Low-Energy $^3He(\alpha, \gamma)^7Be$ Cross-Section Measurements

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The cross section and branching ratio for $^3He(\alpha,\gamma)^7Be$ have been measured from $E_{c.m.}$ = 165 to 1170 keV by counting prompt γ rays from a windowless, recirculating, ^3He gas target. Absolute cross sections were also measured at $E_{c.m.}$ = 945 and 1250 keV by measuring the ^7Be activity produced in a ^3He gas cell with a Ni entrance foil. The inferred zero-energy intercept is $S_{34}(0) = 0.52 \pm 0.03$ keV b. The effect of this extrapolated value on the solar-neutrino problem is discussed.

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The Brookhaven National Laboratory solar-neutrino experiment has measured[1] a neutrino flux of 2.2 ± 0.3 SNU (solar neutrino unit, 1 SNU $= 10^{-36}$ captures per ^{37}Cl atom per second), well below the 7.6 ± 3.3 SNU (3σ error) predicted by current solar models.[2] Since the detector relies on the endoergic ($Q = -0.81$ MeV) neutrino-capture reaction

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-,$$

it is most sensitive to the energetic neutrinos from the decay of ^8B. The production of ^8B proceeds through the weak (0.02%) branch of the proton-proton chain,

$$^3He(\alpha,\gamma)^7Be(p,\gamma)^8B,$$

and the theoretical calculation of the solar-neutrino flux depends on accurate experimental determinations of the low-energy cross sections for these radiative captures, extrapolated to solar temperatures. Preliminary indications of an energy-independent cross-section factor[3] for the reaction $^3He(\alpha,\gamma)^7Be$, contrary to theoretical expectations, have led to several recent theoretical investigations[4] of this reaction and, although the methods of calculation have varied, all have been in agreement with the shape calculated in 1963 by Tombrello and Parker.[5] More recent measurements by Kräwinkel *et al.*[6] agree with this energy dependence but have indicated that the cross-section factor for $^3He(\alpha,\gamma)^7Be$ may be 30–50% lower than previous values (Parker and Kavanagh[7] and Nagatani *et al.*[8]). Because the predicted solar-neutrino detection rate is nearly proportional to the $^3He(\alpha,\gamma)^7Be$ reaction rate, this lower cross section would reduce the theoretical neutrino flux to 5.0 ± 2.1 SNU (3σ error) providing a partial solution to the solar-neutrino problem.[2] The significant disagreement with

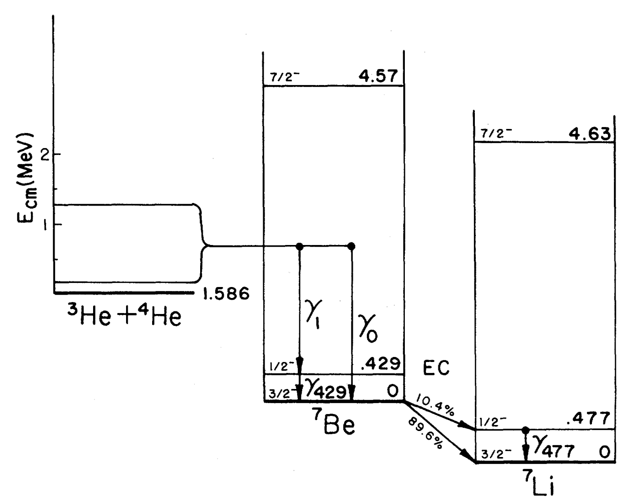

FIG. 1. Level scheme for the $^3He + {}^4He$ reaction and the electron-capture decay of ^7Be, showing the observed γ-ray transitions.

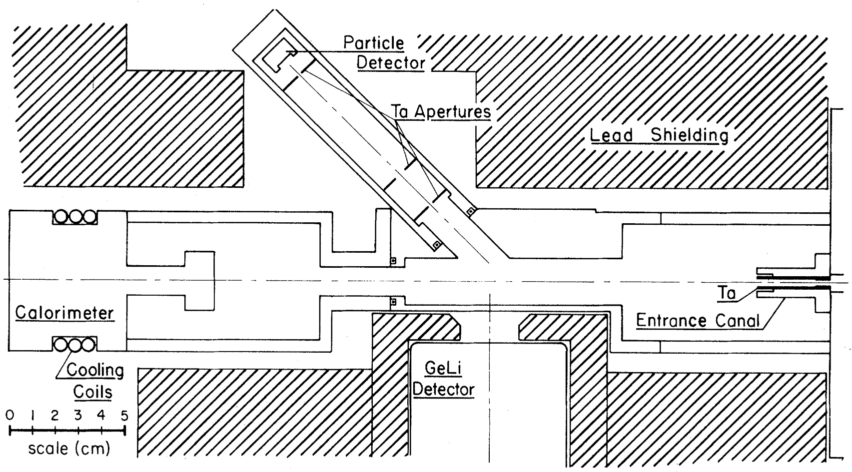

FIG. 2. ^{3}He-gas-target chamber for the windowless, differentially pumped system.

previous values has led us to reexamine this reaction.

We have used two complementary techniques for this measurement. The first method involved the observation of the prompt γ rays (γ_0, γ_1, and γ_{429} in Fig. 1) using α beams from the Office of Naval Research–California Institute of Technology (ONR-CIT) JN electrostatic accelerator and the windowless, differentially pumped, recirculating gas-target system described previously.[9] A new ^{3}He target chamber was designed to accommodate a 100-cm^3 Ge(Li) detector, a rugged silicon surface-barrier particle detector, and a single-cup calorimeter for beam-current integration (see Fig. 2). The windowless target allows measurements to be made at very low energies by reducing the γ-ray background and by eliminating the additional beam-energy spread from straggling in an entrance foil. The energy of the direct-capture γ rays is determined by the energy of the captured α, and provides an independent measurement of the beam energy. The disadvantages of this method are primarily associated with the low target pressure (typically 2.5 to 3 Torr), which requires an extended target, high beam currents (up to 40 μA), and long running times (36 h at the lowest energies). The detection efficiency in the extended target was measured as a function of γ-ray energy and source position by moving calibrated ^{56}Co and ^{152}Eu sources along the beam path. The problem of beam-current integration was solved by using a single-cup solid-copper calorimeter. The beam stop was connected to a large, water-cooled, constant-temperature heat sink by a copper rod 2.5 cm long by 1 cm^2 in cross section. The difference in temperature between the beam stop and the heat sink, ΔT, yields the number of incident beam particles, n_α, by the relation

$$n_\alpha = (A/E_c)\int \Delta T\, dt,$$

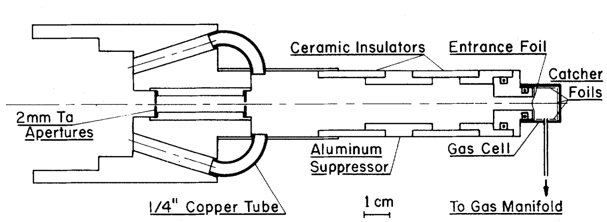

FIG. 3. Gas cell used in the activation measurement. The chamber and detector were surrounded on all sides by 10 cm of lead.

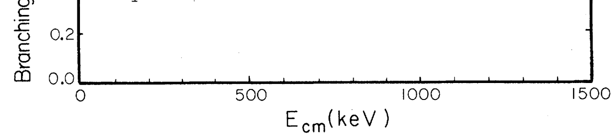

FIG. 4. Experimental results for the ^{3}He(α,γ)^{7}Be cross-section factor, $S_{34}(E_{\mathrm{c.m.}})$, and branching ratio. Triangles indicate the activation measurements. Dashed curves are from the calculations of Liu, Kanada, and Tang (Ref. 4). The theoretical S-factor curve of Ref. 5 is shown normalized to the present data (solid curve).

TABLE I. Comparison of measured values of the cross-section factor zero-energy intercept for the reaction $^3He(\alpha,\gamma)^7Be$.

Reference	$S_{34}(0)$ (keV b)
6	0.30 ± 0.03
7	0.47 ± 0.05
8	0.61 ± 0.07
Present	0.52 ± 0.03

where E_c is the particle energy at the calorimeter and A is the calibration constant in watts per kelvin. The calorimeter was calibrated over a wide range of energies and beam currents and was found to agree with electrical integration to within 1%. The particle detector was used to monitor relative beam current, target pressure, and contaminant gases. By surrounding the detector with 10 cm of lead, γ-ray background was reduced by a factor of $\sim 10^3$ at $E_\gamma \simeq 1.5$ MeV.

In the second measurement, a gas-target cell (Fig. 3) filled with ^3He gas was bombarded by α's from the ONR-CIT EN tandem accelerator through a window consisting of 0.66 μm Ni plus 0.2 μm Cu. The ^7Be produced by the radiative capture was implanted in the 0.025-mm-Pt catcher foil at the end of the cell. The Pt catcher foil was removed from the cell at the end of a run, and the γ rays from the 10% electron-capture branch to the first excited state of ^7Li (γ_{477} in Fig. 1) were counted with a shielded Ge(Li) detector and compared with the yield from a calibrated ^7Be source in the same geometry. This method has the advantages of directly measuring the angle-integrated cross section, σ_{tot}, and of using conventional electrical current integration. Prompt γ rays were monitored using a NaI(Tl) detector during bombardment to establish effective beam energy in the target. Foil thickness and straggling were also measured by examining the known narrow resonances in $^{24}Mg(\alpha,\gamma)$ and $^{14}N(\alpha,\gamma)$ at $E_\alpha = 3.198$ and 2.348 MeV, respectively, in the same geometry. The energy loss in the foil and gas agreed with that implied by the prompt γ-ray energy to within experimental uncertainty (5 keV).

The results of the experiment are shown in Fig. 4. The cross-section factor was calculated from the expression

$$S_{34}(E_{\text{c.m.}}) = \sigma_{tot}(E_{\text{c.m.}})E_{\text{c.m.}}e^{2\pi\eta},$$

where η is the Sommerfeld parameter. The cross-section factor, extrapolated to zero energy by fitting the theoretical expression of Ref. 5 to the experimental data, is $S_{34}(0) = 0.52 \pm 0.03$ keV b (1σ error). Because of the similar shapes of the other theoretical cross-section curves, this value is also consistent with their extrapolated values.

Comparison of this experiment with other measurements is shown in Table 1. The present measurements agree with the earlier results of Refs. 7 and 8, and with the adopted value, $S_{34} = 0.52 \pm 0.15$ (3σ error), used for the most recent solar-neutrino flux calculations of Bahcall *et al.*[2] The substantial disagreement among the values in Table I is currently being studied and will be discussed in the complete report on the present experiments.[10]

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