Study of the ^{2}H(α,γ)^{6}Li Capture Reaction

R.G.H. Robertson, P. Dyer, R.A. Warner[a] R.C. Melin,[b] T.J. Bowles,[c] A.B. McDonald[d]
G.C. Ball,[d] W.G. Davies,[d] and E.D. Earle[d]

As was discussed in a previous Annual Report,[1] the ^{2}H(α,γ)^{6}Li reaction is potentially a source of ^{6}Li in the big bang. Most of the ^{6}Li in the universe is evidently a product of cosmic ray interactions,[2] but since the cross section for the ^{2}H(α,γ) reaction is unknown, significant amounts of ^{6}Li could be primordial in origin.

Our initial measurements, made at MSU using targets of deuterated polyethylene and the Enge split-pole magnet to detect the recoiling ^{6}Li's, left much to be desired in terms of statistical accuracy. Recently, as part of our effort to achieve the highest possible sensitivity in ^{6}Li parity-violation experiments,[3] we moved the experiment to Chalk River and built a new, supersonic gas jet target for use in the chamber of the QDDD magnet there. The gas target permitted a 30-fold increase in beam current, and in addition the tandem Van de Graaff was able to produce alpha particle beams of lower energy than the MSU cyclotron. We therefore took the opportunity to extend and improve on our early measurements of the radiative capture process.

Beams of 1.5-2.0 μa of ^{4}He^{++} were focussed on the D_2 gas jet, formed by expanding 150°K D_2 from a nozzle.[3] Runs were taken at incident energies of 3.0, 4.0, 4.9, 7.0, 8.0 and 9.0 MeV, and the 6.238-MeV data from a previous parity-violation search were also available. Cross sections were normalized to elastically scattered deuterons at 0° which were detected in a Si detector located near the exit of the first dipole (unfortunately, no normalization was obtained at 8.0 MeV). Attempts were made to run at still lower energies and although the MP Tandem was, remarkably, able to produce intense beams at terminal voltages as low as 650 kV, the separation of ^{6}Li ions and α particles in the focal plane detector became impossible below E_{α} = 3.0 MeV owing to large energy losses in the 140 μg-cm^{-2} window of the detector.

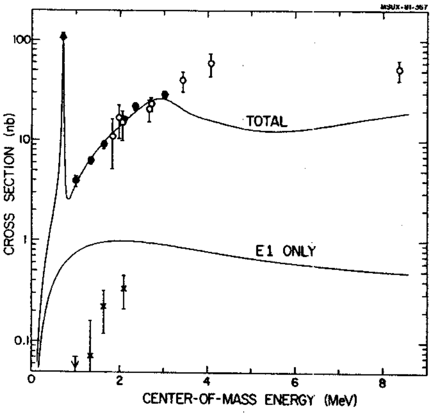

Fig. 1. Measured total cross section and E1 cross section for ^{2}H(α,γ)^{6}Li. Solid circles-Chalk River data. Open circles - MSU data. Solid rectangle - ref. 4. Lines - direct capture calculation (present work).

The total cross sections measured are summarized in Fig. 1. We have also plotted at the peak of 3^{+} resonance (E_{cm} = 0.709 MeV) the measured radiative width of that state[4] converted to capture cross section assuming a Breit - Wigner line shape with Γ_{cm} = 26 keV.

The solid curves in Fig. 1 are calculations from a direct capture code recently written by one of us (R.G.H.R.). Electromagnetic transition matrix elements for E1, E2, E3, M1, M2 and M3 have been treated in the phase - consistent formalism of Rose and Brink.[5] The continuum wave functions are distorted waves generated by the McIntyre-Haeberli potential[6] (which accurately reproduces the d - α phase shifts), and the bound state is generated by the same potential adjusted in depth to give the correct binding energy for ^{6}Li. The agreement between theory and experiment seems quite satisfactory for the total cross section. At energies above E_{cm} = 200 keV, the cross section is essentially all E2.

The gamma recoil following radiative capture slightly alters the momentum of the ^{6}Li ion, and the momentum distribution at the focal plane turns out to be, to an excellent approximation, the gamma - ray angular distribution as a function of cos θ_{γ}. Figure 2 shows the angular distributions at the 4 lowest energies. In addition to the double - lobed structure characteristic of aligned E2 transitions, there is a marked forward-backward asymmetry indicative of E1 - E2 interference. The E1 component is not correctly predicted by the calculation, probably because for ^{2}H(α,γ) it is extremely hindered ($\sim 10^{-5}$). We have extracted the E1 strength by normalizing the E1 operator so as to produce agreement with the angular distributions. The lower set of points in Fig. 1 is the result of that procedure, as are the solid lines in Fig. 2.

We have calculated astrophysical reaction rates from these results and find that the production of ^{6}Li by this mechanism in the big bang is about 4 times <u>less</u> than has been assumed. It then appears that at most a few percent of the ^{6}Li in the universe can be primordial.

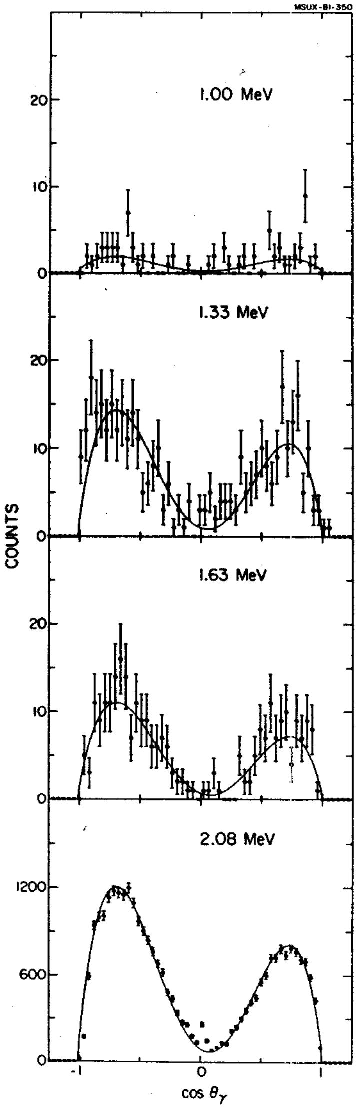

Fig. 2. Angular distributions for $^2H(\alpha,\gamma)^6Li$. The solid curves are the result of the direct capture calculation when the E1 operator is renormalized (at each energy) to give the best fit to these distributions. The E2 and other multipole operators are unmodified.

a Battelle Northwest
b Bell Telephone Laboratories
c Los Alamos National Laboratory
d Atomic Energy of Canada Ltd.

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Tritium β-decay

R.G.H. Robertson, T.J. Bowles,[*] J.C. Browne,[*] A.G. Ledebuhr, R. Mills,[*] M. Maley,[*]
D. Knapp,[*] D. Taylor[*] and J. Wheatley[*]

There is some interest in determining whether the electron neutrino has mass. Recently, a Russian group[1] reported a measurement of the β-spectrum of ^{3}H which shows conclusive evidence for an antineutrino mass between 14 and 46 eV at the 99% confidence level. Despite careful study, no substantial flaw has been detected in the procedure used by the Russians. Nevertheless, many scientists have misgivings about some aspects of the experiment and would, in any case, like to see a confirming experiment. Much of the concern revolves around the use of a solid source (tritiated valine, an amino acid) for which one may not know the atomic and molecular final states of the ^{3}He daughter atom, the scattering and energy loss of β's in the source, and the shape of the background near the end-point as well as one would like.

The ideal source would be free tritium nuclei, but this turns out to be impractical owing to space charge limitations. The next best thing, free tritium atoms, may form the basis of a practical source for which detailed and accurate calculations of the atomic final states and electron energy losses can be performed. Recent advances in the production of dense gases of spin-polarized hydrogen encourage us to believe that a free-atom tritium source of adequate strength can be constructed. A functional plan of the experiment is shown in Fig. 1.

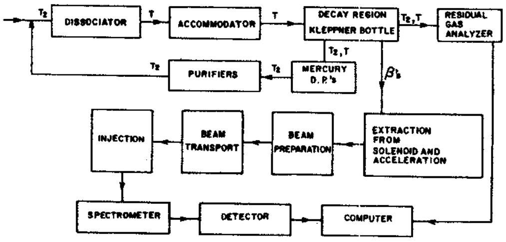

Fig. 1. Functional diagram of tritium β-decay experiment.

Molecular tritium at ~300 μ pressure enters a Pyrex discharge tube cooled to 77° K (LN_2). The molecules are dissociated in an RF discharge and emerge through a small orifice into a transition region (also of Pyrex) in which the atoms are cooled (accommodated) to a temperature near 10° K. In the pioneering work of Silvera and Walraven[2] a flux of 2.4×10^{16} atoms of H at 8.5° K was obtained, and simple modifications are expected to increase the output considerably. It is not yet known, however, to what extent tritium will behave differently from hydrogen. A test apparatus is now under construction at Los Alamos to explore this question.

Atoms emerging from the accommodator enter a 1-m long, cylindrical decay region ("Kleppner bottle") whose walls are coated with a few monolayers of solid T_2 maintained at ~10° K. Studies by Crampton[3] have shown (for hydrogen) that an atom survives more than 500 reflections before recombining. An equilibrium density of atomic T gas is then built up in the bottle as established by the influx and the rates at which T is pumped from the ends of the bottle or recombines on the wall. An equivalent source thickness projected on the cross section of the bottle is conservatively estimated to be about $3 \times 10^{13}/\text{cm}^2$. Depending on the temperature, less than 1% of the gaseous tritium is in molecular form. This is still a weak source by normal standards, but gains in other areas compensate for it.

The Kleppner bottle is placed in a solenoidal magnetic field of about 2 kG with a small axial gradient. Betas ($B\rho \leq 463$ Gauss-cm) spiral about the field lines. At one end of the solenoid a pinch coil with a peak field of about 10 kG reflects most of the β's that start with a velocity component directed towards that end; as a result about 95% of the β's reach the weak-field end of the solenoid. There they are extracted by acceleration through a potential of 20 kV.

An important feature of our experiment is that this energy gain is never compensated by deceleration later in the apparatus: The entire decay region floats at -20 kV. There are two advantages in this; first, 18 keV electrons from the decay region are raised to 38 keV and are well above the energy of any β's from tritium that may find its way into the beam transport or spectrometer; and, second, the configuration component of phase space is reduced. Thus, not only is the background in the region of the shifted end point far lower than it would be at 18 keV, but the emittance of the beam is reduced to the point where approximately 33% of all β's can be accepted by the spectrometer, provided that the source emittance can be optimally matched to the spectrometer acceptance. The ion-optical design of the extraction and injection systems to achieve this optimal matching is one of the major efforts now under way. We might also remark that this idea is equally applicable to solid sources.

The spectrometer itself is patterned on the Russian iron-free toroidal instrument, which has the highest luminosity of any β-spectrometer. However, it is a) considerably larger, at 6 m in length, to allow the use of a larger source area, b) modified to permit injection at a mean angle of 65° rather than 90°, c) designed for lower rigidity particles, which allows a reduction in the fraction of particles striking the conductors. In addition, considerable attention is being paid to construction tolerances and the use of low-Z absorbers (beryllium and graphite) to reduce scattering.

Some experimental work (described elsewhere in this report) has been done on a proportional counter suitable for use as the focal plane detector. There is reason to believe that efficiencies $\geq$ 75% can be achieved with backgrounds in the vicinity of 10^{-3} c/sec.

In the last 100 eV of the spectrum an estimated count rate of 0.004 sec^{-1} can be obtained, about an order of magnitude less than in the Russian experiments. Statistical accuracy is not expected to be a problem, especially if the anticipated backgrounds can be achieved. It is not possible to make a meaningful estimate of the spectrometer resolution until the aberrations have been evaluated, but even if the resolution is as poor as 60 eV, a 35 eV neutrino mass would be apparent as a two-standard-deviation effect in less than one day.

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* Los Alamos National Laboratory

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Forbidden β-decays of ^{18}Ne and ^{19}Ne

T.J. Bowles,* P. Lisowski,* J.C. Browne,* M. Stelts* and R.G.H. Robertson

Much effort has gone into attempting to measure and to calculate theoretically the isovector part of the weak nucleon-nucleon interaction. No observation of parity violation which can unambiguously be attributed to this part of the force has been reported. An analysis[1] of experimental work on ^{18}F, ^{19}F and ^{21}Ne in the framework of the quark model of Desplanques, Donoghue and Holstein[2] has suggested that there may be little or no neutral current contribution to the isovector force.

Interpretation of the experimental data rests on shell models of the relevant nuclear structure, and recently Bennett[3] has pointed out that stringent experimental tests of the nuclear structure calculations can be made by examining the β-decays which are analogous to the parity-violating "transitions". Such tests are feasible in ^{18}F and ^{19}F. In the limit that only two-body (π exchange) currents are important, the β-decay and parity violation operators are identical in form. The additional one-body contributions that appear in recoil order in β-decay slightly vitiate this fine correspondence, but the delicacy of the test of nuclear structure calculations is, if anything, heightened.

In ^{18}F, parity violation is sought between the 0^+ and 0^- states at 1042 and 1081 keV respectively. The analogous β-transition is the decay of ^{18}Ne (0^+, T = 1, 1.7 sec) to the 0^- state in ^{18}F. We have carried out an experiment at Los Alamos to measure this decay branch. During the course of this work, Adelberger et al.[4] published their results on this transition, and we find significant disagreement between the two sets of data.

Most of the decay (~93%) leads to the ground state of ^{18}F, and the 0^+ T=1 analog at 1042 keV receives essentially all of the remainder. Decay to the 1081 keV level is signalled by the presence of a γ ray of that energy. The main sources of background are annihilation in flight of positrons, bremsstrahlung, and pileup on the 1042-keV line. All three of these were reduced by placing the cell in which the ^{18}Ne decayed in a magnetic field. A large, well-shielded Ge(Li) detector could view the cell but no the walls where positrons, deflected by the field, annihilated or suffered bremsstrahlung losses. The resulting spectrum is shown in Fig. 1, which represents about 4 days of data-taking.

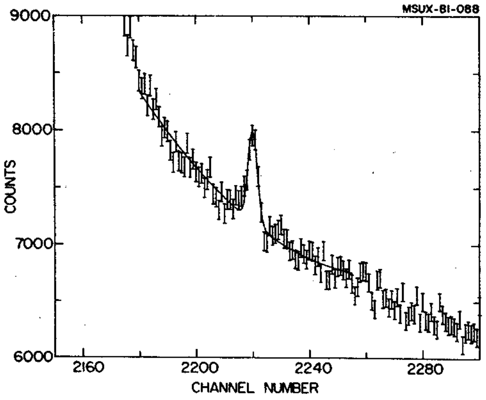

Fig. 1. Spectrum showing 1081-keV line following ^{18}Fe β-decay. The intensity is 2.4×10^{-5} per decay.

The branching ratio, expressed as a fraction of 1042-keV γ intensity, is $(3.10 \pm 0.20) \times 10^{-4}$, which is considerably larger than the value $(1.71 \pm 0.41) \times 10^{-4}$ reported by Adelberger et al.[4] The partial decay rate is 8 times weaker than the original calculations of Haxton, Gibson and Henley, but double the rate predicted by Haxton's revised calculation (see Ref. 4). It raises questions about the reliability of the nuclear structure calculations which are needed to extract information of a fundamental nature from parity-violation experiments. At the same time, there is the prospect that the nuclear structure uncertainties can be largely "calibrated out" by using the analogous β-decay.

In ^{19}F the parity mixing occurs between the $\frac{1}{2}^+$ ground state and the $\frac{1}{2}^-$ first excited state. The analogous β-transition is the decay of ^{19}Ne($\frac{1}{2}^+$, T=½, 17.4 sec) to the $\frac{1}{2}^-$ state at 110 keV in ^{19}F. Essentially the same techniques were used to observe this transition as for ^{18}F. However, there is in this case no strong reference transition like the 1042 keV line to serve as an intensity standard. The only other γ line in ^{19}Ne decay is the very weak 1357-keV transition for which discordant values of intensity per decay have been reported. We have attempted to remeasure this branch relative to annihilation radiation in another geometry which allows the Ge(Li) detector to view the full intensity of 511-keV photons. Analysis of this data is not yet complete, but Fig. 2 shows the 110-keV transition following the $\frac{1}{2}^+ - \frac{1}{2}^-$ β-decay. Its intensity is 5.5 ± 0.6 times that of the 1357 keV line. This value is in good agreement with a measurement made by Adelberger et al.[5], provided one adopts Alburger's result for the 1357 keV intensity.[6]

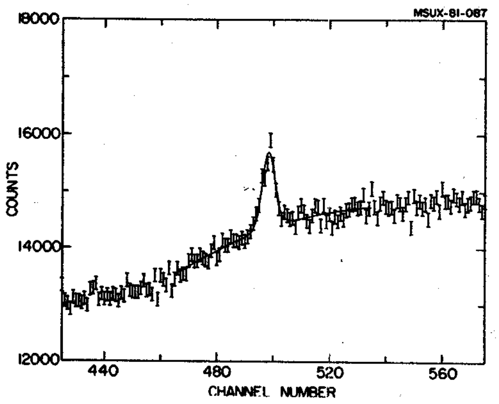

Fig. 2. Spectrum showing 110-keV γ line following ^{19}Ne β-decay. The intensity is 5.5 times the intensity of the 1357-keV line.

[a] Los Alamos National Laboratory.

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Internal Pair Decay of 2.79 MeV $\frac{1}{2}^-$ State of ^{21}Ne

A.B. McDonald,[a] E.D. Earle,[a] J.J. Simpson,[b] R.G.H. Robertson and H.B. Mak[c]

There are two levels in ^{21}Ne near 2.79 MeV excitation separated by only 7 keV. They have spin ½ but opposite parity, and so constitute a likely place to see nuclear parity violation. Photons de-exciting the $1/2^-$ state to the $3/2^+$ ground state were initially expected to have large circular polarizations, perhaps as big as 5%, but recent experiments[1] have set an upper limit of 0.5% on the circular polarization. It is thought that a cancellation is occuring between the isoscalar and isovector parity-violation matrix elements. However, a more mundane interpretation cannot be ruled out, namely that the $1/2^-$ to $3/2^+$ transition is predominantly M2 rather than E1. Only E1 (by admixing with the M1 $1/2^+$ to $3/2^+$ transition) can give rise to a circular polarization, and the lifetime of the state is so long (0.1 ns) that M2 is by no means ruled out.

In order to determine the multipolarity of the transition, we have measured its pair internal conversion coefficient. The experiments were carried out by bombarding targets of $W^{18}O_3$ on thick carbon backings with beams of alpha particles from the Chalk River MP Tendem. Positron-electron pairs were detected in two Si counter telescopes placed close to the target, at ± 135° to the beam. Because the $1/2^+$ and $1/2^-$ states are so close together, no attempt was made to resolve the pair transitions from them. Rather, their total pair intensity was observed, and the beam energy varied in order to change the relative populations of the two states. This population ratio was monitored with a Ge(Li) detector.

The number of pairs (N) detected at each beam energy can be expressed as

$$N = K(\alpha_+\gamma_+ + \alpha_-\gamma_-) \qquad (1)$$

where $\alpha_{+(-)}$ is the pair emission probability (relative angle 90°) for the $1/2^{+(-)}$ level, $\gamma_{+(-)}$ is the number of gammas detected in the Ge(Li) detector from the $1/2^{+(-)}$ level and is a constant involving detector efficiencies which are the same for the $1/2^+$ and $1/2^-$ levels because of their proximity in energy. Hence

$$\frac{N}{\gamma_+} = K\{\alpha_+ + \alpha_-(\frac{\gamma_-}{\gamma_+})\} \qquad (2)$$

and a graph of $\frac{N}{\gamma_+}$ versus $\frac{\gamma_-}{\gamma_+}$ should be a straight line.

The pair spectra from three energies are shown in the figure, along with the resulting

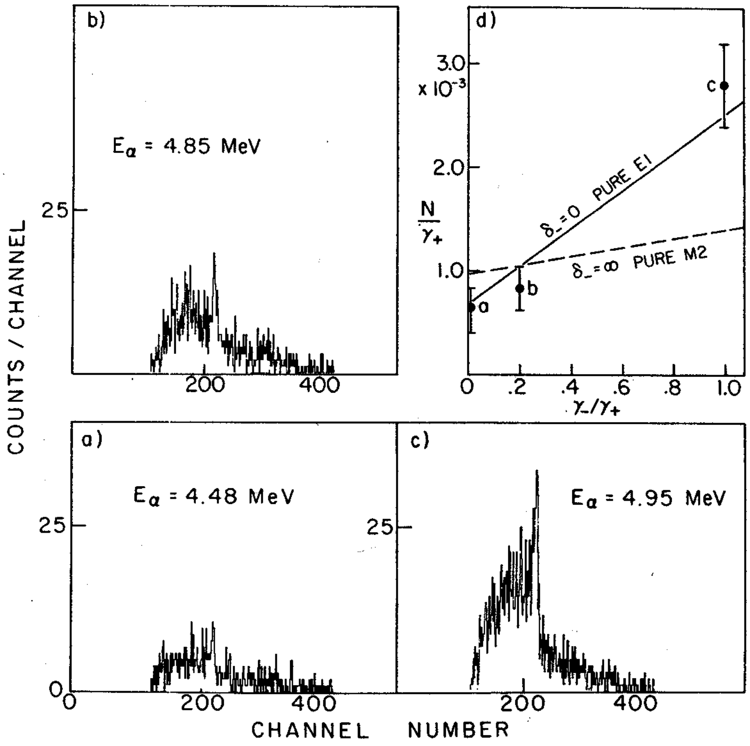

Fig. 1. (a to c) Spectra showing number of 4-fold coincidences versus the sum of the energy deposited in the two telescopes. The peak near channel 210 arises from pair emission from the 1/2 and 1/2 levels at 2.79 MeV in ^{21}Ne. (d) Number of counts in the peaks plotted to correspond to equation 2. The straight lines are expected results for pure E1 and pure M2 from the $1/2^-$ level.

graph. The ratio of slope to intercept is found to be

$$\frac{\alpha_-}{\alpha_+} = 4.6 \pm 2.3 \quad (\chi^2 = 0.46)$$

Now, α_+ is known theoretically for an M1/E2 transition, and we can compare the above result with the theoretical predictions for α_- for either E1 or M2. These predictions are shown on the figure. The data clearly favor E1, and the mixing ratio $|\delta(M2/E1)| \leq 0.6$. This value is small enough that the parity violation experiments have almost full sensitivity. The lack of observed parity violation may indeed be due to isovector - isoscalar cancellation.

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[a] Atomic Energy of Canada Ltd.

[b] University of Guelph

[c] Queen's University

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