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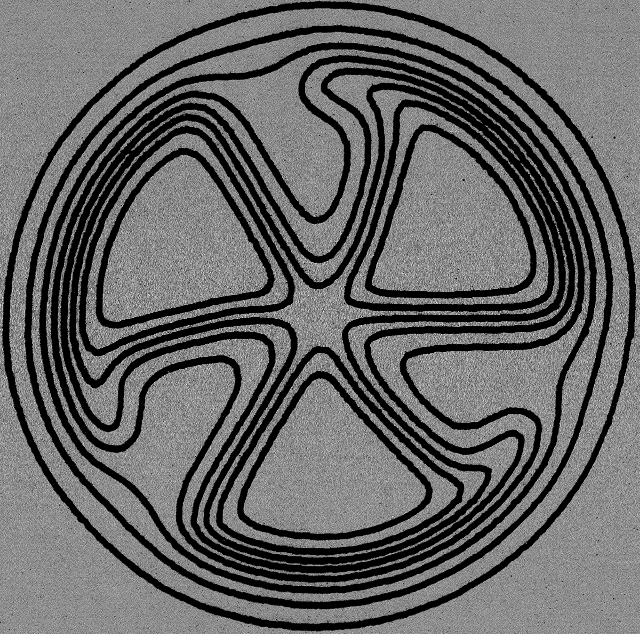

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Production of the Light Elements Lithium, Beryllium and Boron by Proton-Induced Spallation of ^{16}O[†]

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Abstract

Astrophysically important cross sections for the production of isotopes of lithium, beryllium and boron in the proton-induced spallation of ^{16}O were measured for proton energies between 30 and 42 MeV. A time-of-flight method was used for mass identification. The astrophysical significance of the results is discussed.

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I. INTRODUCTION

Proton or alpha-induced spallation of heavier elements is the process most likely responsible for the creation of the bulk of the light elements Li, Be, and B.[1-4] Of the probable targets, chiefly ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{24}Mg, and ^{28}Si, ^{16}O is the most abundant.[5] One might then expect spallation of ^{16}O to dominate the light element production, and this turns out to be true[6] if one assumes that the spallation process takes place in the cosmic rays. It is also possible (see Section IV) that some light element production occurs in stellar surfaces where the particle spectrum is strongly peaked toward low energies. However, the large negative effective Q-values[1] associated with the ^{16}O+p reactions will limit their contributions in stellar environments unless the cross sections should happen to be anomalously large in the threshold region. No measurements are available at such low energies, although there are data[7] at 135 MeV and above.

As part of a program[8,9] of measuring production cross sections of the light elements Li, Be, and B in the proton energy range accessible with the MSU sector-focused cyclotron, we performed cross section measurements on ^{16}O for protons in the threshold energy region above 30 MeV. The experimental technique is described in Section II, the resulting production cross sections are presented in Section III, and their astrophysical significance is discussed in Section IV.

II. EXPERIMENTAL TECHNIQUE

A. Detection Method

The experimental technique was essentially the same as previously described,[8,9] so we give only a brief description here. Because of the large negative Q values and small cross sections for the ^{16}O+p reactions the present experiments were substantially more difficult than the earlier investigations of ^{12}C+p[8] and ^{14}N+p.[9] Thus we present a more detailed description of the techniques used to handle the non-negligible low energy background. The target was oxygen confined in an ultra-thin-window[6] gas cell. Double differential cross sections, $\frac{d^2\sigma}{d\Omega dE}$, of the ^{16}O+p spallation products were measured and then integrated over angle and energy to yield the total production cross sections. Mass identification was performed using a time-of-flight technique. The proton beam arrived in bursts of $\simeq$0.5 nsec duration spaced at precisely the cyclotron radiofrequency (rf). Hence, reaction products originated at a well defined time correlated with the rf. After traversing a flight path d $\simeq$27 cm in a time t they were stopped in a silicon surface barrier detector which yielded a timing pulse as well as a signal proportional to the particle energy E. The relationship $Et^2 = \frac{md^2}{2}$ then identified the mass m of the particle.

This time-of-flight technique has the advantage over identification by radioactivity or mass spectroscopy of being equally sensitive to all isotopes and the advantage over standard ΔE-E particle identification of being sensitive to heavy reaction products down to energies of 0.1 MeV/amu. Although one does not determine the charge of the particle, knowledge of mass is sufficient for many astrophysical applications since only one isobar per mass number is stable in the region $6 \leq A \leq 11$, and most other isobars of the same A produced in this experiment decay to it in a time short compared to astrophysical time scales. Thus the cross sections we measured for a given mass can be identified, for most astrophysical purposes, with a particular isotope as follows: mass 6 = ^{6}Li, mass 7 = ^{7}Li, mass 10 = ^{10}B and mass 11 = ^{11}B. Due to its long half-life ^{10}Be is an exception but it is expected to contribute little to the total mass-10 yield (see Section IV).

B. Gas Cell

The gas cell containing the oxygen gas was the same employed in the ^{14}N spallation measurements.[9] Its important characteristics are a thin reaction product exit window and a collimating system designed to minimize the size of the interaction region seen by the particle detector. The latter property is required to limit the spread in the flight paths and hence flight times. For oxygen gas at a pressure of 25 torr the total exit areal density varied with detection angle from 50 $\mu g/cm^2$ at 90° to 140 $\mu g/cm^2$ at 15°, consisting of a 30 $\mu g/cm^2$ formvar film and the gas traversed by reaction products. Gas pressures were measured with an oil manometer capable of an accuracy of 0.3%. The temperature of the gas cell was also monitored. Changes in the local gas density because of beam heating have been shown to be $\leq 1.5\%$.[9]

III. DATA ACQUISITION AND ANALYSIS

Angular distributions were measured at 30.0, 33.7, 37.9, and 41.9 MeV. Data was taken under control of an XDS Sigma 7 computer and the MSU general purpose data acquisition code.[10] The quantity Et^2 was calculated on-line and displayed vs E in a 128x128 channel array. A sample is shown in Fig. 1. The horizontal bands labeled by their mass number yield[9] the energy spectra shown in Fig. 2.

At 37.9 MeV and 41.9 MeV proton energy it was found that background events arising from neutron-induced reactions in the silicon detector contaminated the low energy part of the spectrum. Therefore, runs were also taken with no gas in the cell so that this background contribution could be subtracted. Fig. 3 shows the energy spectrum for the background events corresponding to Fig. 2. The energy spectra exhibit a low energy cut off due to the finite flight time (62 ns at 30.0 MeV, 53 ns at 41.9 MeV) available for particle identification.[9] This cutoff had a maximum value of 1.6 MeV for ^{11}C at E_p=41.9 MeV; at lower beam energies (longer rf period) and for reaction products with A<11 it was always smaller. The existence of a low energy cut off also implies that there is a maximum angle in the angular distribution beyond which no data can be acquired.

To obtain the total yield we integrated over particle energy at each angle and then over the total solid angle. The extrapolations in the energy spectra from the cut off energy to zero energy and to unmeasured angles near 0° and 180° introduced the greatest uncertainties in all of our experiments,[8,9] but are more severe for $^{16}O+p$ than previously because of the low cross sections and high negative Q values. At the beam energies where the background contribution was significant a simple subtraction of the yield due to background was done for masses 10 and 11. For masses 6 and 7 the cross sections were lower and hence the statistics were poorer. For this reason we cut off the particle energy spectra at the point where the background started to contribute (see Fig. 2 and Fig. 3) and assigned an estimated yield per channel below this energy as was done for the low energy cut off correction due to finite flight time, the estimated yield per channel being based on the last few non-zero channels at the low energy end of the spectrum. At each angle half of the value of the correction was assigned as a conservative estimate of the uncertainty. Samples of the angular distributions which result are shown in Fig. 4. The integration over angle was performed as in Ref. 9. The resulting total production cross sections are shown in Table I and Fig. 5. The uncertainties quoted for the cross sections were determined as follows: At each angle the statistical error of the yield and the low energy cut off error (0.5 of the correction) were combined in quadrature. These were then summed linearly over angle and 0.5 of the yield extrapolation to unmeasured back angles of the angular distribution and 0.2 of the yield extrapolation to forward angles were also added linearly to obtain a total uncertainty. This linear addition was used in case all cut off corrections were in error in the same direction; however, some mutual cancellation is likely and therefore, the quoted uncertainties are probably conservative.

The uncertainties in detector solid angle, current integration and gas density totaled about 3.3% and were generally negligible compared to the extrapolation errors.

IV. DISCUSSION

A. Production of ^{10}Be

Since ^{10}Be has a lifetime of about 10^6 years and hence does not necessarily decay to ^{10}B on astrophysical time scales, it is in principle necessary to distinguish it from the other mass-10 isobars. The threshold for ^{10}Be producing reactions is 36.5 MeV. At 135 MeV the production cross section is reported[11] to be 0.37±0.12 mb. If the excitation function is similar to that observed for the other light isotopes (see Fig. 5), this corresponds to a cross section of about 0.15 mb at 40 MeV. Thus the present measurements at 30.0 and 33.7 MeV are entirely unaffected and ^{10}Be contributes perhaps 3% of the mass-10 yield at the higher energies.

B. Comparison with other Results

The present cross sections and others available in the literature[7] are graphed in Fig. 5. At energies below 135 MeV, only the present results are available. It is clear that with the possible exception of ^{11}B, all the cross sections rise in a smooth fashion with no anomalous behavior near threshold.

C. Implications for Astrophysics

The mechanism responsible for the production of Li Be and B is not understood at present. For some time it was thought that each star made its own share of these elements in an early stage of its evolution.[1,12,13] However, it was then realized that the energy requirements of such an autogenic mechanism were unrealistic,[14] at least if one insisted on forming all of the light elements in this fashion. A proposal that a substantial part of the production took place in cosmic rays,[2] augmented by formation of ^{2}H, ^{3}He, ^{4}He and possibly ^{7}Li in a big bang[3,4,6] accounted for the bulk of the Li Be B abundances. However, difficulties with production of ^{11}B and ^{7}Li led Audouze and Truran[12] to invoke production of these elements in the shock waves occurring in supernova envelopes. Other mechanisms may also produce ^{7}Li, but it is not yet clear whether they make a substantial contribution to its galactic abundance.[13]

In this confused situation a meaningful assessment of the contribution of the ^{16}O+p reaction to the element abundances is difficult. We have made a rough estimate of this contribution by calculating the production rate using an approach developed for the autogenic theories.[1] The production rate r for one of the light isotopes from a particular target nucleus (density = n per cm^3) is

$$r = n \int_{E_0}^{\infty} \phi(E)\, \sigma\,(E)\, dE$$

where ϕ (E) is the proton flux, σ(E) is the spallation cross section for the target and product in question and E_0 is the threshold for the production reaction. To obtain the total yield one simply sums over all targets. It is common[1] to assume that

$\phi \propto E^{-\gamma}$ where a value near $\gamma=3$ is observed in solar flares.[15]

We have surveyed the available proton spallation data and have calculated production rates for a range of γ. These results will be reported in more detail in another publication; in Table II are shown a sample of results relevant to the present measurements. For a target composition $^{12}C:^{14}N:^{16}O=3:1:5$[5] and the proton spectra considered, we find that except in the case of ^{6}Li, proton induced spallation of ^{16}O is responsible for only a rather small fraction of the light elements.

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REFERENCES

1. R. Bernas, E. Gradsztajn, H. Reeves and E. Schatzman, Ann. Phys. 44, 426 (1967).
2. H. Reeves, W. A. Fowler and F. Hoyle, Nature (Lond.) 226, 727 (1970).
3. M. Meneguzzi, J. Audouze and H. Reeves, Astron. and Astrophys. 15, 337 (1971).
4. H. Reeves, J. Audouze, W. A. Fowler and D. N. Schramm, Astrophys. J. 179, 909(1973).
5. E. A. Müller, in Origin and Distribution of the Elements, edited by C. H. Ahrens (Pergamon Press, Oxford, 1968), p. 155.
6. H. E. Mitler, Astrophys. and Space Sci. 17, 186 (1972).
7. F. Yiou, C. Seide and R. Bernas, J. Geophys. Res. 74, 2447 (1969); review of most of the available data.
8. C. N. Davids, H. Laumer and S. M. Austin, Phys. Rev. C1, 270 (1970).
9. H. Laumer, S. M. Austin, L. M. Panggabean and C. N. Davids, Phys. Rev. C8, 483 (1973).
10. D. L. Bayer, Michigan State University Report No. MSUCL-34, 1971 (unpublished).
11. F. Yiou, M. Baril, J. Dufaure de' Citres, P. Fontes, E. Gradsztajn, and R. Bernas, Phys. Rev. 166, 968 (1968).
12. J. Audouze and J. W. Truran, Astrophys. J. 182, 839 (1973).
13. Pertinent references are given in refs. 4 and 12, along with some discussion.
14. C. Ryter, H. Reeves, E. Gradsztajn, and J. Audouze, Astr. Astrophys. 8, 389 (1970).
15. K. C. Hsieh and J. A. Simpson, Astrophys. J. 162, L191 (1970).

TABLE I.--Summary of measured total cross sections for proton spallation of ^{16}O. All cross sections are in mb.

E(MeV)	Mass 6	Mass 7	Mass 10	Mass 11
30.0	1.5±0.5			2.3±0.5
33.7	2.7±0.8	1.8±0.6	2.0±0.7	17.±5.
37.9	4.4±1.7	4.1±1.5	4.5±1.7	31.±6.
41.9	3.8±1.5	4.5±1.5	8.0±2.5	42.±10.

TABLE II.--Percentage[a)] of production of Li, Be and B from ^{16}O+p reactions for a target composition of ^{12}C:^{14}N:^{16}O=3:1:5.

γ	^{6}Li	^{7}Li	^{10}B	^{11}B
2.5	30	15	15	5
4.0	20	5	5	0.5

a) Values rounded to the nearest 5%, except for ^{11}B at γ=4.0 which is rounded to the nearest half-percent.

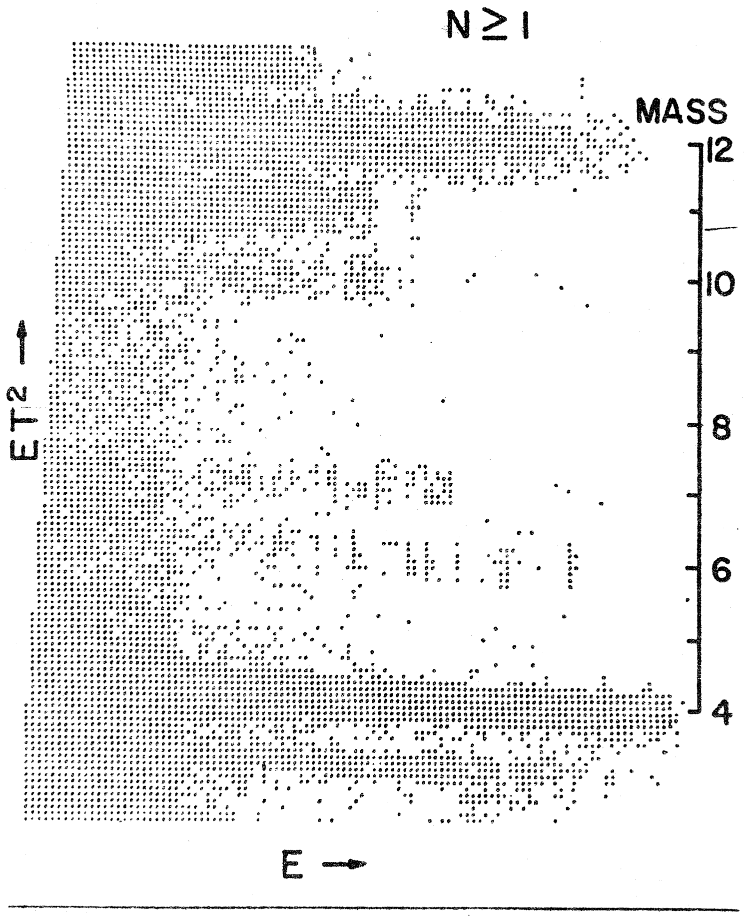


Fig. 1a

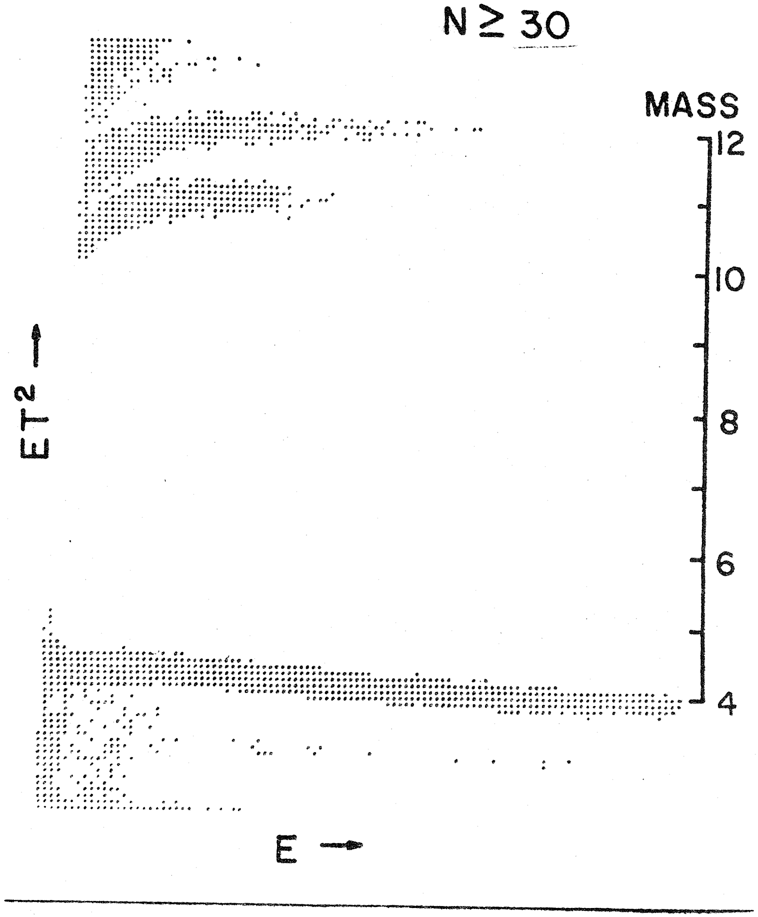
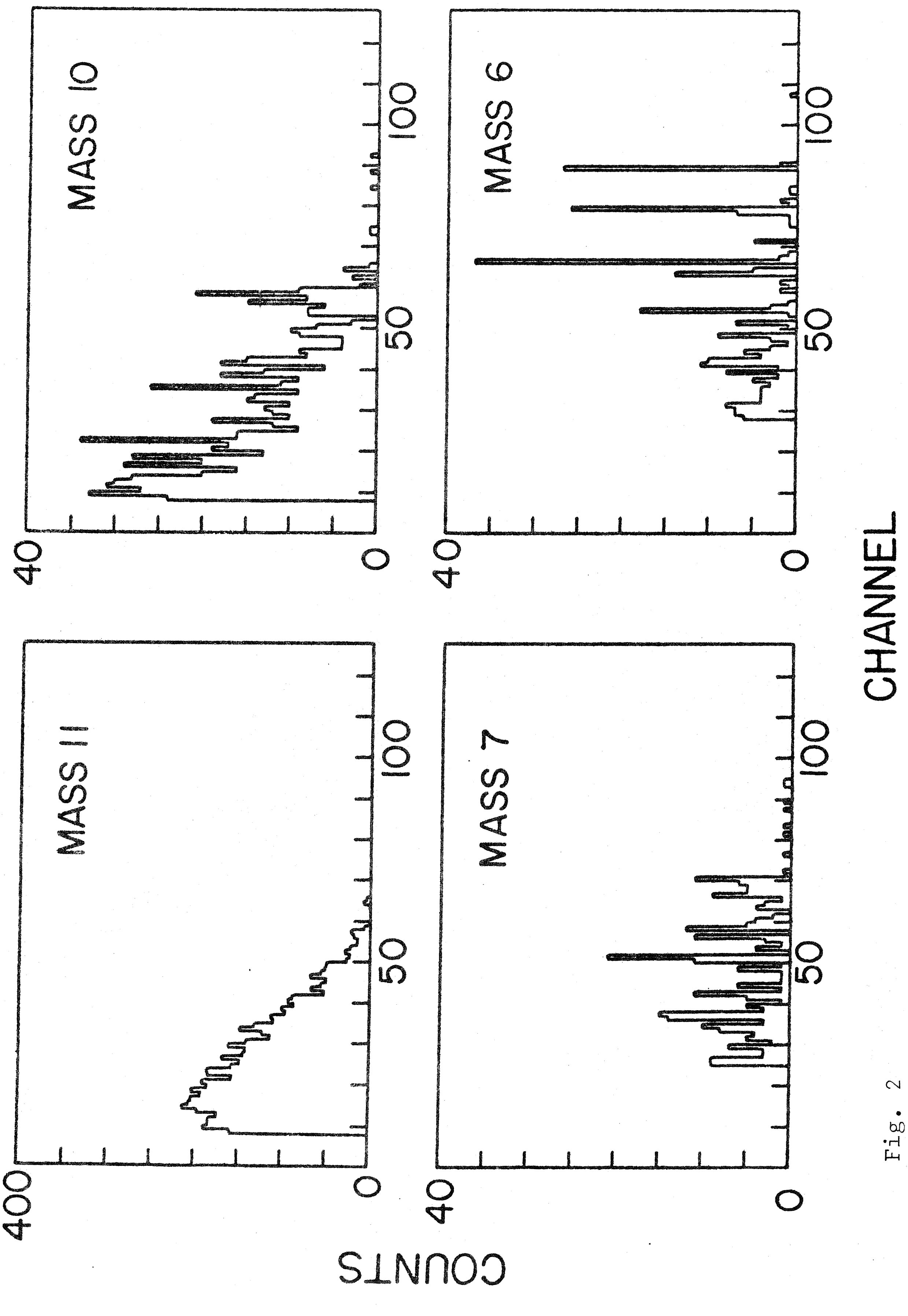


Fig. 1b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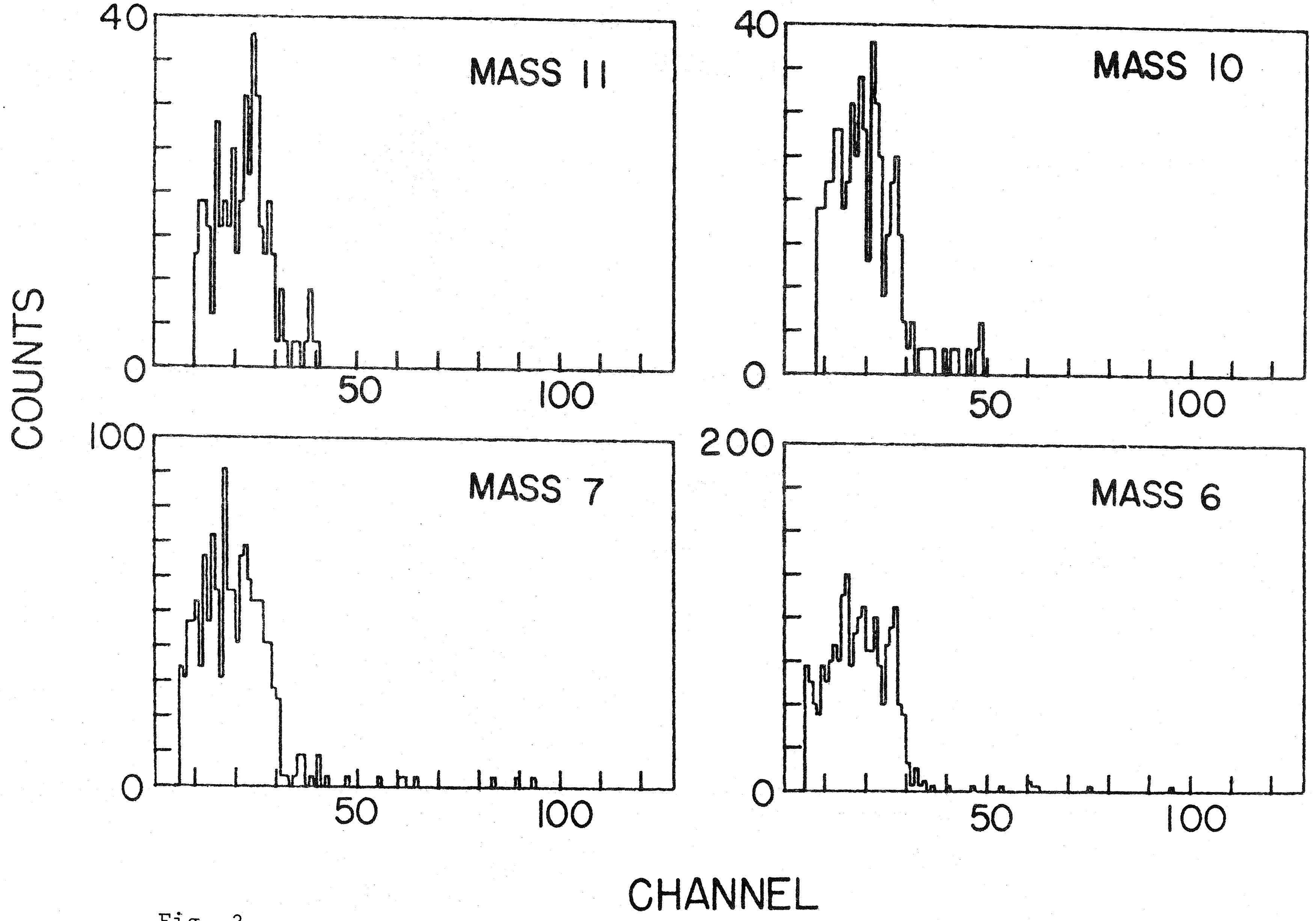
MASS 10
MASS 7
MASS 6
COUNTS
CHANNEL
400
40
40
40
0
50
100

Fig. 2


COUNTS
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MASS 11
50
100
40
0
MASS 10
50
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100
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MASS 7
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100
200
0
MASS 6
50
100
CHANNEL

Fig. 3.

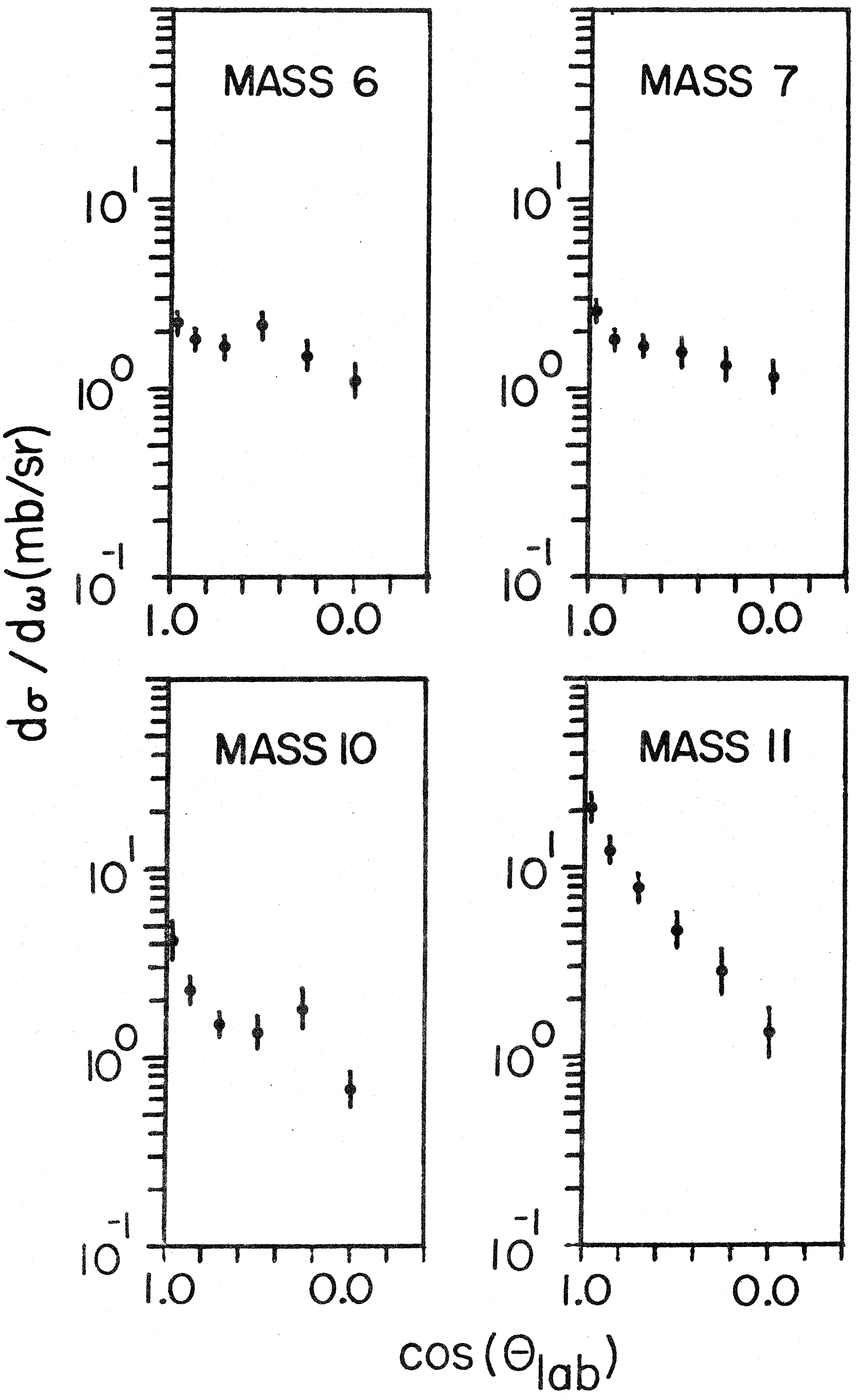
MASS 6
MASS 7
MASS 10
MASS 11
10^1
10^0
10^{-1}
1.0
0.0
dσ / dω(mb/sr)
cos(Θ_lab)

Fig. 4.

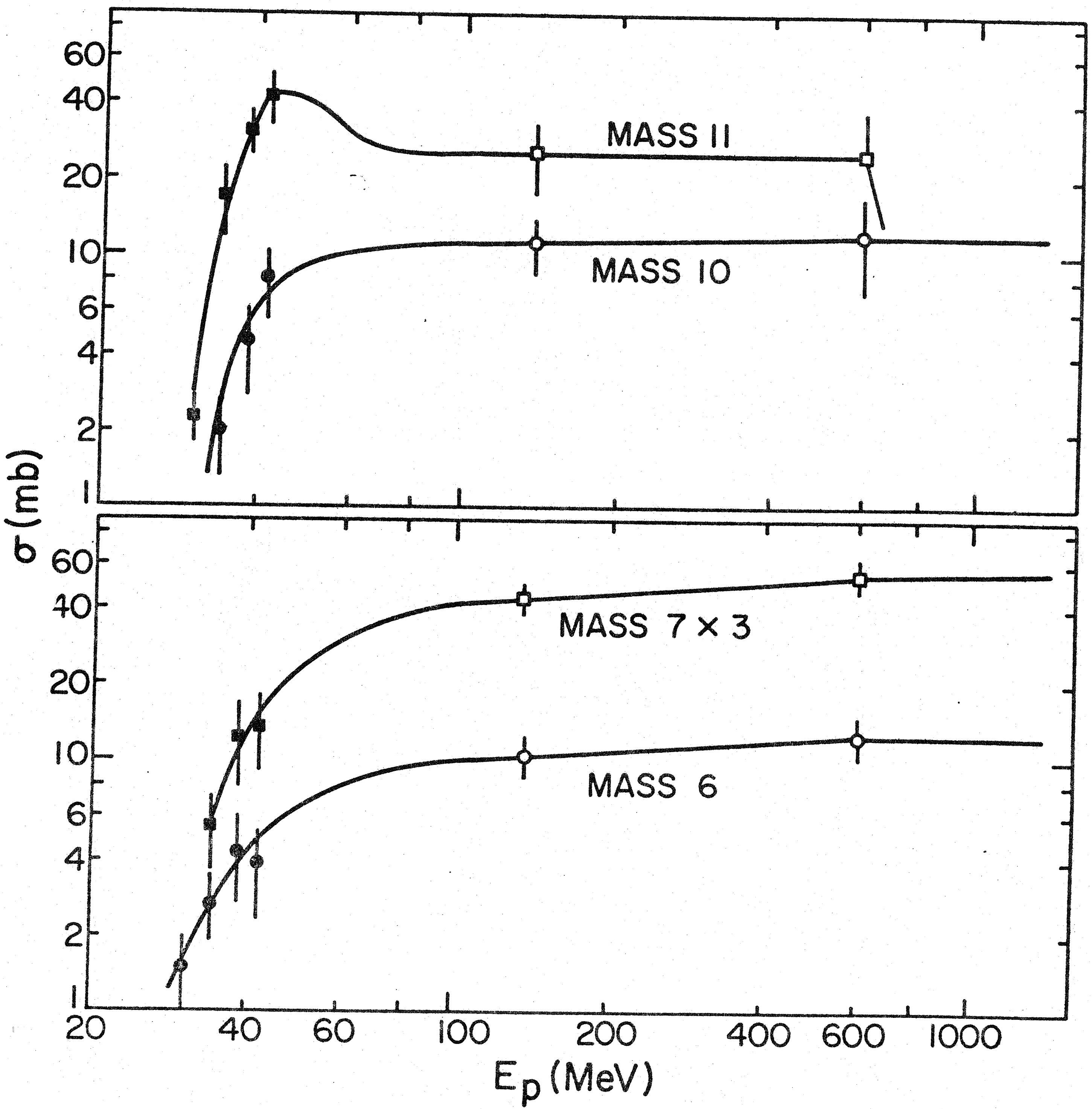
MASS 11
MASS 10
MASS 7 × 3
MASS 6
σ (mb)
60
40
20
10
6
4
2
1
20
40
60
100
200
400
600
1000
E_p (MeV)

Fig. 5