$C^{12}(n,\alpha)Be^9$ Reaction Induced by 14-MeV Neutrons*

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The reaction has been studied with emulsions. Total cross section for the forward hemisphere (lab) and first 5-MeV excitation is 144±57 mb, of which 62±15 mb is associated with the ground-state group. These are consistent with earlier estimates, and with measured values for the inverse process. Angular distributions of the ground and 2.4-MeV excited state groups have the direct interaction form, and a spin of 3/2 is indicated for the excited state. This value supports earlier arguments for *LS* coupling in Be^9, and suggests that the 2.4-MeV state consists of Be^8 in its first excited state and a *p*-state neutron. Comparison of the ratio of reduced widths, for transitions to the 0.0- and 2.4-MeV states, with an estimate of the ratio of the corresponding coefficients of fractional parentage, favors a knockout mechanism.

INTRODUCTION

EXPERIMENTAL evidence for direct interactions has been found in reactions involving the exchange of more than one particle, such as (p,t), (p,α), and (n,α), but interpretations are unsettled. Nilsson and Kjellman[1] have noted discrepancies in the mechanisms invoked to explain various data on specific (α,n) reactions. Similarly, in the case of (n,α) the large measured cross sections of Paul and Clarke[2] constitute evidence for direct processes, while Kumabe *et al.*[3] have been able to interpret their data by compound nucleus theory alone. Direct (n,α) reactions can proceed by pickup or knockout mechanisms, depending largely on the probabilities that He^3 or He^4 exist in the target nucleus. Alpha-particle clusters seem more likely than other configurations, in a system of 6 protons and 6 neutrons. This intuition is confirmed by the finding of Ostroumov and Filov[4] that a nucleon on the surface of the C^{12} nucleus spends about 50% of its time as a part of an alpha particle. Thus, a direct knockout mechanism in $C^{12}(n,\alpha)Be^9$ is likely *a priori*.

This study was made in the hope of collecting information bearing on the reaction mechanism and establishing the spin of the 2.4-MeV state of Be^9. All theoretical[5] and experimental[6,7] work indicate that this state should have a spin $\geqslant 3/2$, but a definite value has not been established.

EXPERIMENTAL

Targets of C^{12} (0.6 mg/cm^2) were prepared from commercial Aquadag. Two such targets on opposite sides of a copper sheet were inserted between two facing emulsions, barely out of contact, to record simultaneously particles emitted in forward and backward directions. The assembly was exposed to a total flux of 7.8×10^8 neutrons from the $H^3(d,n)He^4$ reaction. The plane of targets and emulsions made an angle of 45° with the incident neutrons, which were normal to the deuteron beam. This plate arrangement resembles that of Kumabe *et al.*,[3] but energy definition is improved by the use of equatorial neutrons, whose energy spread resulting from the slowing of deuterons in the tritium target is minimal.

Detection efficiency is a function of the angle (θ) which the emitted alpha particle makes with the incident neutron. It is 100% for $0\leqslant\theta\lesssim25°$, and decreases as θ increases beyond 25°, as a result of absorption in the carbon target and plate scanning inefficiency for steeply dipping tracks. The effective solid angle of the emulsion detector for various θ, clearly a function of alpha-particle energy, was calculated at intervals of 5°.

Sensitivity of the emulsions used (Ilford, 100 μ, *K*-1) was tested by exposures to neutrons and thorium alphas (Fig. 1). Complete desensitization to protons of all energies was achieved by direct immersion in chromic acid (1%), but the technique was not used in the experiment because of attendant distortion. Adequate discrimination against protons was achieved by controlled development. The developer of Stiller *et al.*[8] was used, with slightly altered concentration and temperature control. A 10-min dry development at 20°C was found to give the best differentiation between tracks produced by protons and alpha particles in the energy range of interest. Background was assessed by a duplicate independent exposure.

Computations of energy, reaction angle, and the correction for energy loss in the carbon target were carried out on Brown University's IBM 7070 Computer.

CROSS SECTIONS

The highest 5 MeV of alpha energy spectrum integrated from 0° to 90° (lab), is shown in Fig. 2. The

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† Submitted in partial fulfillment of the requirements for the Ph.D. degree at Brown University.
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[4] V. I. Ostroumov and R. A. Filov, Zh. Eksperim. i Teor. Fiz. **37**, 643 (1959) [Soviet Phys.—JETP **10**, 459 (1960)].
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[7] R. G. Summers-Gill, Phys. Rev. **109**, 1591 (1958).
[8] B. Stiller, M. M. Shapiro, and F. W. O'Dell, Rev. Sci. Instr. **25**, 340 (1954).

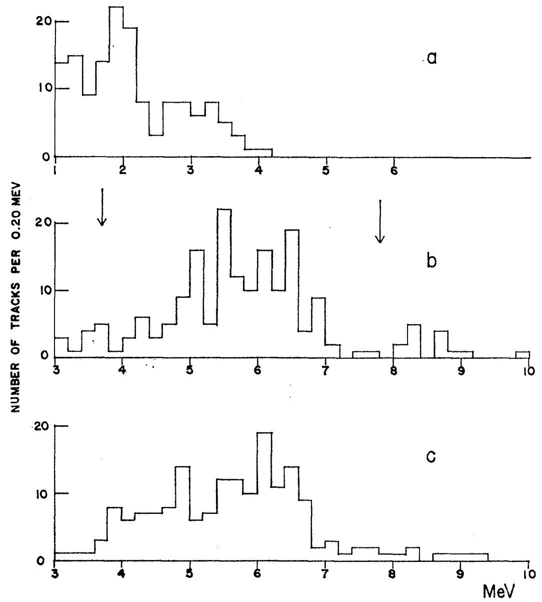

FIG. 1. Emulsion sensitivity: (a) the energy spectrum of recoil protons as recorded on K-1 emulsion plate exposed to 14.1-MeV neutrons; (b) the energy spectrum of thorium alphas as recorded by the same emulsion; (c) the energy spectrum of thorium alphas recorded on a K-1 plate after immersion in chromic acid. The abscissa represents the number of measured tracks in the energy interval indicated. Arrows show the energies of alpha particles having the same ranges in emulsion as protons of 1 and 2 MeV.

decrease of yield above the third excited state energy is real, for the short-track cutoff takes effect at $Q \leqslant -10.0$ MeV for most tracks.

Total cross sections are 62±15 mb for the ground-state transition and 144±57 mb for the first 5 MeV of residual excitation. Both values measure yields to the forward laboratory hemisphere and so may be somewhat less than the true cross sections. However, they are quite consistent with the corresponding values (80±20 mb and 140±50 mb) of Graves and Davis,[9] inferred from neutron absorption measurements.

It is of interest to compare the ground-state transition cross section with that for the inverse process. From the result quoted, the reciprocity theorem gives for $Be^9(\alpha,n)C^{12}$ at 10.6-MeV alpha energy (lab) a cross section of 18±4 mb. At 13.5 MeV the observed[1] (α,n) ground-state transition cross section is 13±2 mb and at lower energies, in the absence of resonant effects, similar values are found (e.g., 14 mb at 3.2-MeV alpha energy).[10] The much larger values occurring in the range 2.0–5.8 MeV (up to 80 mb) are associated with compound nucleus resonances.[10]

ANGULAR DISTRIBUTIONS

Limitations on the precision of track measurements and finite size of the neutron source are the principal causes of the rather poor energy resolution, which precludes locating any energy group with less than 1 MeV absolute uncertainty. Nevertheless, the spectrum seems to give a clean enough indication of the 0.0- and 2.4-MeV state groups, and their angular distributions have been determined (Figs. 3–6). Each distribution is shown with two theoretical direct-interaction curves, for a knockout mechanism with $l=1$, $R=5$ F, and for a pickup mechanism with $l=1$ and $R=4.45$ F. For the ground-state transition the l value must be 1; for the excited state, only $l=1$ gives a fit with reasonable radius ($l=3$ requires 9.5 F for pickup, more for knockout). The values represented in Figs. 3–6 are quite consistent with the general systematics of direct interaction radii, and afford no discrimination as to the detailed mechanism involved. This in not surprising, since the shape of the angular distribution, plane-wave Born approximation and distorted-wave Born approximation, is independent of such specific assumptions. The

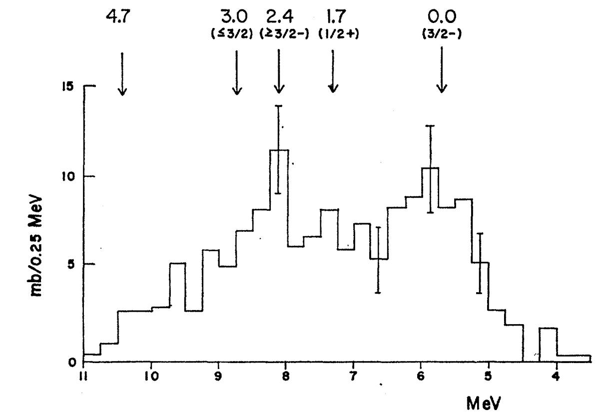

FIG. 2. Energy spectrum of the emitted alpha particles. The ordinate is the total cross section between 0° and 90° in the laboratory system and the abscissa is $-Q$. Arrows show the known levels of Be^9, labeled with excitation (MeV), spin and parity (reference 11).

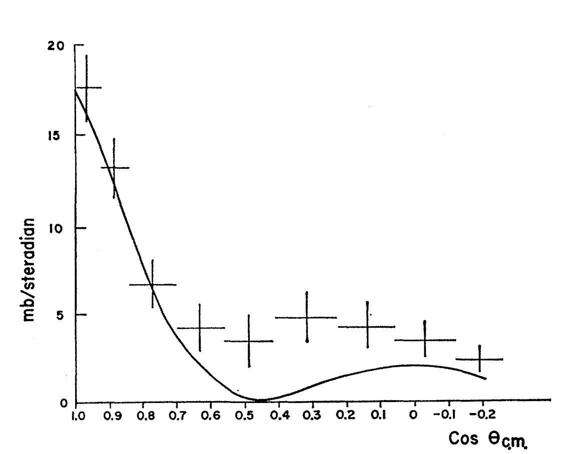

FIG. 3. Angular distribution for transitions to the ground state ($-6.2<Q<5.2$). The solid curve is a theoretical Butler curve with $l=1$ and $R=5$ F. A knockout mechanism is assumed.

[9] E. R. Graves and R. W. Davis, Phys. Rev. **97**, 1205 (1955).
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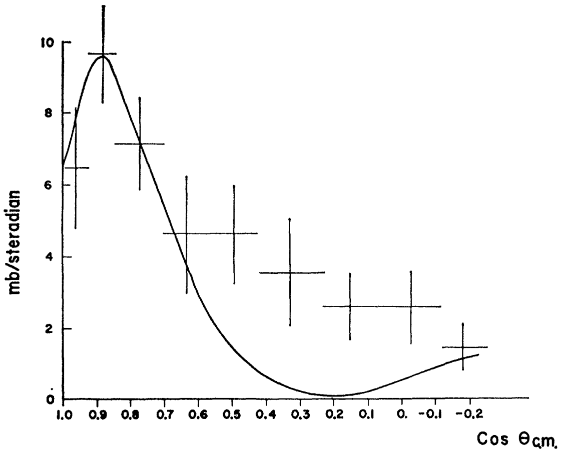

FIG. 4. Angular distribution for transitions to the 2.4-MeV state ($-8.6<Q<-7.6$). The theoretical curve is obtained by using $l=1$ and $R=5$ F, and assuming a knockout mechanism.

difference in the dynamical factors for the two mechanisms is too small to be of any help.

An $l=1$ fit is consistent with the prediction of the shell model for the ground state of Be^9, which has an odd parity and a spin of 3/2.

In the case of the 2.4-MeV level, the observed $l=1$ fit assigns an odd parity and a spin of 1/2 or 3/2; the final state's spin is determined by the observed angular momentum change and the neutron spin, the target nucleus and alpha particle being spinless. Spin 1/2 is ruled out because it has been found that this level can be excited by the pickup of a proton, and, in fact, all available experimental evidence[6,7] indicates that the 2.4-MeV level has a spin $\geqslant 3/2$. On the basis of a study of inelastic scattering of deuterons and alpha particles by Be^9, the possibility of spin 3/2 has been challenged because of the failure of $l=0$ to fit the distributions.[7] However, Pinkston[12] has questioned this conclusion

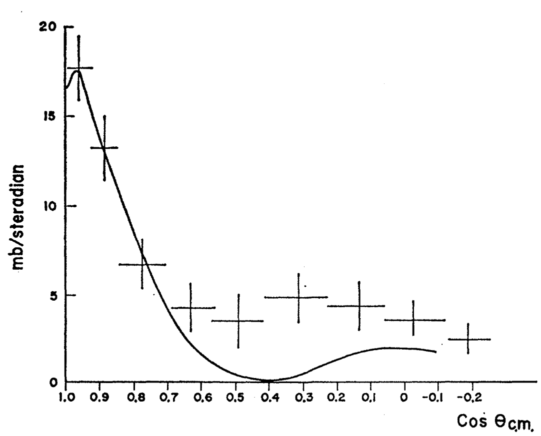

FIG. 5. The ground-state angular distribution, with pickup curve, $l=1$ and $R=4.45$ F.

[11] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 63 (1959).
[12] W. T. Pinkston, Phys. Rev. **115**, 963 (1959).

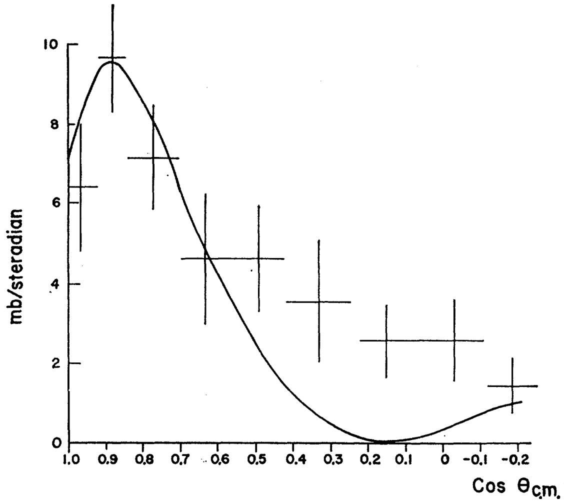

FIG. 6. The 2.4-MeV state angular distribution, with pickup curve, $l=1$ and $R=4.45$ F.

since no state in the P shell can be excited by $l=0$ waves unless there is a spin-flip term in the interaction or a change in the configuration. The present data establish the 2.4-MeV level spin as 3/2, unless the energy scale is so bad that the group in question in fact reflects the 3.0-MeV level, which does not seem likely.

Theoretically, a 5/2 level at about 2.4-MeV excitation is predicted by the alpha-particle model, intermediate-coupling, and LS coupling shell models[5]; only extreme LS coupling predicts a 3/2 level, as a member of the $^{22}D[41]$ doublet. The higher l value contributed by the 5/2 level, if present, would form a peak at about 77° in the c.m. system and probably contribute little to the cross section in the angular region studied, relative to the contribution from the 3/2 state. Hence, this work does not argue against the presence of a spin-5/2 level near 2.4-MeV, but does indicate the presence of a spin-3/2 level in that region. It gives evidence, thereby, of the operation of LS coupling in Be^9, consistent with calculations of Kurath[13] showing that the intermediate coupling parameter a/K is small.

Within the LS shell model, the observed $l=1$ implies that in forming the 2.4-MeV level the neutron is captured into a p state with respect to a Be^8 substructure. Of the two levels in Be^9 formed by p neutrons with unexcited Be^8, that of $l_n=J=3/2$ is known to be the ground state and that of $l_n=J=1/2$ cannot, as noted above, be the 2.4-MeV level; it may well be the spin-1/2 level known[14] at 3.04 MeV. Hence, the 2.4-MeV level must consist of a p-state neutron and an excited state of Be^{8*}, undoubtedly the first (2.9 MeV, 2+). The excitation is about right, Be^9 levels of both $J=3/2$ and $J=5/2$ are generated (among others), and

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[14] P. D. Kunz, Ann. Phys. (N.Y.) **11**, 275 (1960). The state labeled 3/2− in the middle column of Fig. 3 should be 1/2− according to the text.

it has been shown that, with properly antisymmetrized wave functions, a large component of $Be^{8*}+\alpha$ is available in the C^{12} ground state.[15]

REDUCED WIDTHS

Following the discussion of Butler and Hittmair[16] and assuming a structureless alpha particle, one can estimate the ratio of the reduced widths associated with transitions to the ground and the 2.4-MeV states. This ratio was observed to be 1.5, determined from differential cross sections of the main peaks in Figs. 3 and 5. Reliable values of the corresponding coefficients of fractional parentage (cfp) are not available for comparison; these coefficients have been computed only for single nucleon in both *LS* and *jj* coupling and for two nucleons in *LS* coupling.[17] For three or more nucleons, computing the cfp's by simple iteration of the single-nucleon values[18] is a questionable procedure in view of possible coherence among the intermediate states. Lacking a valid theoretical study, however, we have used the method of iteration to estimate the cfp's for a pickup process ($A=12\rightarrow A=9$), and for a knockout process ($A=12\rightarrow A=8$). In the second case, only those states of $A=8$ which can couple vectorially to a neutron to produce the desired state of Be^9 were considered. The results of these calculations give, for the ratio of $(\text{cfp})^2$ for the 0.0- and 2.4-MeV states, 6.9 for pickup, and 1.1 for a knockout process. The experimental ratio appears to favor the latter.

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Decay Energy of Tb^{161}†

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The beta decay of 7.1-day Tb^{161} has been studied with a double-focusing magnetic spectrometer. The end point of the highest beta group was found to be 584 ± 6 keV.

INTRODUCTION

End points of the highest energy beta-ray group in the decay of Tb^{161} have been reported at 500 ± 3,[1] 540 ± 5,[2] 550 ± 10,[3] 571 ± 4,[4] and 610 ± 15 keV.[5] The spread in these values is considerably greater than the uncertainties quoted. The present work was undertaken in an attempt to clear up these discrepancies.

PROCEDURE

Enriched Gd^{160} was irradiated for one week in the Oak Ridge Research Reactor. Tb^{161} resulted from the beta decay of Gd^{161}. The terbium was separated by an ion-exchange process using Dowex 50WX-12 cation exchange resin, with α-hydroxy-isobutyric acid as the eluant.[6] The spectrometer source was made by evaporation onto a 1.2 cm×0.2 cm backing of $\frac{1}{4}$-mil aluminized Mylar.

The measurements were made with a double-focusing iron-core beta-ray spectrometer with resolution of 0.8%. An automatic field-regulating system kept the spectrometer field constant to a few parts in 10^4. The energy calibration was performed with *K*- and *L*-conversion lines from Cs^{137} and Ir^{192}. Electron detec-

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