improve estimates of $^6Li$ production in the galactic cosmic rays, (c) cross sections for $\alpha$+CN→LiBeB reactions at $E_\alpha<50$ MeV, which affect nucleosynthesis by low energy particles and (d) evaluation of the uncertainties in big bang nucleosynthesis due to uncertainties in the nuclear reaction rates.

## 9. CONCLUDING REMARKS.

We have reviewed the abundances of the light elements ($A < 12$) and have found that these are known rather well, generally to within a factor of two and, in the case of $^4He$, to better than 10 %. While these elements, except for $^4He$ and perhaps $^3He$ are too fragile to be made in stars, the site of most other nucleosynthesis, they are synthesized rather naturally by other well documented mechanisms. A standard model of the creation of the light elements has evolved, in which these elements are synthesized as shown in Table 9.1. Namely, $^6Li$, $^9Be$ and $^{10,11}B$ are made slowly in the galactic cosmic rays by a flux of particles whose average intensity is very close to that observed at present, while $^2H$, $^{3,4}He$ and $^7Li$ are made primevally during the big bang expansion of a Universe with a present mean baryon density of about $5 \times 10^{-31}$ g/cm$^3$.

Table 9.1 Sources of the light elements.

| Isotope | Galactic Cosmic Rays [a] | Big Bang [a] | Other |
|---|---|---|---|
| $^2H$ | No | Yes | Unlikely |
| $^3He$ | No | Yes | Likely |
| $^4He$ | No | Yes | ≈ 20 %, H burning |
| $^6Li$ | Yes | No | Possible (-)[b] |
| $^7Li$ | ≈ 10 % | Yes | Possible (+)[b] |
| $^9Be$ | Yes | No | Possible (-)[b] |
| $^{10}B$ | Yes | No | Possible (-)[b] |
| $^{11}B$ | Yes | No | Yes [c] |

a) The entry "yes" means the computed yield is in quantitative agreement with observation and "no" that it is hopelessly low.

b) If a flux of low energy particles, $\phi \propto E^{-\gamma}$ is responsible for $^{11}B$ as suggested in the text, it may (depending on the value of $\gamma$) also produce significant quantities of the other isotopes. Hence the word "possible". A following (+) indicates that additional sources also seem likely, a(-) that they do not.

c) In this instance "yes" means that while some $^{11}B$ is produced in the GCR the ratio $^{11}B/^{10}B$ is not reproduced, so there must be another source of $^{11}B$.

In principle, this model is free of parameters, but in practice one must introduce two (or three) of them. Nucleosynthesis during the big bang expansion depends so strongly on the mean baryon density that it is not adequate to fix it from other astronomical evidence. Rather, one must take $\rho_B$ as a parameter: the density that best fits the four observed abundances. One then finds the concordant value of $\rho_B$ noted above. Another parameter is connected with the one ad hoc element in the model. The galactic cosmic rays yield the absolute



amounts of $^{10}B$ and $^{11}B$ within their uncertainties, but not the accurately known value of their ratio, giving $^{11}B/^{10}B \approx 2.5$ rather than the observed value of 4.05. One can make $^{11}B$ in a number of ways (Section 6.1) but it seems most plausible to appeal to spallation production by a flux of low energy particles. The second parameter describes the intensity of this flux.

It is less clear that a third parameter is necessary. Production rates based on the present cosmic ray flux adequately reproduce the abundances of $^6Li$, $^9Be$ and $^{10}B$. But one does not have evidence that these fluxes were in fact constant to better than a factor of two, even over the last $10^9$ years. There is no information for earlier times. One would not, then, have hesitated to renormalize the cosmic ray flux, provided the change was not large. The third parameter is this normalization constant, fixed to reproduce the best known abundance, that of $^9Be$.

Systematic uncertainties are of two sorts. First of all, plausible alternative sources of most of the light elements have been suggested and, in the absence of detailed calculations, cannot always be rigorously ruled out (or in). Some judgment, representing that of the present and other reviewers, of the likelihood of such sources being important is noted in Table 9.1, but this is clearly rather subjective and may reflect to some extent the effort devoted to searching for such sources. This has been largest for $^2H$ and $^7Li$. Second are the changes in the abundances wrought by the processes of galactic evolution, including astration (or processing by stars) and possible infall into the galactic disk of more primitive material which dilutes the interstellar medium. Models of these processes indicate that their effects on big bang produced nuclides tend to be small, perhaps a factor of two; for these nuclides the effects of astration and infall tend to cancel. Indeed, effects substantially larger than this would be difficult to reconcile with a big bang origin of $^2H$. Effects can be larger for the cosmic ray nuclides, but since they are all diluted equally by infall, to the extent that they are also affected equally by astration, normalization to any one of them, as we have done, accounts for evolution effects as well as for possible time variations of the cosmic ray flux. For examples, see Audouze and Tinsley (1974).

In sum, the eight abundances at our disposal have been described within uncertainties by a theory with three parameters. The mechanisms involved are "inevitable" in the sense that they were introduced to explain other well documented phenomena and nucleosynthesis of the light elements is a natural, almost unavoidable, byproduct. Moreover, the parameters introduced turn out to have reasonable values. By the usual astrophysical standards this is a smaching success and it was natural to adopt this standard model of the creation of the light elements as a working hypothesis and to see what further implications could be drawn from it.

These included : an estimate of the rate of infall of primitive material into the galactic plane ; a determination that the density of baryons is insufficient to close the Universe, which will then continue to expand forever; and a limit of three on the number of weakly interacting light neutrinos which indicates that no more heavy leptons remain undiscovered and that there are only six quark flavors in nature. These are far reaching conclusions and one must immediately follow their statement by the caveat that the cosmological model on which they are based is not established with complete certainty. But what does seem certain is that there are strong interconnections among nuclear physics, light element nucleosynthesis, cosmology and particle physics and that it is no longer possible to consider these subjects in isolation. Thus, a new measurement of the neutron lifetime may change our estimate of the number of quarks in nature, through the intermediary of $^4He$ synthesis in a standard big bang cosmology.

In the past the flow of information has been from nuclear and particle



physics toward astrophysics and cosmology. But now some flow in the other direction is discernable ; indeed as Steigman (1979) has pointed out, the early Universe may provide a laboratory for particle physics at energies and densities which far exceed those available in any terrestrial laboratory. This development can only entrance the interest and progress in already exciting fields.

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## GLOSSARY

| | |
|---|---|
| A | Atomic weight |
| Astration | Processing by stars. Material incorporated into stars has been astrated. |
| $^{Z}A/^{Z'}A'$ | Ratio by number of isotope $^{Z}A$ to isotope $^{Z'}A'$. |
| G CR | Galactic cosmic rays. |
| G | Gravitional constant = $6.67 \times 10^{-8}$ cm$^3$ g$^{-1}$ sec.$^{-3}$. |
| HII regions | Regions where hydrogen has been ionized. |
| $H_o$ | Hubble constant ; its definition follows Eq. 5.2. |
| Infall | Material entering the galactic disk. See begining of Section 6. |
| ISM | Interstellar medium. |
| $L_e$ | Electronic lepton number $L_e \equiv n(e^-)-n(e^+)+n(\nu_e)-n(\bar{\nu}_e)$, where the n's are number densities. |
| $L_\mu$ | Muonic lepton number ; defined analogously to $L_e$, |
| Light element | Any isotope with A < 12. |
| Mpc | Megaparsec. a unit of distance = $3.3\times10^6$ light yr = $9.5\times10^{23}$ cm. |
| Metal | Any element except hydrogen and helium. |
| $\Omega$ | $\Omega \equiv \rho/\rho_c$ |
| $\Omega_B$ | $\Omega_B \equiv \Omega_B/\Omega_c$ |
| $\phi(E)$ | Energy spectrum of cosmic rays after transport. |
| Primeval | Also primitive or primordial. Of or relating to the earliest ages. Applied to the big bang and to isotopes synthesized in it. |
| q(E) | Energy spectrum of cosmic ray sources. |
| $\rho$ | Density (g/cm$^3$). Usually refers to mean universal density |
| $\rho_B$ | Mean universal density of baryons. |
| $\rho_c$ | Critical density. For $\rho > \rho_c$ the Universe is closed (Eq. 5.2) |
| $\sigma^i_{PT}$ | Cross section for P+T→i+ anything. The label "i may specify a particular isotope or may be cumulative in the sense that it includes all isotopes of a given mass. |



| | |
|---|---|
| ⊙ | Referring to the sun. Thus $M_\odot$ is the mass of the sun. |
| Standard big bang | Usual model of the big bang defined by the assumptions at the beginning of section 5.1 |
| $X_i$ | Fraction of total mass in an isotope (or element) labelled "i". |
| $X(^{Z}A)$ or X(Z) | Fraction of total mass in isotope $^{Z}A$ or element with atomic number Z. E.g. $X(^2H)$ or X(Li) |
| Y | $Y \equiv X(^4He)$, mass fraction of $^4He$. |
| Z | $Z \equiv X(A>4)$, mass fraction of metals. Also, atomic number. |

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FIGURE CAPTIONS.

FIG. 2.1 Schematic curve of the relative number-abundances. The labels on the curves correspond to the different processes which produce a given range of elements. For further details, see Clayton (1968). (From Rolfs and Trautvetter 1978).

FIG. 2.2 Measurements of $^{2}H/^{1}H$ deduced from Lyman series absorption of light from O and B stars. The solid boxes give the mean value along a given line of sight. For details and references see Laurent et al. (1979) from which the figure was taken.

FIG. 2.3 Comparison between observed He and heavy element abundances (Y and Z). The filled circles are the higher quality observations, the cross represents the Orion nebula and the solid line is a least squares fit to all the data.

FIG. 2.4 Boron abundance (log B/H) of 18 stars as a function of stellar surface temperature. The point at $\sim$ 6000 K is the sun. All values must be increased by about 50 % to account for effects of non local-thermal-equilibrium. This has been done in Table 2.4. (From Boesgaard and Heacox 1978).

FIG. 4.1 Relative abundances of the elements in the solar system and in the cosmic rays, normalized to Carbon = 100. (From data given by Meyer, Ramaty and Weber, 1974).

FIG. 4.2 Fate of reaction products from light and heavy cosmic rays.

FIG. 4.3 Factors entering the integrand of Eq.4.1. The height of the shaded histograms on the right hand scale shows the fraction of element production in the corresponding interval.

FIG. 4.4 Energy spectra at a laboratory angle of 90° for 2.1 GeV protons on $^{12}C$ (Westfall et al. 1978). The solid lines are fitted to the data shown and the dashed lines to the data of Greiner et al. (1975) taken with 2.1 GeV per nucleon $^{12}C$ ions bombarding a hydrogen target.

FIG. 4.5 Relative importance of various reactions for light element production *(Lower panel)* : Products $N_T\phi_p$ calculated from the target abundances of Meyer (1978) and for cosmic ray fluxes with $\phi_p/\phi_\alpha = 10$. *(Upper panel)* : Products $N_T\phi_p\sigma_{pT}$. In some cases the products have been divided by the factor shown. Values less than 0.1 have not been plotted.

FIG. 4.6 Cross sections for production of LiBeB by p+$^{12}C$ and p+$^{16}O$ reactions, denoted (⧫) and (✱) respectively. The cross sections have been multiplied by the factor shown for display purposes. Note the change in scale at 100 MeV. The bars on the right hand ordinate show results for p+$^{12}C \rightarrow {}^{6,7}Li$, $^{9}Be$ at 300 GeV and the arrows show the thresholds for reactions on $^{12}C$ and $^{16}O$. Where there is a significant difference it happens that the threshold for $^{12}C$ is at lower energy.

FIG. 4.7 Excitation functions for production of masses 6 and 7 in the $\alpha + \alpha$ reaction. Data below 50 MeV are from King et al. (1977) and those at higher energies from Glagola et al. (1978), solid symbols, and Alard et al. (1979), open circles. (a) $^{7}Be$ and $^{7}Li$ (b) Various contributions to mass-6 : (●,○) total production ; (▲) $^{6}Li$+pn; (■) $^{6}Li$+d; (x) $^{6}He$+2p. (Adapted from Glagola et al. 1978).

FIG. 4.8 Production of $^{6,7}Li$, $^{9}Be$, $^{10,11}B$ by the galactic cosmic ray source compared to the abundances of Table 2.4. The uncertainties shown include only those in the abundances. *(Left hand panel)* : Production rates of MR (1975) continued for $10^{10}$ yr. *(Center panel)*: Relative production rates of MR normalized to the observed abundances of $^{9}Be$. *(Right hand panel)*:



Effect of addition of a source of the form $\phi(E) \propto E^{-5}$ with strength adjusted to fit the $^{11}B/^{10}B$ ratio. The relative production rates are normalized to fit the observed abundance of $^{9}Be$.

Fig. 4.9 Thresholds (in MeV/nucleon) for p and $\alpha$ induced reactions which produce LiBeB. The targets considered are $^{12,13}C$, $^{14}N$, $^{16}O$, $^{20}Ne$ (From Jacobs 1974).

Fig. 5.1 Various Friedman models of the Universe as classified by the relationship between $\rho$ and $\rho_c$. R(t) is a scale factor of the Universe as a function of time t. (Adapted from Tinsley 1977).

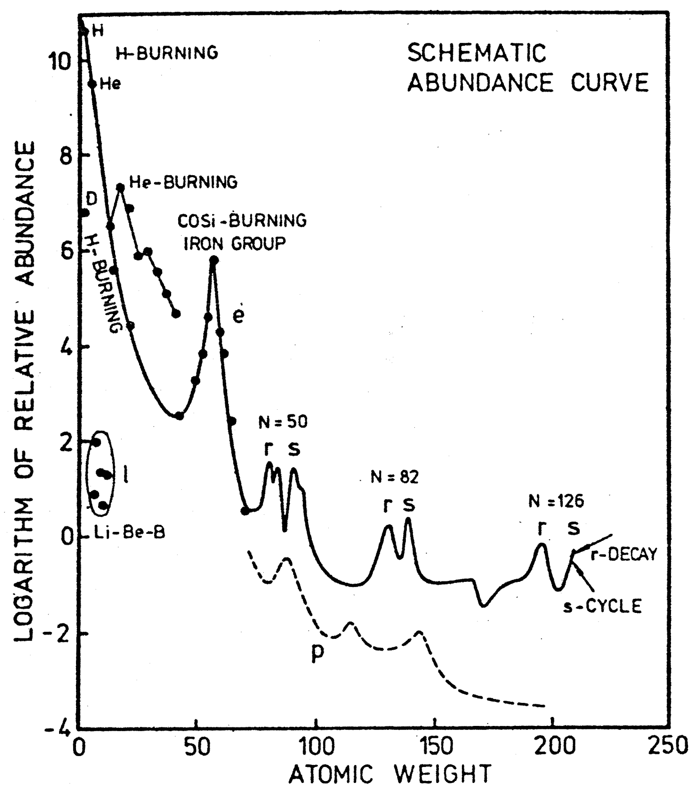
Fig. 5.2 Big bang reaction at net work for A < 12. All reactions indicated by arrows were included in the calculations of Wagoner (1973). (Adapted from Wagoner 1973).

Fig. 5.3 Abundances $X_i$ produced in a standard big bang expansion. These abundances depend only on the present value of the baryon density $\rho_B$ and the temperature T describing the background microwave spectrum (From Schramm and Wagoner 1977).

Fig. 5.4 Determination of the universal baryon density $\rho_B$ from big bang nucleosynthesis. The calculations are from Wagoner (1973), and for $^{7}Li$, also from Beaudet and Yahil (1977), labelled BY. The curve for $^{3}He$ has been divided by 100 for display purposes. The long shaded bar at $5.4 \times 10^{-31}$ g/cm$^{-3}$ is the resulting concordant density. Also shown are the values of $\rho_B$ corresponding to $\Omega_B = 0.04$, a lower limit on the density in galaxies (see Eq. 5.3), and $\Omega_B = 1.0$ which divides closed from open universes. Both are calculated for $H_o = 55$ km sec$^{-1}$ Mpc$^{-1}$.

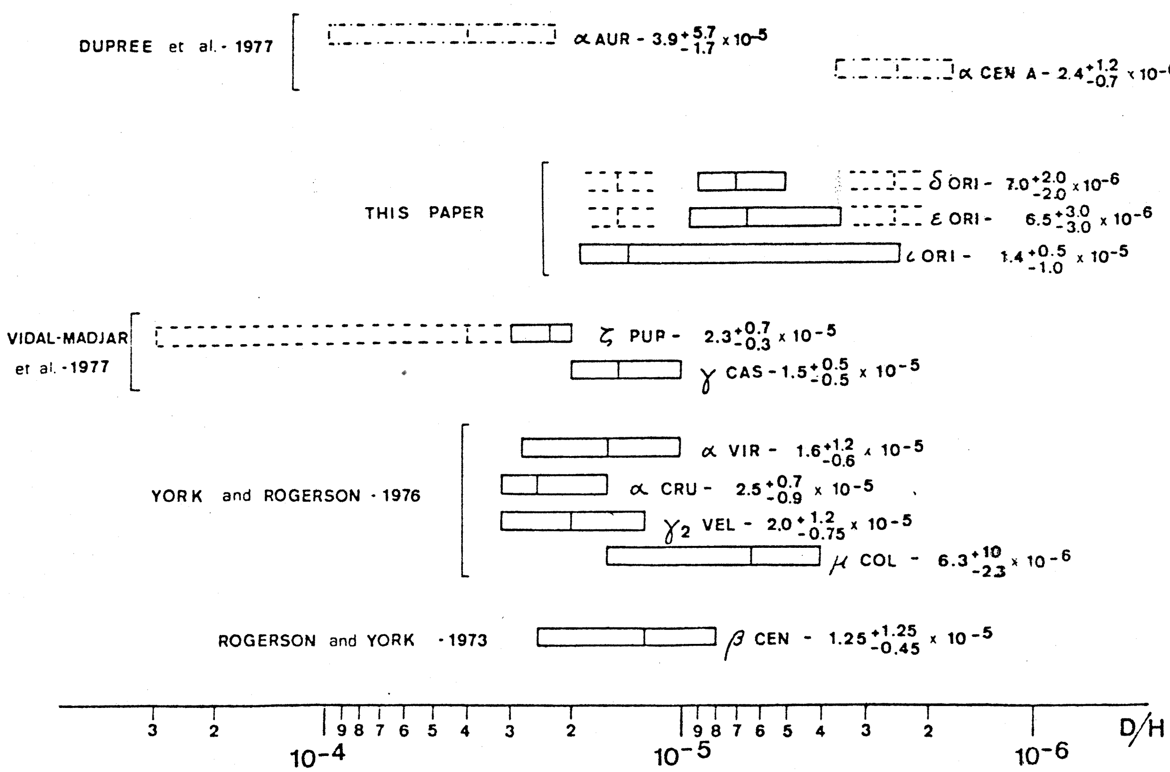
Fig. 7.1 Results of big bang calculations for various numbers of neutrinos.

The standard model includes only the electron and muon neutrinos. The dashed line is the assumed upper limit ($X(^4He) \leq 0.25$) on the helium abundance and the arrow indicates the concordant density obtained here by fitting the observed abundance of $^2H$, $^{3,4}He$, $^7Li$. (Adapted from Yang et al. 1979).



SCHEMATIC ABUNDANCE CURVE
H
He
H-BURNING
He-BURNING
D
H-BURNING
COSi-BURNING
IRON GROUP
e
N = 50
r s
N = 82
r s
N = 126
r s
r-DECAY
s-CYCLE
l
Li-Be-B
p
LOGARITHM OF RELATIVE ABUNDANCE
ATOMIC WEIGHT
10
8
6
4
2
0
-2
-4
0
50
100
150
200
250


Fig. 2.1



DUPREE et al. - 1977
α AUR - 3.9 +5.7 -1.7 x 10-5
α CEN A - 2.4 +1.2 -0.7 x 10-6
THIS PAPER
δ ORI - 7.0 +2.0 -2.0 x 10-6
ε ORI - 6.5 +3.0 -3.0 x 10-6
ι ORI - 1.4 +0.5 -1.0 x 10-5
VIDAL-MADJAR et al. - 1977
ζ PUP - 2.3 +0.7 -0.3 x 10-5
γ CAS - 1.5 +0.5 -0.5 x 10-5
YORK and ROGERSON - 1976
α VIR - 1.6 +1.2 -0.6 x 10-5
α CRU - 2.5 +0.7 -0.9 x 10-5
γ2 VEL - 2.0 +1.2 -0.75 x 10-5
μ COL - 6.3 +10 -23 x 10-6
ROGERSON and YORK - 1973
β CEN - 1.25 +1.25 -0.45 x 10-5
3 2 9 8 7 6 5 4 3 2 9 8 7 6 5 4 3 2
10-4
10-5
10-6
D/H


Fig. 2.2

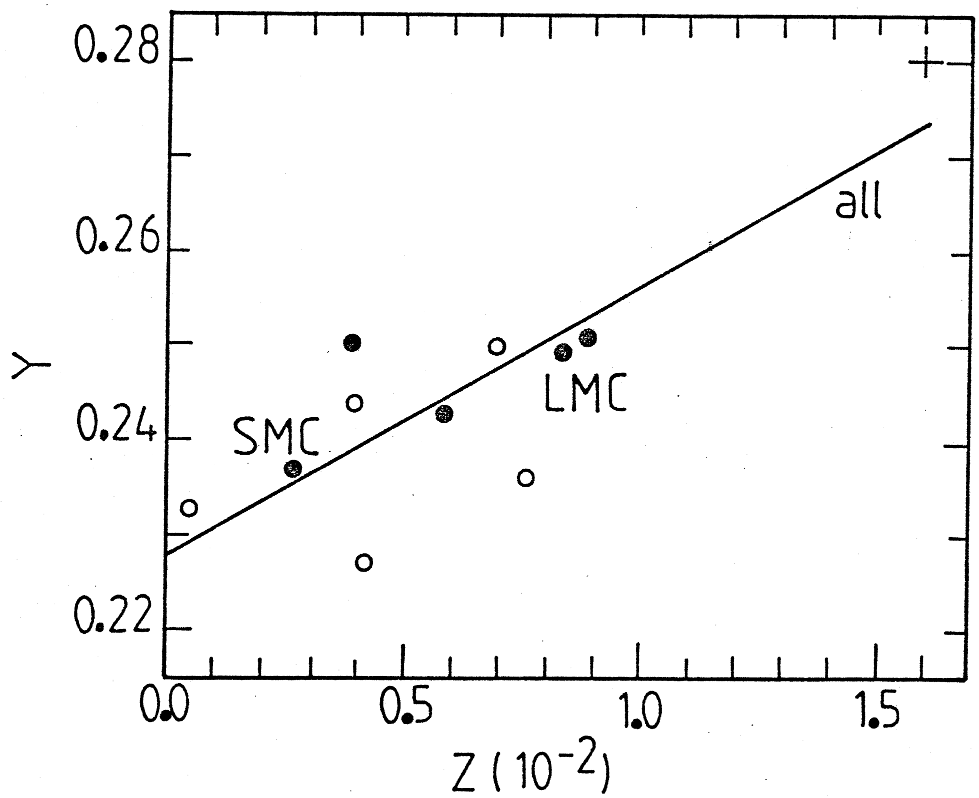



Fig. 2.3

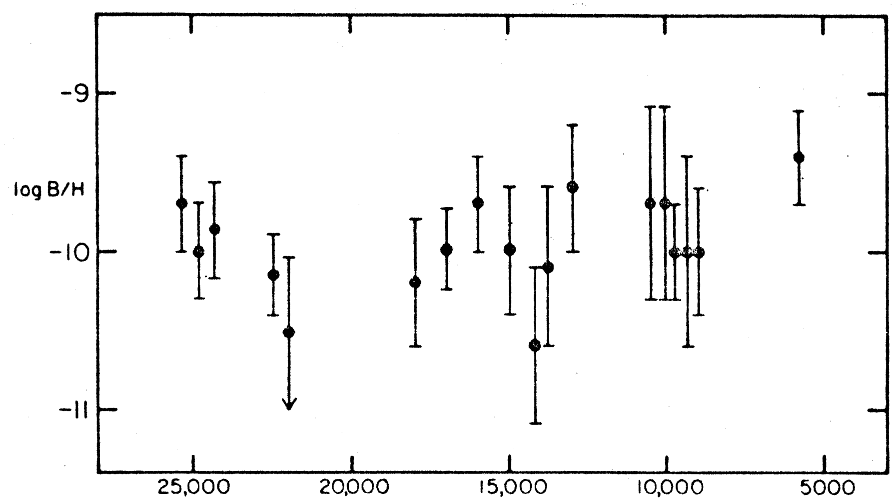
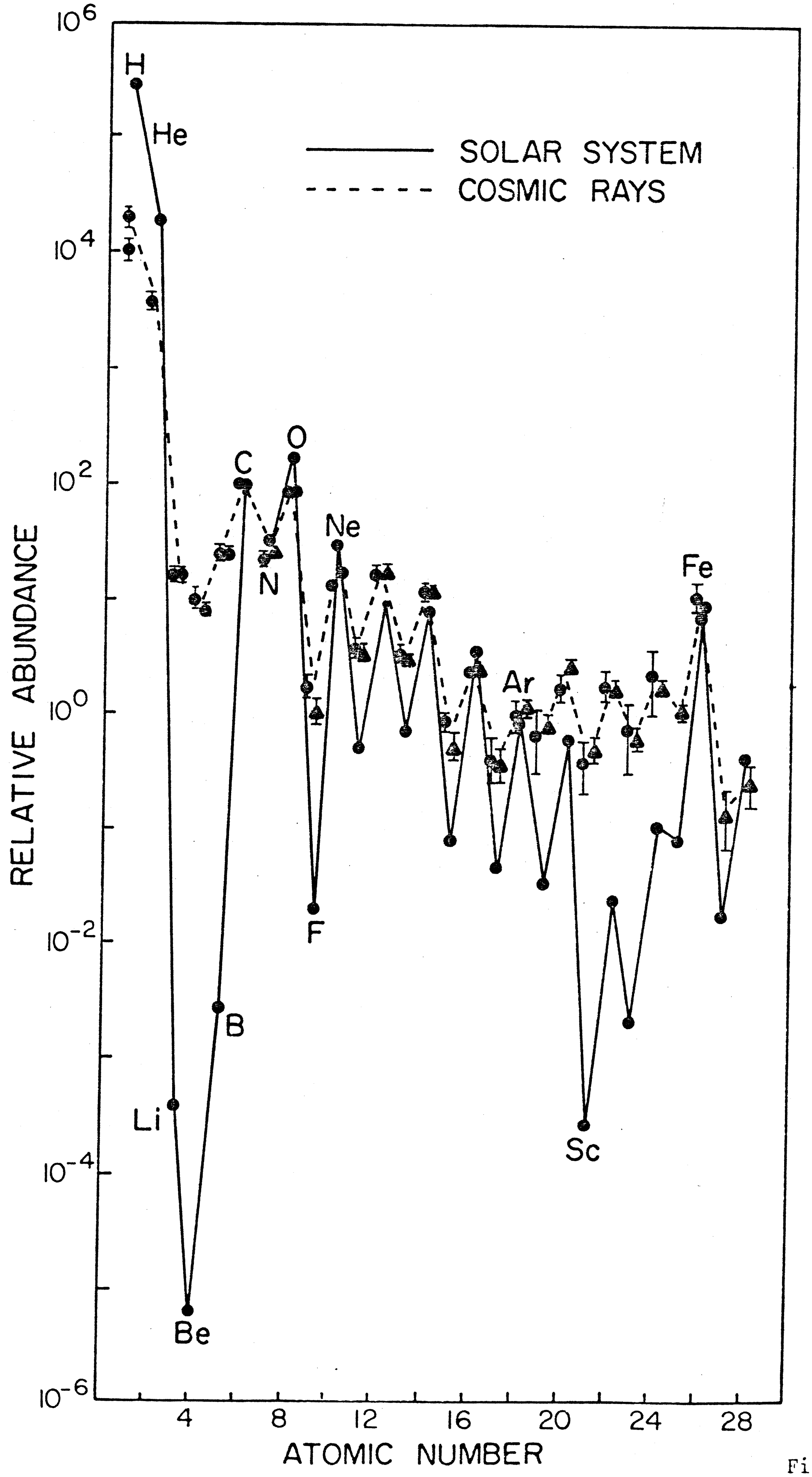
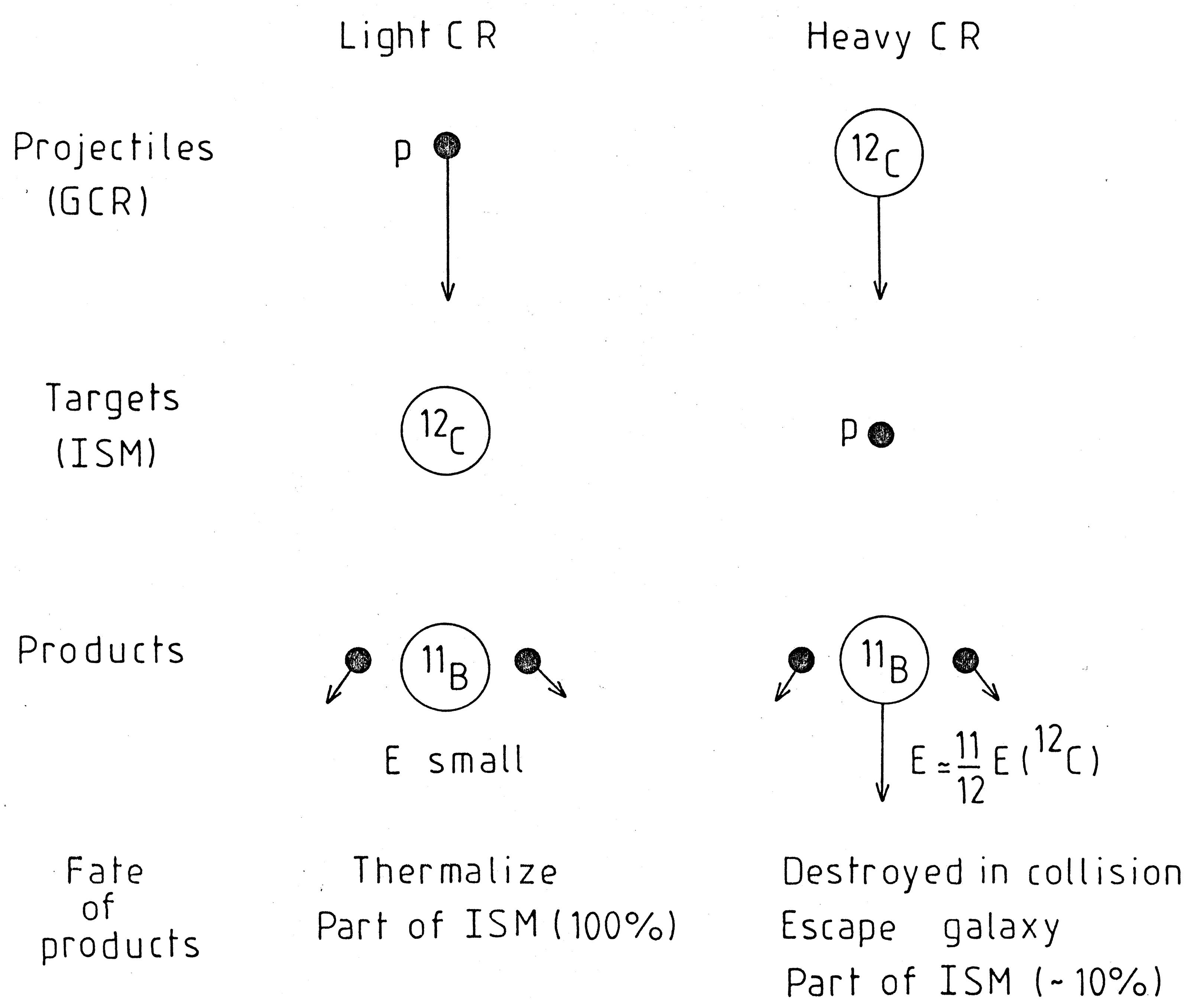



Fig. 2.4



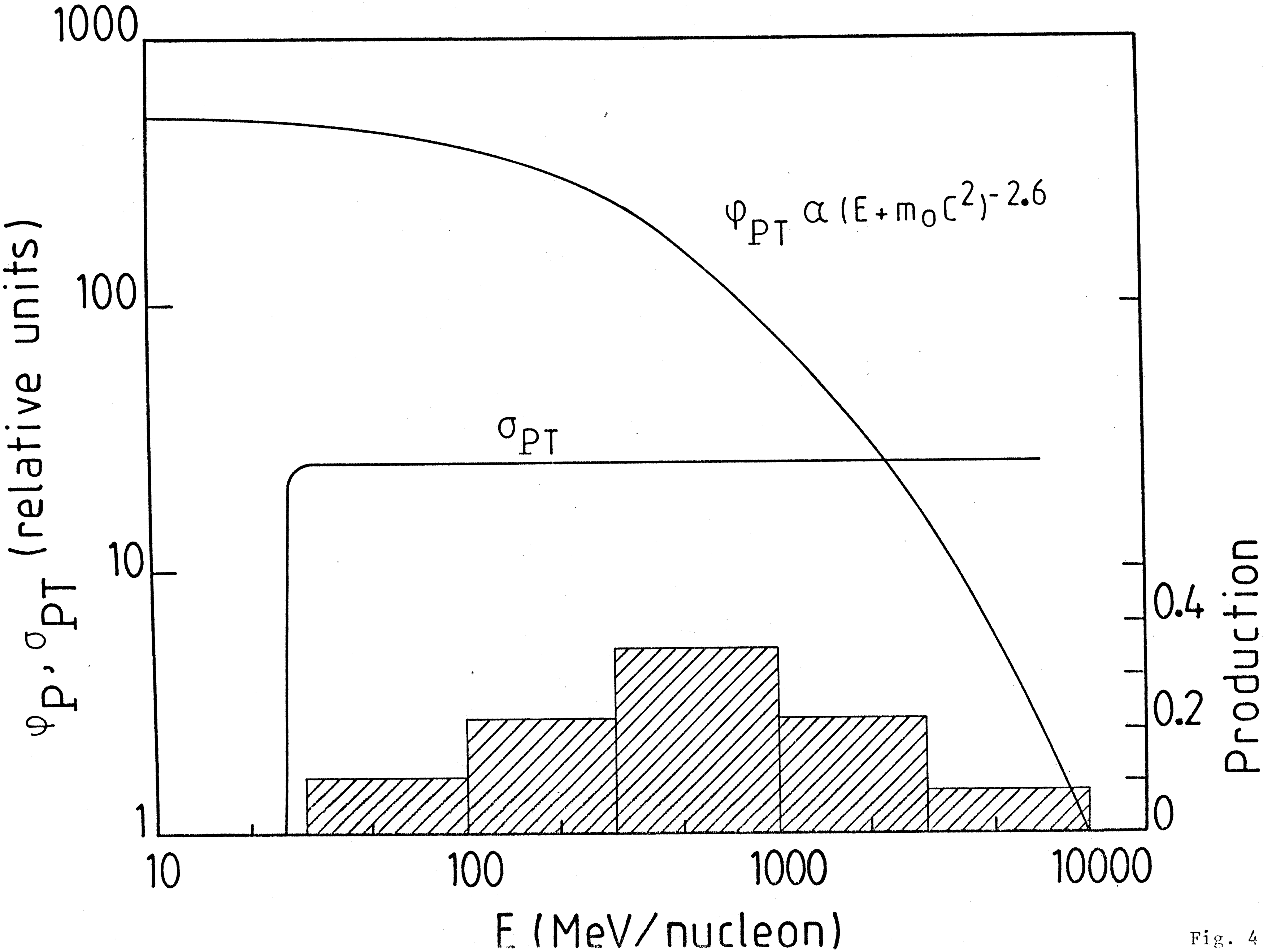
SOLAR SYSTEM
COSMIC RAYS
RELATIVE ABUNDANCE
ATOMIC NUMBER
$10^6$
$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
$10^{-6}$
4
8
12
16
20
24
28
H
He
Li
Be
B
C
N
O
F
Ne
Ar
Sc
Fe


Fig. 4.1.



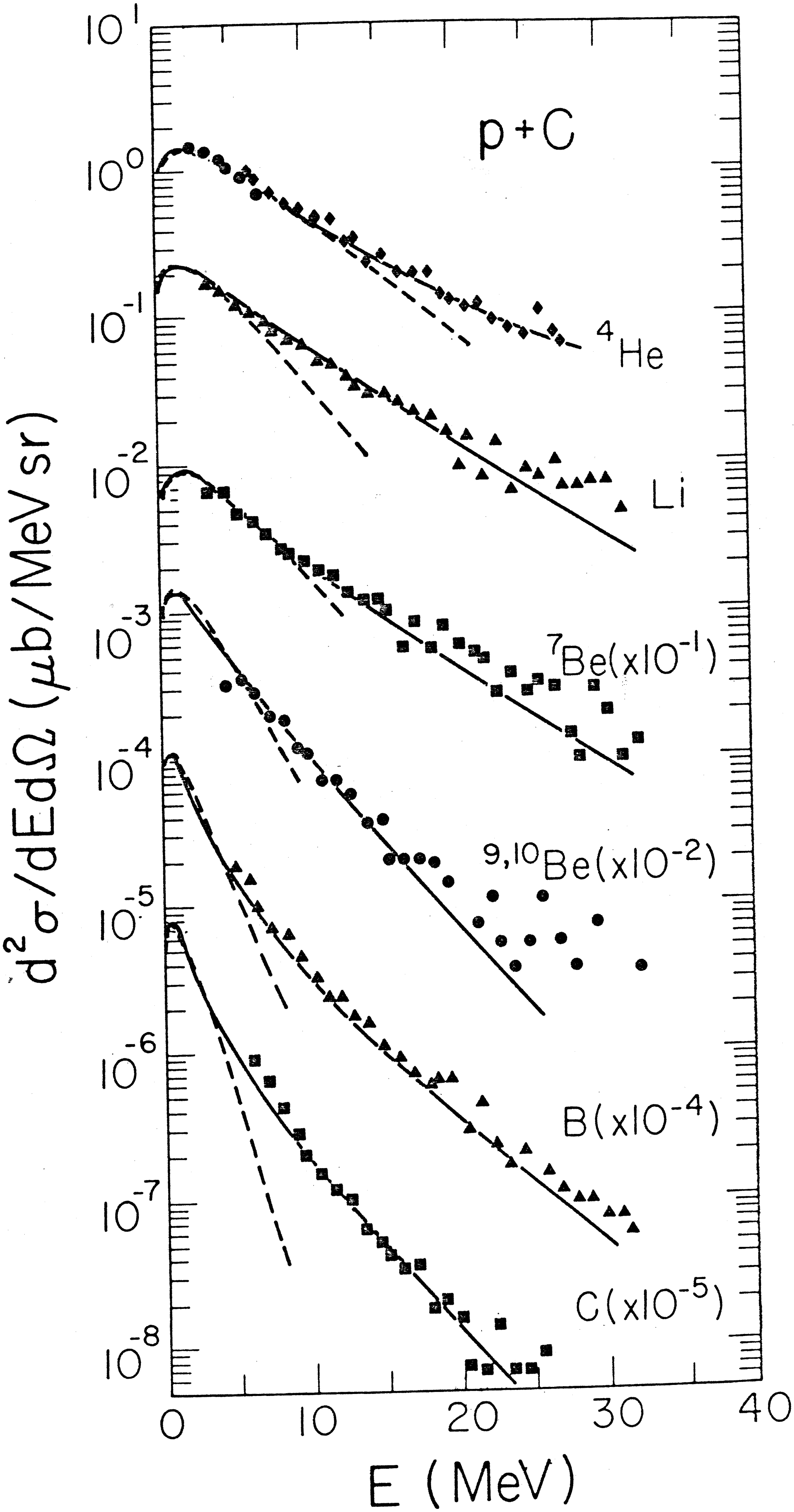
Light C R
Heavy C R
Projectiles (GCR)
p
12C
Targets (ISM)
12C
p
Products
11B
11B
E small
E ≃ 11/12 E (12C)
Fate of products
Thermalize
Part of ISM (100%)
Destroyed in collision
Escape galaxy
Part of ISM (~10%)


Fig. 4.2



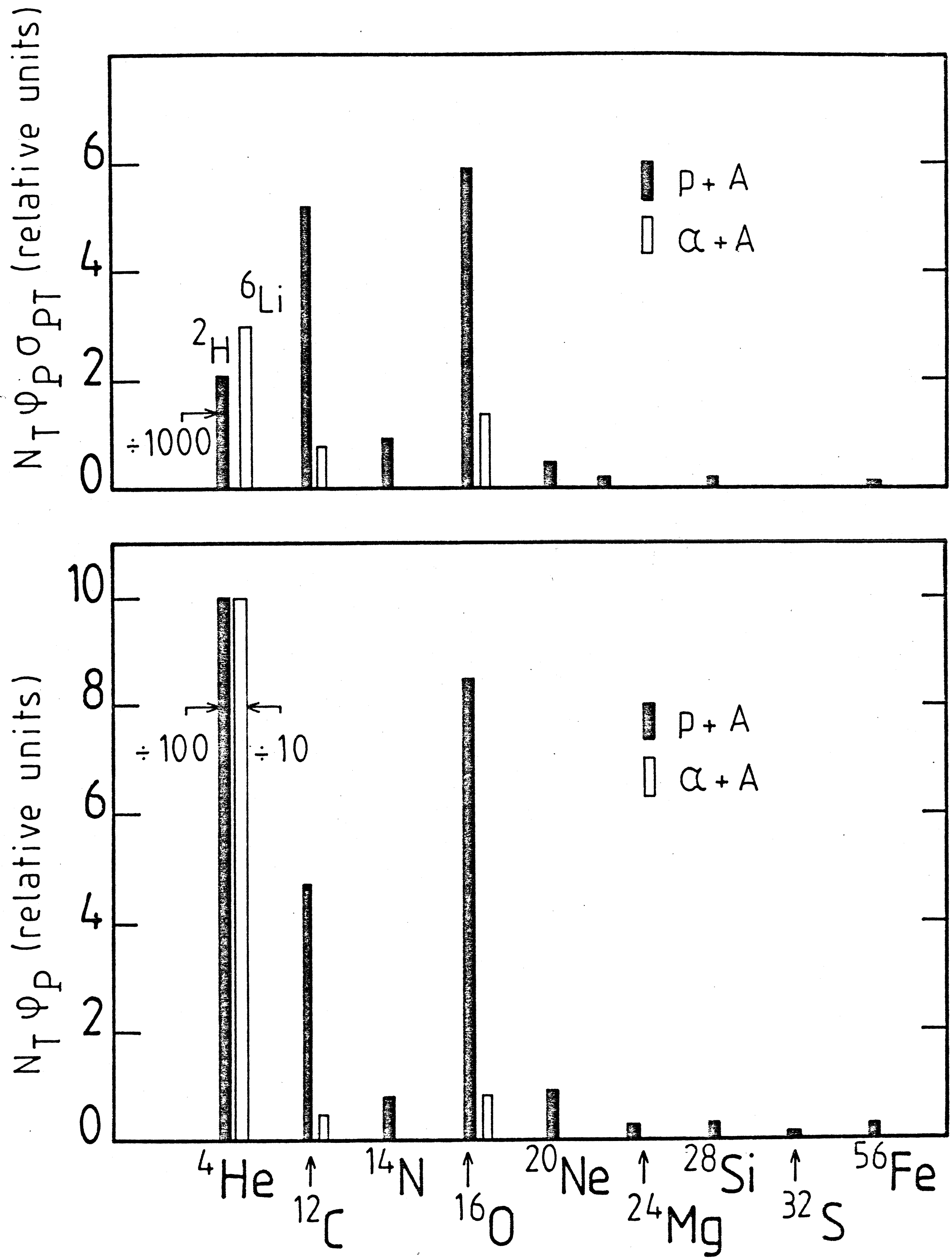
1000
100
10
1
10
100
1000
10000
E (MeV/nucleon)
φP, σPT (relative units)
φPT α (E+m0C2)-2.6
σPT
0.4
0.2
0
Production


Fig. 4 .3



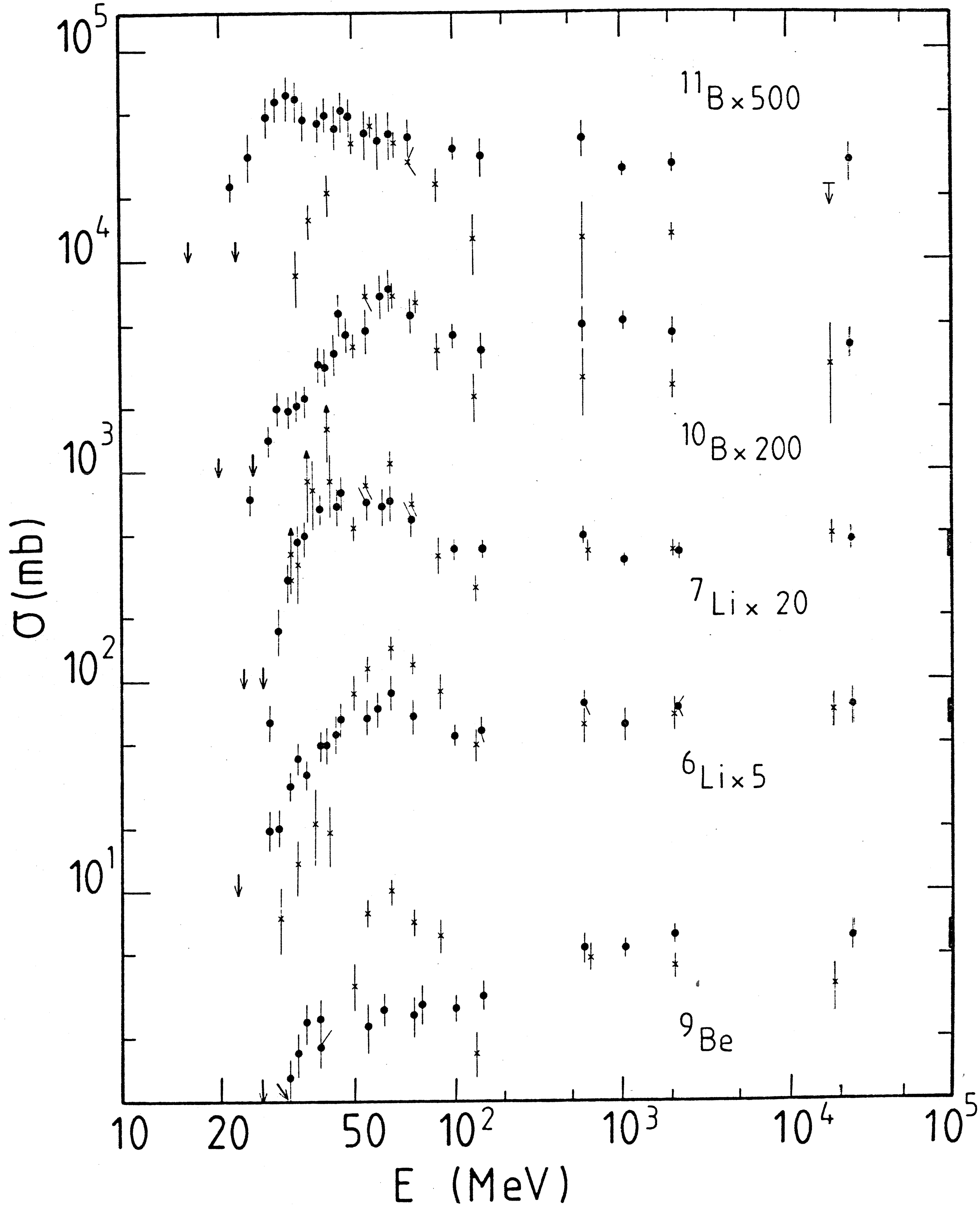
p+C
$^4$He
Li
$^7$Be(x10$^{-1}$)
$^{9,10}$Be(x10$^{-2}$)
B(x10$^{-4}$)
C(x10$^{-5}$)
$d^2\sigma/dEd\Omega$ ($\mu$b/MeV sr)
E (MeV)
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
0
10
20
30
40


Fig. 4.4



$N_T \varphi_P \sigma_{PT}$ (relative units)
0
2
4
6
÷1000
$^2H$
$^6Li$
p + A
α + A
$N_T \varphi_P$ (relative units)
0
2
4
6
8
10
÷100
÷10
p + A
α + A
$^4He$
$^{12}C$
$^{14}N$
$^{16}O$
$^{20}Ne$
$^{24}Mg$
$^{28}Si$
$^{32}S$
$^{56}Fe$


Fig. 4.5



$^{11}B \times 500$
$^{10}B \times 200$
$^{7}Li \times 20$
$^{6}Li \times 5$
$^{9}Be$
σ (mb)
E (MeV)
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
10
20
50


Fig. 4.6

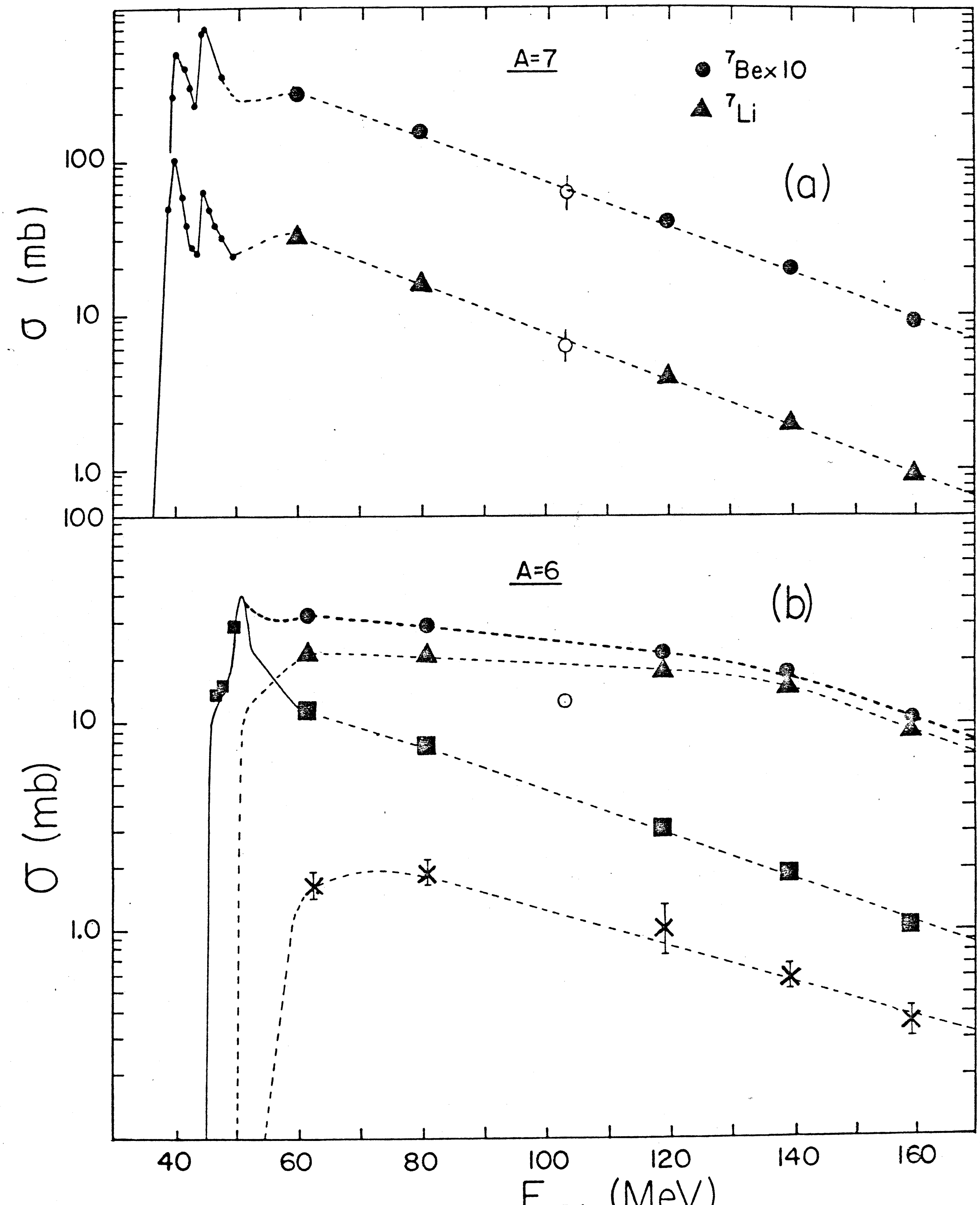
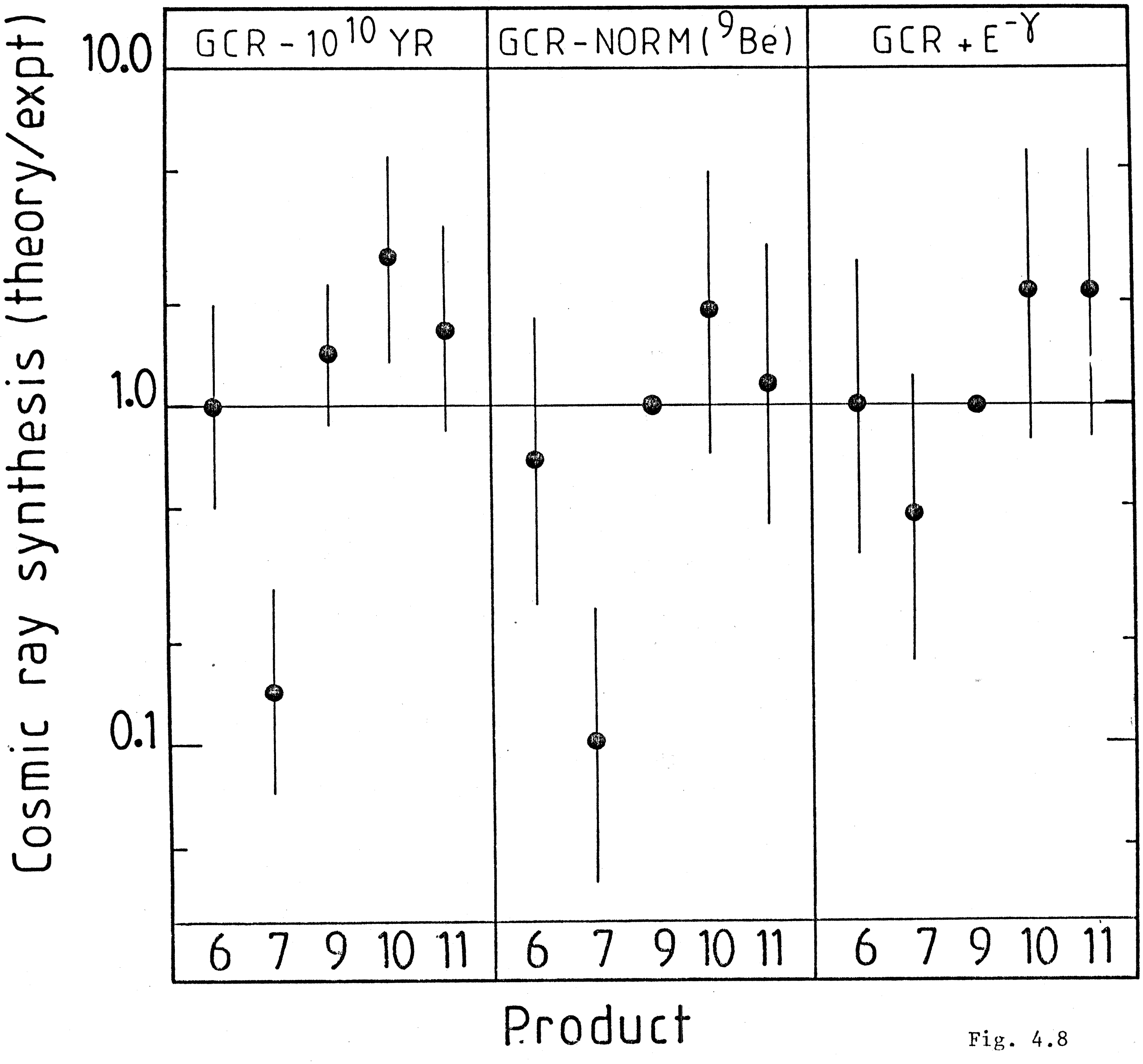
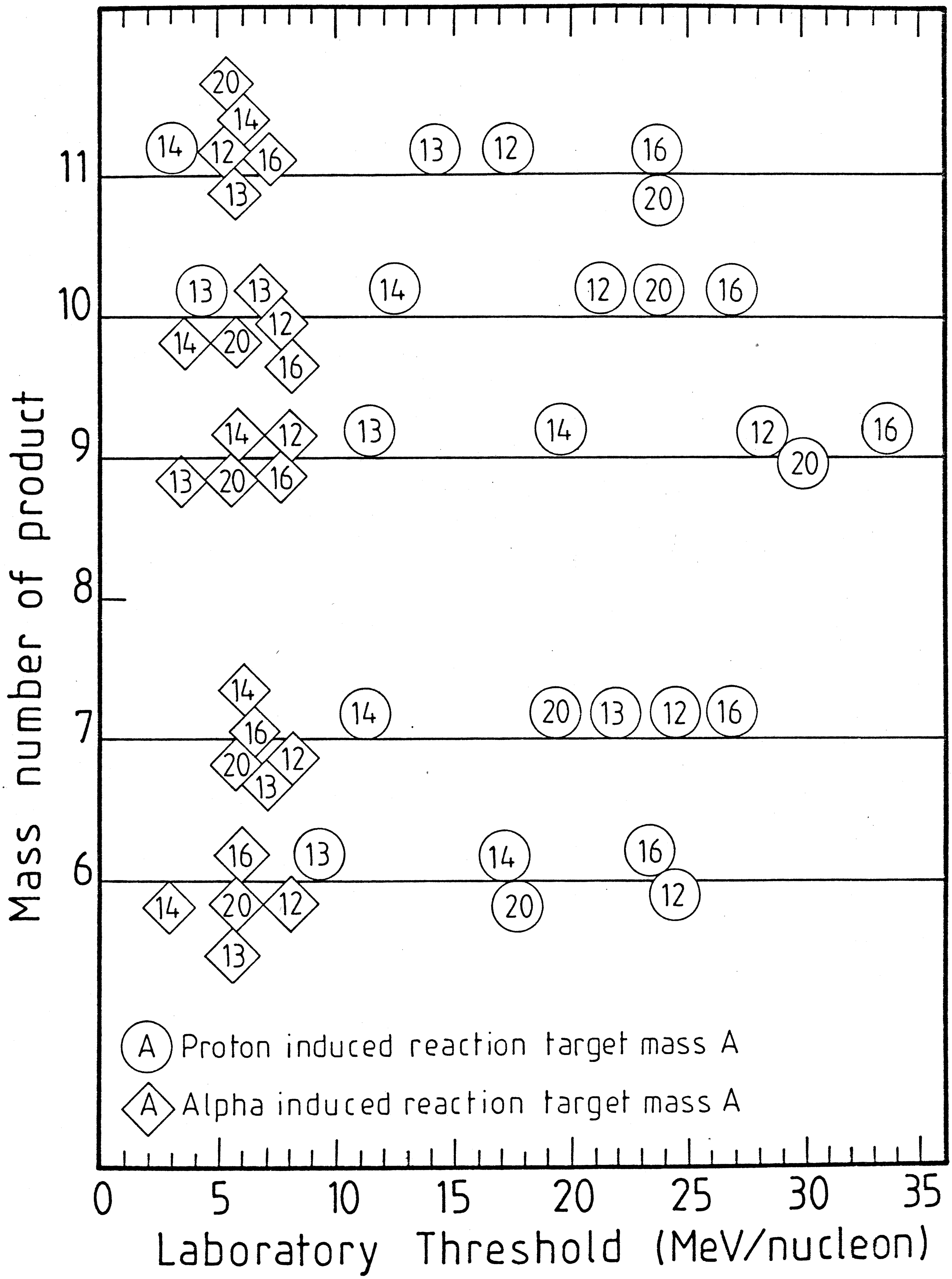

A=7
$^7$Be×10
$^7$Li
(a)
A=6
(b)
σ (mb)
100
10
1.0
40
60
80
100
120
140
160
$E_\alpha$ (MeV)

Fig. 4.7



Cosmic ray synthesis (theory/expt)
10.0
1.0
0.1
GCR - 10^10 YR
GCR-NORM(^9Be)
GCR + E^-γ
6 7 9 10 11
6 7 9 10 11
6 7 9 10 11
Product


Fig. 4.8



Mass number of product
Laboratory Threshold (MeV/nucleon)
0
5
10
15
20
25
30
35
6
7
8
9
10
11
Ⓐ Proton induced reaction target mass A
◇A Alpha induced reaction target mass A


Fig. 4.9

**FRIEDMAN MODELS WITH $\Lambda = 0$**

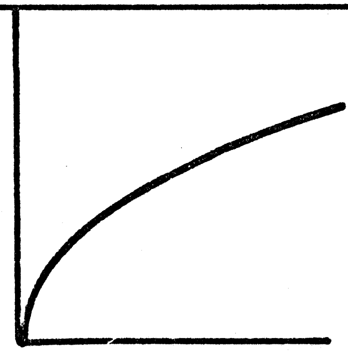
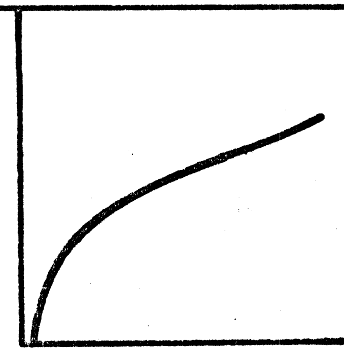
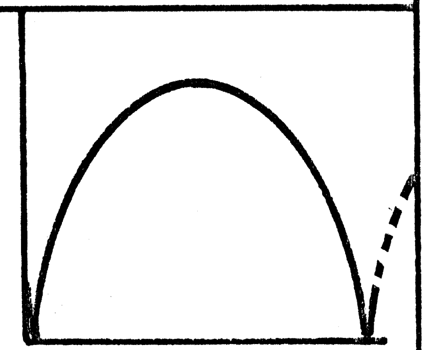
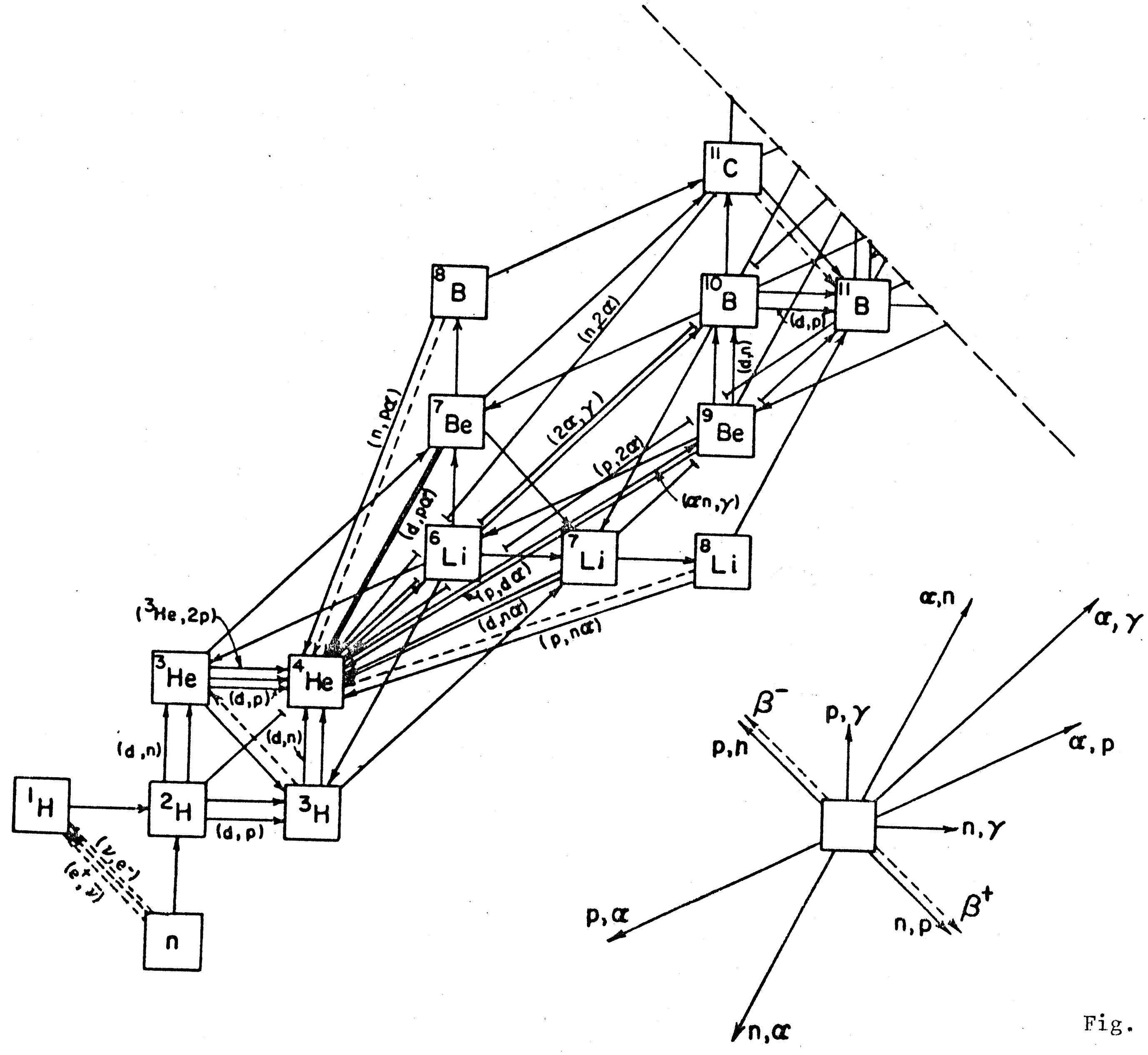
| | OPEN | CRITICAL | CLOSED |
|---|---|---|---|
| R(t) |  |  |  |
| FUTURE | EXPAND FOREVER | EXPAND FOREVER | COLLAPSE |
| CURVATURE | HYPERBOLIC | FLAT | SPHERICAL |
| DENSITY | $\rho < \rho_c$ | $\rho = \rho_c$ | $\rho > \rho_c$ |

Fig. 5.1



1H
2H
3H
n
3He
4He
6Li
7Li
8Li
7Be
9Be
8B
10B
11B
11C
(ν,e-)
(e+,ν)
(d,n)
(d,p)
(d,p)
(d,n)
(3He,2p)
(n,pα)
(d,pα)
(n,2α)
(2α,γ)
(p,2α)
(αn,γ)
(p,dα)
(d,nα)
(p,nα)
(d,n)
(d,p)
α,n
α,γ
α,p
n,γ
β+
n,p
n,α
p,α
p,n
β-
p,γ


Fig. 5.2

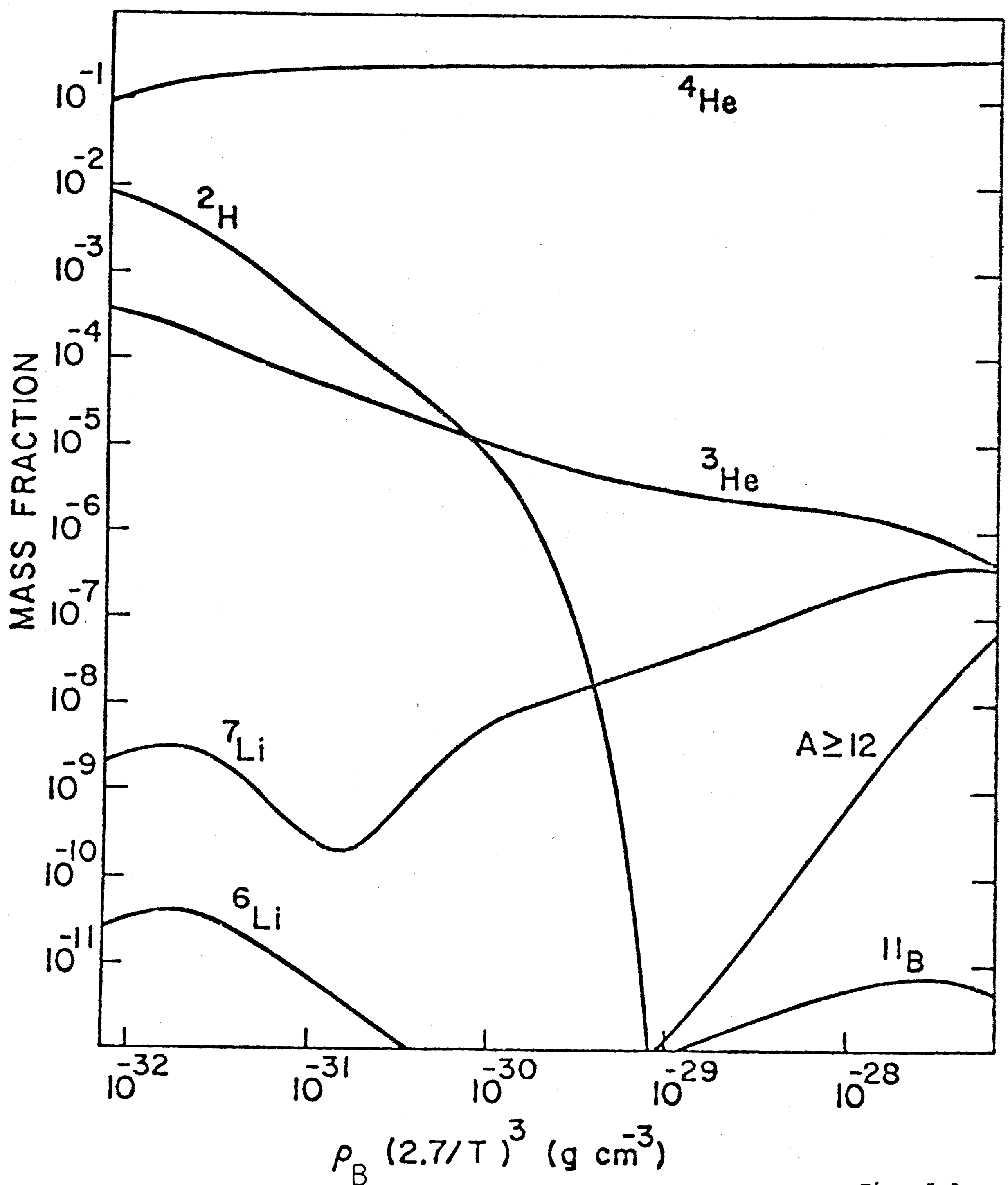

MASS FRACTION
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
4He
2H
3He
7Li
6Li
A≥12
11B
10^-32
10^-31
10^-30
10^-29
10^-28
ρB (2.7/T)^3 (g cm^-3)

Fig. 5.3

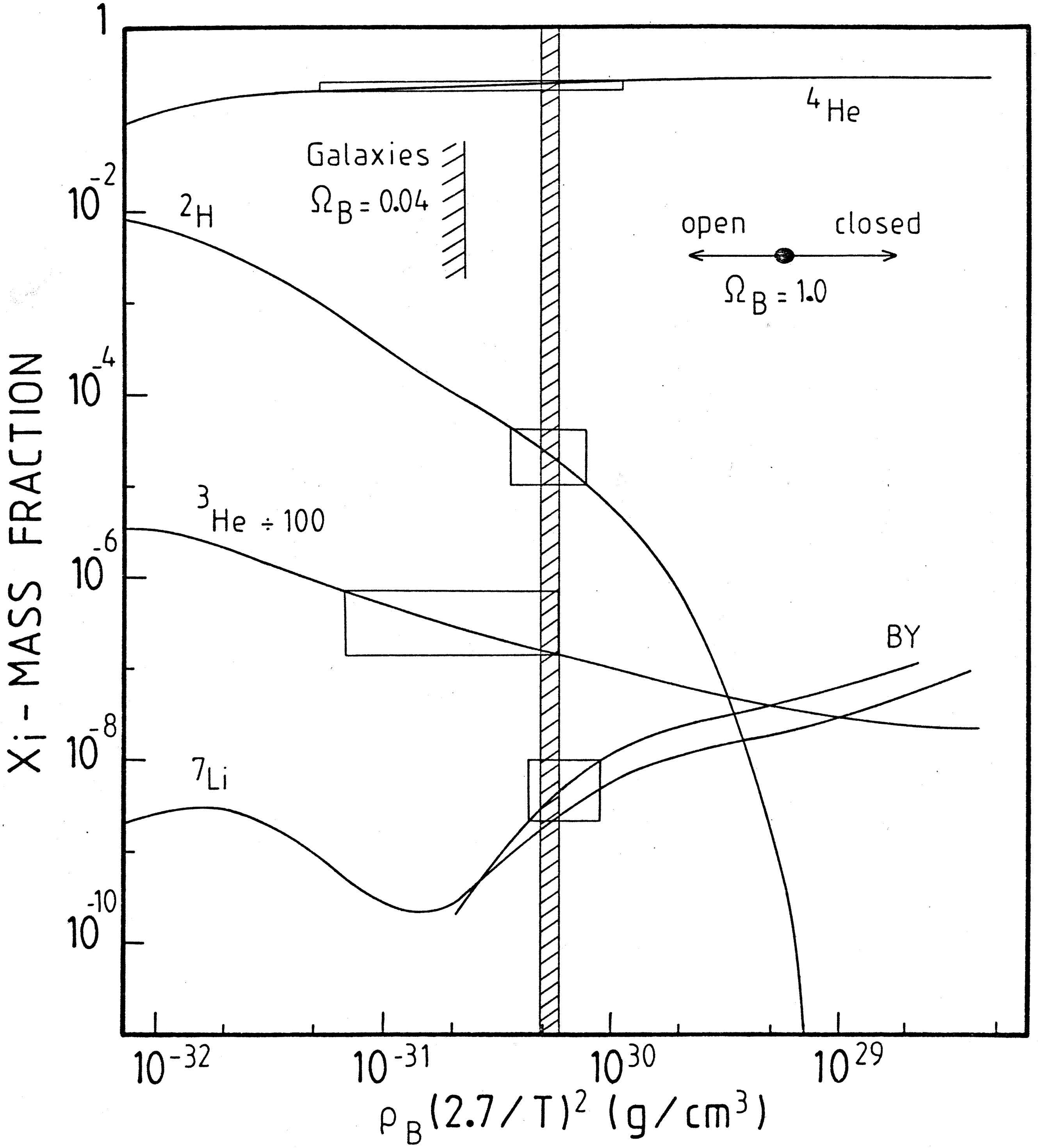
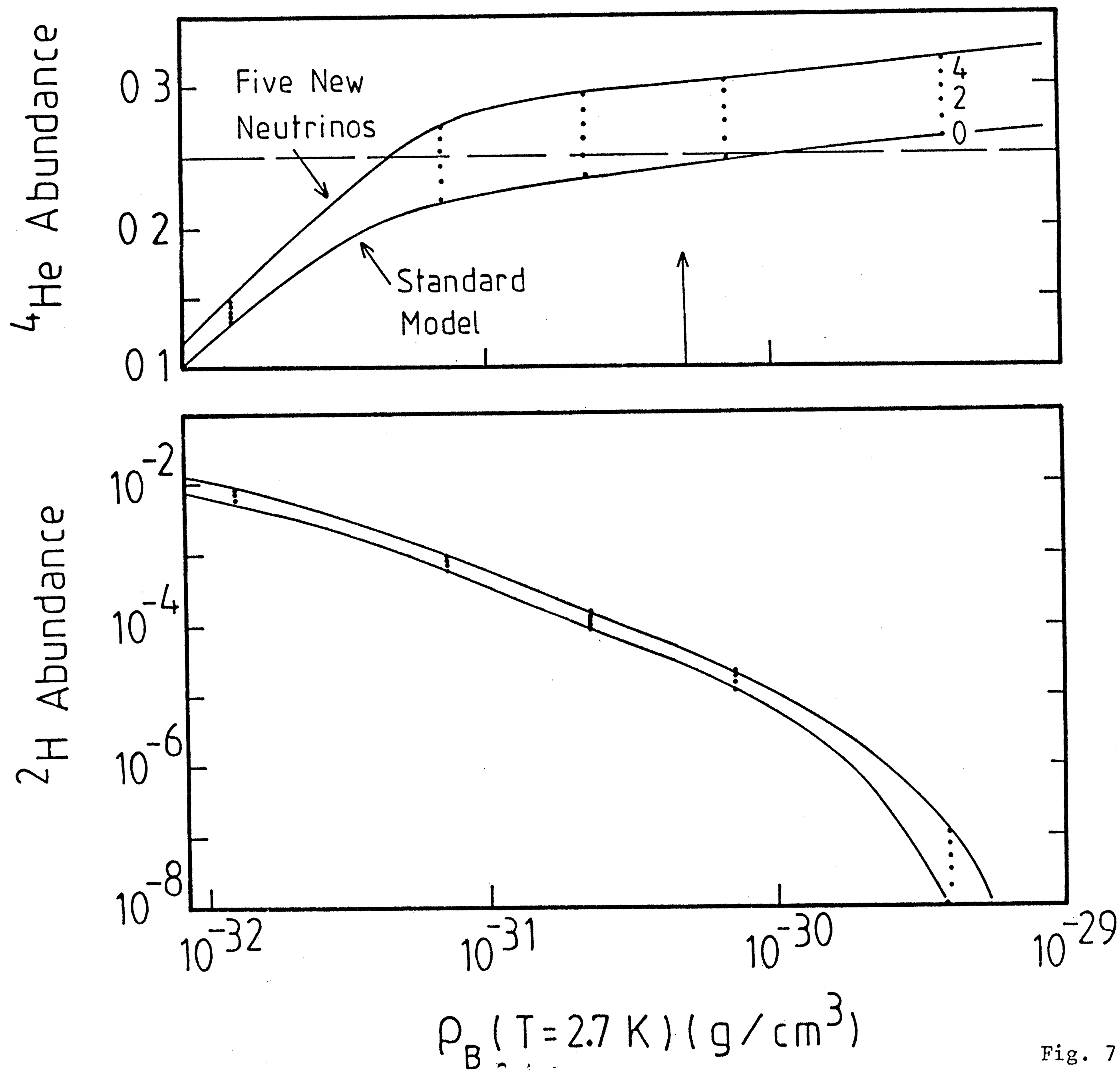

Xi - MASS FRACTION
1
10^-2
10^-4
10^-6
10^-8
10^-10
4He
Galaxies
ΩB = 0.04
2H
open
closed
ΩB = 1.0
3He ÷ 100
BY
7Li
10^-32
10^-31
10^30
10^29
ρB(2.7/T)^2 (g/cm^3)

Fig. 5.4



4He Abundance
0 3
0 2
0 1
Five New
Neutrinos
Standard
Model
4
2
0
2H Abundance
10-2
10-4
10-6
10-8
10-32
10-31
10-30
10-29
ρB (T=2.7 K) (g/cm3)


Fig. 7.1