Observation of the Capture Reaction $^2H(\alpha, \gamma)^6Li$ and Its Role in Production of ^6Li in the Big Bang

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The capture of α particles by deuterium has been observed by using a magnetic analysis technique to detect the recoiling ^6Li ions. Measurements of the cross section down to 1 MeV in the center-of-mass system can be interpreted accurately in terms of a direct-capture model, and it is found that production of ^6Li in the big bang is 5 times smaller than has been assumed

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One of the successes of the standard big-bang model of the universe[1] is a quantitatively correct prediction of the abundances of the light isotopes ^2H, ^3He, ^4He, and ^7Li. Not only does the big bang produce these elements in a natural, straightforward way, but also it produces only those isotopes for which no other plausible source has been found.[2] It does appear that cosmic-ray interactions account for, among other things, a few percent of the ^7Li in the universe and all of the ^6Li.[3,4] However, the picture is clouded by the fact that there is no experimental determination of the rate of the reaction $^2H(\alpha, \gamma)^6Li$, which is the only mechanism likely to produce significant amounts of ^6Li in the big bang. The estimate of the reaction rate now in use[1] is based on a direct-capture (DC) calculation[5] which set upper limits for dipole radiation. Fowler[6] estimated the contribution from the well-known 3^+ resonance in ^6Li (whose radiative width has been measured by electron scattering[7]) to be less than 1% of the DC, and it was then concluded that only a fraction of a percent of the ^6Li could be produced in the big bang. However, these estimates are very uncertain and lacking in experimental verification, and substantial amounts of ^6Li could possibly have been synthesized, especially should the universal baryon density be lower than is suggested by the abundances of ^2H and ^7Li.[8]

An experimental study of the reaction $^2H(\alpha, \gamma)^6Li$ is rendered difficult by the very low cross sections expected, of the order of a few nanobarns. The $E1$ and $M1$ transitions usually found in radiative capture are, in fact, strongly inhibited, and (as we shall show) $E2$ is the dominant multipolarity. In the course of experiments[9] searching for a parity impurity in the 3.56-MeV state of ^6Li, we developed techniques which allowed us to observe this reaction. Rather than attempt to detect the γ rays emitted, we used a magnetic spectrograph at 0° to the incident α beam and recorded $^6Li^{+++}$ ions in a focal-plane proportional counter. Particle identification methods gave virtually background-free spectra. Because the ^6Li ions were confined to a cone of half-angle approximately 1°, the detection efficiency was just equal to the triply charged fraction, approaching 100%. Furthermore, the γ recoil direction is reflected in the ^6Li momentum, and a complete angular distribution was obtained automatically at each incident energy. An initial series of experiments was performed at Michigan State University (MSU) with use of an Enge split-pole spectrograph and solid targets of deuterated polyethylene, and the final experiments (at center-of-mass energies $E_{c.m.} = 1.00$, 1.33, 1.63, 2.08, 2.33, and 3.01 MeV) were carried out at Chalk River Nuclear Labs (CRNL) with the quadrupole-triple-dipole spectrograph and a supersonic gas-jet target having a thickness of 1.7 $\mu g\ cm^{-2}$ of pure D_2. The ^6Li counts were normalized to elastically scattered deuterons from $^2H(^4He, d)^4He$ at 0° (and in some MSU runs, 25° as well). The scattering reaction has been extensively studied,[10] and the uncertainties in the cross sections derived from a composite of various works range from 5% to 10%, depending on energy. Charge-state fractions for $^6Li^{+++}$ from both solid and gaseous (D_2) targets were measured directly.

The total capture cross-section data are summarized in Fig. 1. In addition, the point at the peak of the low-energy resonance is the radiative width of the 3^+ state[7] converted to capture cross section on resonance. The results can be understood in terms of a direct-capture model in which an electromagnetic transition occurs from a continuum state of an α and a deuteron to a pure ^3S state in which they are bound by 1.475 MeV, the ^{6}Li ground state. The continuum states are distorted waves generated by the McIntyre-Haeberli potential,[11] a real Woods-Saxon potential with a spin-orbit force which reproduces the d-α phase shifts accurately. The same geometry is used for the bound state, but the well depth is adjusted to give the correct binding energy. Transition matrix elements for multipolarities $E1$, $E2$, $E3$, $M1$, $M2$, and $M3$ have been calculated in the phase-consistent formalism of Rose and Brink.[12] Both electric and magnetic operators include center-of-mass corrections and spin-dependent parts, but the long-wave approximation is employed. Apart from normalization, the calculation is parameter-free in the sense that it is independent of any radiative-capture data. It

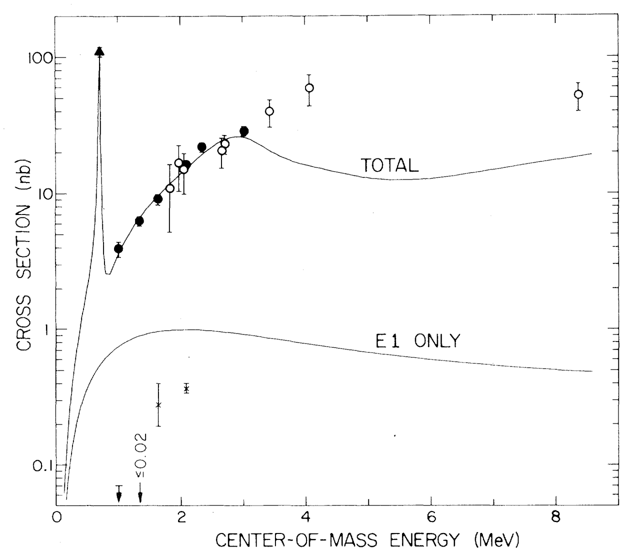

FIG. 1. Cross section for the reaction $^2H(\alpha,\gamma)^6Li$. Open circles, MSU data; closed circles, CRNL data; triangles, $^6Li(e,e'd)$ (Ref. 7); crosses, CRNL data for $E1$ component. The curves are a direct-capture calculation.

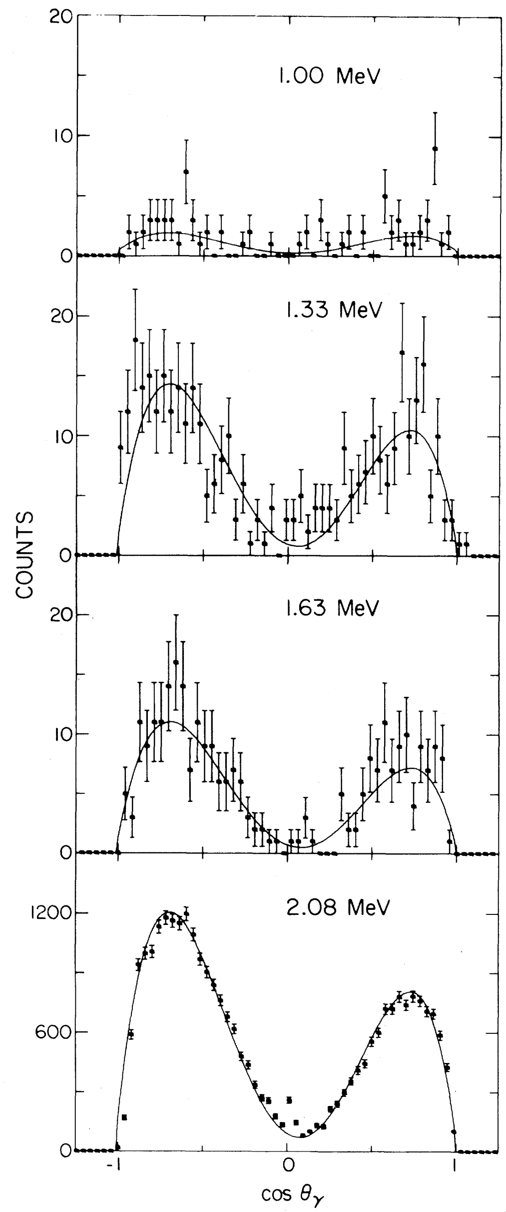

FIG. 2. Measured ^{6}Li momentum distributions for $^2H(\alpha,\gamma)^6Li$ at four center-of-mass energies. The momentum varies linearly as the cosine of the angle between the incident beam and the outgoing photon, θ_γ. The curves are a direct-capture calculation in which the $E1$ operator has been renormalized. The small peak in the center of the lowest distribution is due to a weak ^{6}Li component in the beam, which was removed by means of a velocity filter in the other, more recent, data. The peak width is roughly the instrumental resolution.

predicts that the capture is overwhelmingly $E2$ with a small $E1$ contribution, a conclusion borne out by the measured ^{6}Li recoil distributions as discussed below. The overall normalization of the theoretical curve represents the spectroscopic overlap between the ^{6}Li ground state and α-d clusters. Fitting the data below $E_{c.m.} = 2.1$ MeV (and taking the $E1$ strength from the angular distributions as described below), we find the normalization to be 0.85 ± 0.04. The uncertainty in this spectroscopic factor is experimental and does not take into account the usual uncertainties in the optical-model radius and diffuseness, but there is a clear discrepancy between these results and the calculation of Bornand, Plattner, Viollier, and Adler,[13] who, *using the same potential,* find a spectroscopic factor of only 0.42 from α-d elastic-scattering data. Our results are perhaps the most direct experimental evidence for large α-d cluster parentage in ^{6}Li.

At center-of-mass energies greater than 2.08 MeV, radiative capture can occur to the 0^+, $T = 1$ state, which will then decay radiatively to the ground state. This capture cannot occur in the framework of a DC model because the spectroscopic overlap between the 0^+, $T=1$ state and α-d is identically zero. Nevertheless, it may occur weakly through many-body degrees of freedom and isospin mixing, and it is to these processes that we attribute the excess cross section measured above $E_{c.m.} = 3$ MeV. The intensity is small, about 1% of a normal allowed $E1$ transition.

The direct $E1$ transition to the ground state is also enormously hindered, because of the small electric dipole moment of the d-α system. The hindrance is so large (10^5) that we may expect many-body effects to have comparable importance. The γ-ray angular distributions (Fig. 2) show, in addition to the pronounced double-lobed $E2$ pattern predicted by the DC calculation, a marked forward-backward asymmetry indicative of $E1$-$E2$ interference. However, the DC calculation, although it predicts the even-order Legendre coefficients very well, does not even give the correct sign for the odd-order terms. This is undoubtedly due to the extreme hindrance of the cluster-model $E1$, and we have extracted the $E1$ strength from the data by renormalizing the $E1$ operator (only) in the DC calculations to give the best fit to the odd-order terms at each energy. Reasonable fits to the angular distributions are then obtained (solid lines in Fig. 2). The resulting $E1$ cross sections are shown in Fig. 1, together with the (original) DC calculation for $E1$. We remark that $M2$ and $E3$ amplitudes are calculated to be an order of magnitude weaker than the revised $E1$.

Although the data are not sensitive to an $M1$ contribution less than a few percent of the $E2$, there are several considerations which make a significant $M1$ contribution very unlikely. In the limit that ^{6}Li consists of d-α clusters in a relative S state, $M1$ terms vanish in the long-wave limit. Considering the accuracy of these approximations, we estimate the $M1$ capture cross section to be at least three orders of magnitude weaker than $E1$ and therefore neglect it.

To assess the influence of the new results on the synthesis of ^{6}Li in the big bang, the calculated cross section has been numerically integrated over the Maxwell-Boltzmann velocity distribution as a function of temperature[14] to obtain the reaction-rate parameter $\langle \sigma v \rangle$. The results may be parametrized in the usual way[14] by the expression

$$N_A \langle \sigma v \rangle = 30.14 T_9^{-2/3} e^{-\tau}(1 + 0.056 T_9^{1/3} - 4.85 T_9^{2/3} + 8.85 T_9 - 0.585 T_9^{4/3} - 0.584 T_9^{5/3}) + 85.47 T_9^{-3/2} \exp(-8.228 T_9^{-1}) \text{ cm}^3 \text{ sec}^{-1} \text{ g}^{-1},$$

where $\tau = 7.423 T_9^{-1/3}$, T_9 is the temperature in units of 10^9 K, and N_A is Avogadro's number. The precision of this expression as a parametrization of the DC calculation is better than 3% over the temperature range $0.1 < T_9 < 5$, and the normalization uncertainty is 5%, but the major uncertainty rests in the poorly known $E1$ contribution at low energies. We have assumed that, at very low energies, the many-body effects are unimportant and that the $E1$ capture therefore has the magnitude given by the DC calculation. If, however, the $E1$ cross section remains as depressed at low energies as it is in the range we have measured, the reaction rate will be from 10% (at $T_9 = 5$) to 30% (at $T_9 = 0.1$) lower than given by the expression above.

At $T_9 = 0.8$, the temperature appropriate to ^{6}Li production, the reaction rate is 5 times lower than the estimate currently in use.[1] Even if the baryon density is no higher than the density of observable matter in galaxies (about 3×10^{-31} g cm^{-3}), less than 2% of the universal ^{6}Li can be primordial in origin, and the percentage falls rapidly for larger baryon densities.[1,8] These conclusions remove a long-standing uncertainty in big-bang nucleosynthesis and are consistent with the view that essentially all ^{6}Li is produced in the galactic cosmic rays.

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[1]D. N. Schramm and R. V. Wagoner, Annu. Rev. Nucl. Sci. 27, 37 (1977); R. V. Wagoner, Astrophys. J., Suppl. Ser. 18, 247 (1969).

[2]H. Reeves and J.-P. Meyer, Astrophys. J. 226, 613 (1978).

[3]S. M. Austin, Prog. Part. Nucl. Phys. 7, 1 (1981).

[4]H. Reeves, W. A. Fowler, and F. Hoyle, Nature (London) 226, 727 (1970); M. Meneguzzi, J. Audouze, and H. Reeves, Astron. Astrophys. 15, 337 (1971).

[5]R. V. Wagoner, private communication.

[6]W. A. Fowler, private communication.

[7]F. Eigenbrod, Z. Phys. 228, 337 (1969).

[8]J. Yang, D. N. Schramm, G. Steigman, and R. T. Rood, Astrophys. J. 227, 607 (1979).

[9]R. G. H. Robertson, A. B. McDonald, G. C. Ball, W. G. Davies, E. D. Earle, P. Dyer, R. C. Melin, and T. J. Bowles, Bull. Am. Phys. Soc. 25, 577 (1980).

[10]F. Ajzenberg-Selove, Nucl. Phys. A320, 1 (1979).

[11]L. C. McIntyre and W. Haeberli, Nucl. Phys. A91, 382 (1967). The radius parameter has been adjusted from 1.15 to 1.1555 fm to produce the correct energy for the 3^+ state.

[12]H. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967).

[13]M. P. Bornand, G. R. Plattner, R. D. Viollier, and K. Alder, Nucl. Phys. A294, 492 (1978).

[14]W. A. Fowler, G. R. Caughlan, and B. A. Zimmerman, Annu. Rev. Astron. Astrophys. 13, 69 (1975); and 5, 525 (1967).

Coherent Pion Production near Threshold with a ^{3}He Projectile

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Pion production in ^{3}He-^{3}He collisions has been measured at energies below the threshold for production in free ^{3}He-nucleon reactions, with use of the ^{3}He beam from the Orsay synchrocyclotron. Discrete states of the recoil nucleus, corresponding to the coherent process ^{3}He(^{3}He, π^+) ^{6}Li, have been observed with sizable cross sections at 268.5- and 282-MeV kinetic energy. The ground-state data are consistent with pionic atom information.

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High-momentum-transfer processes such as coherent (p, π) (Ref. 1) or (p, d) (Ref. 2) reactions have been investigated intensively in medium-energy nuclear physics over the past decade, but there is still much controversy surrounding the basic reaction mechanisms.[3] It could be that further valuable clues will be provided by reactions which involve the transfer of two or more nucleons and in this hope we have started a program to study coherent pion production with a low-energy ^{3}He beam.

There have, as yet, been very few attempts at

