The reaction $d(\alpha,\gamma)^6$Li at low energies and the primordial nucleosynthesis of ^{6}Li

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We have searched for the reaction $d(\alpha,\gamma)^6$Li at an α-d center-of-mass energy of 53 keV. An upper limit on the reaction S factor is 2.0×10^{-7} MeV b at the 90% confidence level, corresponding to a limit on the synthesis of ^{6}Li from a standard big bang of 0.9% of the present abundance for a total baryon-to-photon ratio $2.86<\eta_{10}<3.77$. Equivalently, the ^{6}Li-to-^{7}Li isotopic abundance ratio immediately after a standard big bang is constrained to be less than 0.85%, considerably less than a recent measurement of this ratio in a metal-poor, Population II halo star.

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The reaction $d(\alpha,\gamma)^6$Li remains the object of considerable attention, both experimental and theoretical, because of the possibility, evident in the original standard big-bang calculations of Schramm and Wagoner [1], that this reaction may, as an alternative to galactic cosmic ray spallation [2], constitute a source of the present abundance of ^{6}Li. More recent standard big-bang calculations [3,4] likewise predict the synthesis of ^{6}Li from this reaction. This possibility relies on the value of the reaction cross section at the energies appropriate to the big-bang temperatures. On the basis of recent standard big-bang calculations of the synthesis of ^{7}Li from the t-α reaction, the ''most-effective'' center-of-mass (c.m.) energies for the d-α capture reaction range from about 45 to 150 keV [5].

There have been two direct measurements of the $d(\alpha,\gamma)^6$Li reaction. Robertson *et al.* [6] have measured the reaction down to a c.m. energy of 1 MeV and extrapolated their results to lower energies using a direct capture model. At an α-d c.m. energy of 150 keV, they calculate a reaction cross section 0.08 nb corresponding to an astrophysical S factor of about 0.4×10^{-8} MeV b. They originally concluded that less than 2% of the present universal abundance of ^{6}Li may be attributed to the primordial α-d capture reaction but recently revised this upper limit to 0.12% [7]. Mohr *et al.* [8] have measured the reaction in the vicinity of the resonance at an α-d c.m. energy of 711 keV. Since the width of this resonance is relatively narrow, $\Gamma_{\text{c.m.}}=24\pm2$ keV [9], the contribution of this resonance to the total reaction cross section at low energies may be neglected in comparison to the extrapolation of the direct measurements by Robertson *et al.* [6].

In addition to those of Robertson *et al.* [6], there have been a number of other calculations of the $d(\alpha,\gamma)^6$Li reaction at low energies [10–13]. While all agree with the measured cross sections of Ref. [6] between c.m. energies of 1 and 4 MeV, there is considerable disagreement when these calculations are extended to low energies with cross sections at, for example, 300 keV varying from 0.09 to 0.8 nb. A measurement of the $d(\alpha,\gamma)^6$Li reaction cross section in the c.m. energy range of a few hundred keV is needed in order to eliminate the dependence upon the extrapolation through theoretical calculation.

This need has been addressed by Kiener *et al.* [14] and Hesselbarth *et al.* [15] who have measured the α-d breakup reaction of energetic ^{6}Li ions by heavy targets and used the cross section for this reaction to determine the cross section for the $d(\alpha,\gamma)^6$Li reaction. This technique has, likewise, been used to investigate the ^{3}H$(\alpha,\gamma)^7$Li reaction by measuring the analogous breakup of ^{7}Li [16,17]. This technique is complicated, however. Gazes *et al.* [17], for example, have concluded that the presence of the target nuclear field and of final state interactions will ''... severely complicate the extraction of radiative capture cross sections from the direct break-up data.'' This conclusion is consistent with the results of Utsunomiya *et al.* [16] who extract a low-energy S factor for the ^{3}H$(\alpha,\gamma)^7$Li reaction significantly in excess of the recent direct measurements of this reaction by Brune *et al.* [5]. There is likewise significant disagreement between the indirect measurement of Kiener *et al.* [14], who deduce an S factor for the $d(\alpha,\gamma)^6$Li reaction at a c.m. energy of 150 keV of $(1.35\pm0.2)\times10^{-8}$ MeV b and the extrapolated calculations of Robertson *et al.* [6], which yield $S=0.4\times10^{-8}$ MeV b at this energy. Because of the uncertainties of using the indirect ^{6}Li breakup data and because of the uncertainties of the extrapolation to low energies of this reaction, we feel that the cross section reaction should be measured directly at low energies.

We have tried to observe the $d(\alpha,\gamma)^6$Li reaction directly at a c.m. energy of 53 keV by bombarding a pressed, water-cooled, wafer of deuterated polyethylene with a 160 keV beam of $^4He^+$ ions from the Colorado School of Mines air-insulated accelerator [18] and measuring the γ ray spectrum from the target during the bombardment. The target was about 1 mm in thickness so that the beam stopped in the target. The target was mounted at the end of the exit arm of a 45° bending magnet. The last 50 cm of this arm was electrically connected to the target and insulated from the rest of the beamline and the total beam charge on the target was measured by integrating the current on the target. The detector consisted of a 30% relative efficiency high-purity Ge detector. The front face of the detector was located about 3 mm from the target and was perpendicular to the direction of the incoming beam with a solid angle $\Delta\Omega=5.56$ sr relative to the

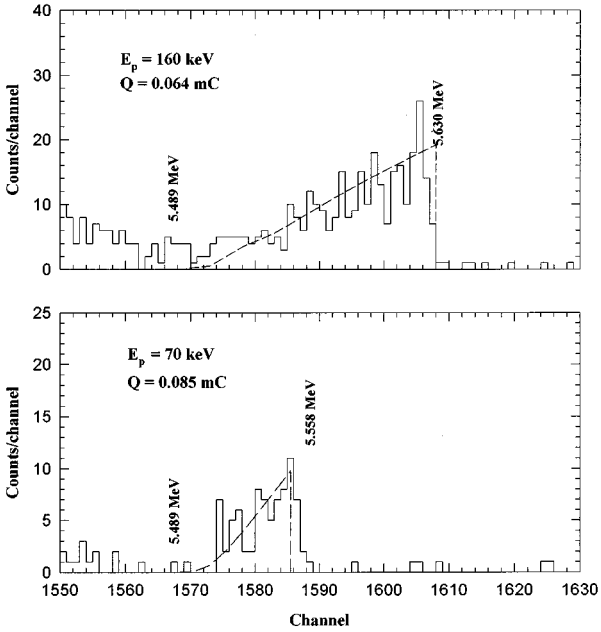

FIG. 1. Energy spectra measured during proton bombardments of the deuterated polyethylene target.

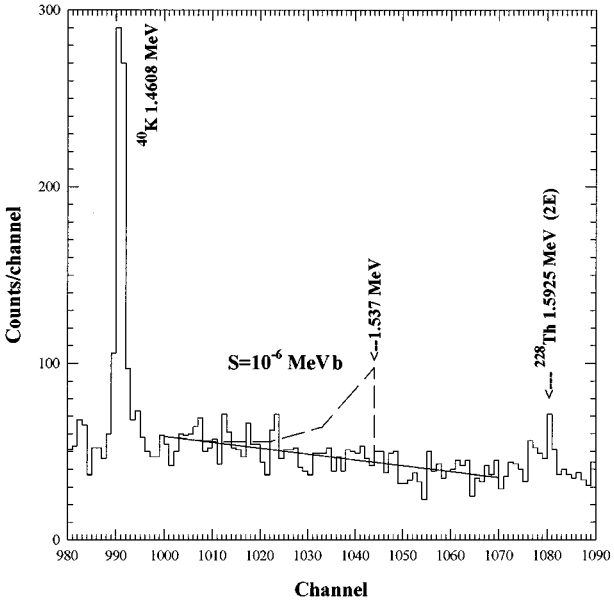

FIG. 2. Energy spectra measured during 5 C 160 keV $^4He^+$ bombardment of deuterated polyethylene target.

center of the target. The absolute peak efficiency of this detector has been well characterized [19]. Since we used a thick target, and since the expected cross section for the reaction is quite small ($\sigma<1$ nb), a number of experimental factors had to be considered. As a check on these factors, the reaction $d(p,\gamma)^3$He, for which the cross section is well known at low energies [20], was measured using the same target, detector, and analytical techniques as were used for the $d(\alpha,\gamma)^6$Li reaction.

(i) γ ray energy. The energies of the γ rays from the $d(p,\gamma)^3$He and $d(\alpha,\gamma)^6$Li reactions will depend upon the energy of the projectile and hence will form a continuum for a thick target. The energies of the γ rays emitted at 0° (or 90°) from the beam direction for an incident proton or α particle energy of 160 keV will then range from 5.630 (or 5.620) to 5.489 MeV and 1.537 (or 1.530) to 1.474 MeV, respectively, for these two reactions. The shape of this γ ray energy continuum will reflect the reaction cross section as the projectile slows down from the incident beam energy to zero energy,

$$dN_\gamma/dC_\gamma = f\varepsilon(E_\gamma)\sigma(E_p)/[(dE_p/dn)(dE_\gamma/dE_p)] \times (dE_\gamma/dC_\gamma), \quad (1)$$

where $\varepsilon(E_\gamma)$ is the efficiency, which depends on the γ ray energy E_γ, f is the number of target atoms per molecule, and dE_p/dn is the projectile stopping power per molecule [21]. The derivatives dE_γ/dE_p are nearly constant and have the respective values 0.39 and 0.88 for α particle and proton energies up to 200 keV, and the derivatives (dE_γ/dC_γ) are the slopes of the linear energy calibrations of the spectra.

Two of the spectra measured during the proton bombardments are shown in Fig. 1. The slewed peak shape is the result of the beam slowing down in the target and not characteristic of the detector. The dashed line is the peak shape calculated using Eq. (1). The cross section in Eq. (1) was calculated using the known S factor for this reaction. The spectrum measured over the course of the 5 C $^4He^+$ bombardment of the target is shown in Fig. 2. For comparison the peak shape calculated assuming a constant S factor of 1×10^{-6} MeV b is indicated by the dashed line above a constant linear background.

(ii) Detector shielding. Since the cross section for the $d(\alpha,\gamma)^6$Li reaction is quite small, it was essential that the detector be well shielded from room background. The main background in the spectrum will then be the Compton continuum from the 2.614 MeV γ ray from the decay of the naturally occurring ^{232}Th. The detector was carefully surrounded on all sides by 20 cm of lead brick. The attenuation for 2.6 MeV γ rays from external sources should then be about 2×10^{-5}. In fact, an attenuation of only 10^{-3} was observed. This discrepancy could be attributed to trace quantities of ^{232}Th in the target holder, the detector housing, or the lead shielding bricks themselves.

(iii) Target deterioration. It was essential that the near-surface deuterium content of the target be monitored in the face of carbonization of the deuterated polyethylene target or hydrocarbon deposition on the target. This deuterium content was monitored by measuring the yield of the $d(p,\gamma)^3$He reaction at the beginning of, in the middle of, and at the end of the α bombardment. The deuterium content in the ranges sampled by the 160 and 70 keV protons decreased by about 15% over the course of the 5 C $^4He^+$ bombardment. The ranges of these protons in polyethylene are 1.9 and 0.9 μm, respectively, bracketing the 160 keV $^4He^+$ ions, which have a range of 1.25 μm.

(iv) Reaction yield. Since the beam stops in the target, the total reaction yield is the integrated yield between the incident beam energy and zero. The count rate is then the product of the reaction yield and the detection efficiency:

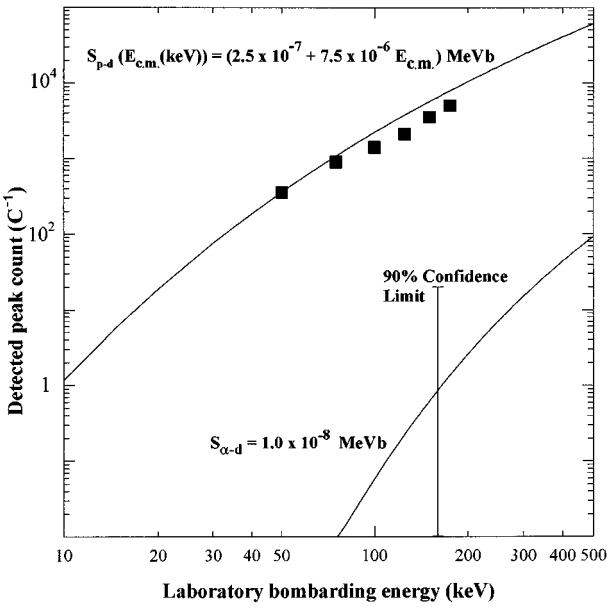

FIG. 3. Comparison of measured and calculated yields of the γ rays from the p-d and α-d experiments.

$$N_\gamma(E_0)=\int f[\varepsilon(E_\gamma)\sigma(E)/(dE/dn)]dE, \qquad (2)$$

where $N\gamma(E_0)$ is the number of detected full-energy peak counts per incident projectile, and the limits on the integral are zero and the incident beam energy. The other terms in this expression are the same as in Eq. (1). Since the detection efficiency $\varepsilon(E_\gamma)$ was determined from isotropic sources, Eqs. (1) and (2) assume an isotropic distribution of reaction γ rays. In practice, due to the large solid angle of the detector, Eqs. (1) and (2) rely rather on the forward-backward symmetry of the reaction γ rays. In their measurements at higher energies, Robertson *et al.* [6] observed a forward-backward *asymmetry*, with the backward lobe of the distribution yielding about 1.33 more than the forward. We assume the same asymmetry in the reaction γ rays in the present experiment. The predicted yields (in units of counts/C of incident beam) for the two reactions are shown in Fig. 3, where the S factors used are indicated in the figure. The S factor for the $d(\alpha,\gamma)^6$Li reaction of 1×10^{-8} MeV b was used for reference. The measured yield of the $d(p,\gamma)^3$He reaction is also shown in Fig. 3 by the solid squares. There is no evidence for the d-α capture γ ray in Fig. 2. The normalized integrated χ^2 distribution over the peak region as a function of assumed S factor exceeds 0.90 for an S factor of 1.7×10^{-7} MeV b. This upper limit should be corrected for the forward-backward asymmetry in the reaction γ rays noted above. Consequently, the S factor for the $d(\alpha,\gamma)^6$Li reaction must, at a 90% confidence level, be less than 2.0×10^{-7} MeV b. Using Eq. (2), this S factor upper limit for the $d(\alpha,\gamma)^6$Li reaction corresponds to a total measured peak yield (per coulomb) of about 20 counts. This yield is indicated in Fig. 3, where it is compared to the yield predicted assuming an S factor of 1×10^{-8} MeV b.

As is clear from Fig. 3, the present inferred upper limit on the S factor for the $d(\alpha,\gamma)^6$Li reaction is well above that of Robertson *et al.* [6] as well as the indirect measurements of this reaction and the various calculations. Consequently, we are unable to use our measured upper limit to distinguish between these various quoted values of the S factor for this reaction. The upper limit may, nonetheless, serve to provide a fairly stringent, albeit model-dependent, estimate of the maximum amount of ^{6}Li which could have been produced in the big bang. Two standard big-bang calculations are used to provide this estimate:

(i) Schramm and Wagoner [1] assume a reaction rate for the $d(\alpha,\gamma)^6$Li reaction for $0.1<T_9<0.6$ which corresponds to a constant S factor of about 5×10^{-8} MeV b. The final modeled abundances depend upon the present photon temperature and baryon density ρ_0 in the universe. For a photon temperature of 2.7 K and a baryon density $\rho_0=3\times10^{-31}$ g/cm^3, they predict a final ^{6}Li abundance (relative to hydrogen) of about 1×10^{-12} and hence would predict, based upon the present observed abundance of ^{6}Li of 2×10^{-10} [2], that 0.5% of the present abundance of ^{6}Li could have been produced in the big bang. Our upper limit on the S factor for the $d(\alpha,\gamma)^6$Li reaction is four times the value assumed by Schramm and Wagoner [1]. Hence we are able to place an upper limit of 2.0% on the amount of the present abundance of ^{6}Li which could have been synthesized during the big bang.

(ii) Using the model described by Smith, Kawano, and Malaney [4], and assuming the *present upper limit* of 2.0×10^{-7} MeV b for the S factor for the $d(\alpha,\gamma)^6$Li reaction, a range of final abundances of ^{6}Li has been calculated [22] for values of the baryon-to-photon ratio η_{10} from 2.85 to 3.77 (this range of η_{10} corresponds to a range of the present baryon density of the universe from 2.03×10^{-31} to 2.67×10^{-31} g/cm^3 for a present photon temperature of 2.76 K). For this range of values of the baryon-to-photon ratio, the final predicted abundances of ^{6}Li (relative to hydrogen) range from 1.7×10^{-12} down to 1.15×10^{-12}, corresponding to an upper limit of 0.9% on the amount of the present abundance of ^{6}Li which could have been synthesized during the big bang. These calculations of Smith *et al.* are based upon a network of cross sections which have been considerably revised since the original calculations of Schramm and Wagoner [1]. Consequently, we adopt the later upper limit as the more accurate of the two. This adopted upper limit of 0.9% on the amount of the present abundance of ^{6}Li which could have been synthesized during the big bang is thus consistent with the generally accepted conclusions of Reeves, Fowler, and Hoyle [2], that a very high fraction of the present abundance of ^{6}Li is generated by postprimordial galactic cosmic ray spallation.

Similarly, we may place a constraint on the ^{6}Li-to-^{7}Li isotopic abundance emerging from the big bang. Smith [22], again assuming the *present upper limit* of 2.0×10^{-7} MeV b for the S factor for the $d(\alpha,\gamma)^6$Li reaction, predicts this ratio to vary from 0.85% to 0.23%, again as the baryon-to-photon ratio η_{10} ranges from from 2.85 to 3.77. This range of upper limits for the ^{6}Li-to-^{7}Li isotopic abundance ratio is considerably less than the ratio in the protostellar gas of $8.0\pm0.3\%$ [23] or of the ratio in the metal-poor Pop II star measured by Smith, Lambert, and Nissen [24] of $5\pm2\%$, both of which have been suggested [2] as possible indicators of the primordial isotopic abundance ratios.

Finally, we would like to stress that a conclusive direct measurement of this reaction at low energies is still wanting. We would point out that if our present experiments were repeated at an α particle bombarding energy of 500 keV (well beyond the range of our accelerator facility but still within the range of effective energies for the standard big bang), then the thick target yield, at a given S factor, while remaining quite small on an absolute scale, would, referring to Fig. 3, be nearly two orders of magnitude greater than at the 160 keV at which the present measurements were conducted.

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[1] D. N. Schramm and R. V. Wagoner, Annu. Rev. Nucl. Sci. **27**, 37 (1977).
[2] H. Reeves, W. A. Fowler, and F. Hoyle, Nature **226**, 727 (1970); Hubert Reeves, Rev. Mod. Phys. **66**, 193 (1994).
[3] J. Yang, D. N. Schramm, G. Steigman, and R. T. Rood, Astrophys. J. **227**, 697 (1979).
[4] M. S. Smith, L. H. Kawano, and R. A. Malaney, Astrophys. J. Suppl. Ser. **85**, 219 (1993).
[5] C. R. Brune, R. W. Kavanaugh, and C. Rolfs, Phys. Rev. C **50**, 2205 (1994); C. R. Brune, Ph.D. thesis, California Institute of Technology, 1994 (unpublished); and private communication.
[6] R. G. H. Robertson, P. Dyer, R. A. Warner, R. C. Melin, T. J. Bowles, A. B. McDonald, G. C. Ball, W. G. Davies, and E. D. Earle, Phys. Rev. Lett. **47**, 1867 (1981).
[7] R. G. H. Robertson, P. Dyer, R. A. Warner, R. C. Melin, T. J. Bowles, A. B. McDonald, G. C. Ball, W. G. Davies, and E. D. Earle, Phys. Rev. Lett. **75**, 4334 (1995) (Erratum to Ref. [6]).
[8] P. Mohr, V. Kolle, S. Wilmes, U. Atzrott, G. Staudt, J. W. Hammer, H. Krauss, and H. Oberhummer, Phys. Rev. C **50**, 1543 (1994).
[9] F. Ajzenberg-Selove, Nucl. Phys. A **490**, 1 (1988).
[10] K. Langanke, Nucl. Phys., A **457**, 351 (1986).
[11] K. Langanke and C. Rolfs, Z. Phys. A **325**, 93 (1986).
[12] N. A. Burkova, K. A. Zhaksibekova, and M. A. Zhusupov, Phys. Lett. B **248**, 15 (1990).
[13] S. Typel, G. Bluge, and K. Langanke, Z. Phys. A **339**, 335 (1991).
[14] J. Kiener *et al.* Phys. Rev. C **44**, 2195 (1991).
[15] J. Hesselbarth, S. Khan, Th. Kihm, and K. T. Knöpfle, Z. Phys. A **331**, 365 (1988).
[16] H. Utsunomiya *et al.*, Phys. Rev. Lett. **65**, 847 (1990).
[17] S. B. Gazes, J. E. Mason, R. B. Roberts, and S. G. Teichmann, Phys. Rev. Lett. **68**, 150 (1992).
[18] F. E. Cecil, D. Ferg, R. King, B. Kriss, H. Liu, and J. Scorby, Nucl. Instrum. Methods Phys. Res. Sect. B **40/41**, 934 (1989).
[19] F. E. Cecil, D. Ferg, H. Liu, J. Scorby, J. A. McNeil, and P. D. Kunz, Nucl. Phys. A **539**, 75 (1992).
[20] G. M. Bailey, G. M. Griffiths, M. A. Olivo, and R. L. Helmer, Can. J. Phys. **48**, 3059 (1970).
[21] The stopping powers were calculated with the code TRIM92 which was written by J. Bierstadt and J. F. Zeigler.
[22] Michael S. Smith, Oak Ridge National Labs (private communication).
[23] D. Krankowski and O. Muller, Geochim. Cosmochim. Acta **31**, 1833 (1967).
[24] V. Smith, D. Lambert, and P. Nissen, Astrophys. J. **408**, 262 (1993).