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Particle decay of ^{6}Be†

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The particle decay of the ground state of ^{6}Be was observed following population in the ^{6}Li(^{3}He, t)^{6}Be reaction. The α particle decay spectrum corresponds to the ordinary three body phase space shape for energies above about 100 keV in the ^{6}Be center-of-mass system. At lower energies the relative yield exceeds the available phase space. It is shown that neither the phase space spectrum modified by the proton-proton final state interaction nor the spectrum corresponding to sequential decay through the ^{5}Li ground state have shapes consistent with the data. The enhanced yield of low energy α particles is not accounted for by either process.

[RADIOACTIVITY ^{6}Be; measured $\sigma(E_\alpha)$.
NUCLEAR REACTIONS ^{6}Be; ^{6}Li(^{3}He, t)^{6}Be$\rightarrow\alpha+2p$, E=24 MeV measured E_t, E_α coin.]

INTRODUCTION

Two-proton radioactivity has been predicted to be the dominant decay mode of several proton-rich nuclei.[1,2] The conditions necessary for two-proton radioactivity to occur are illustrated in Fig. 1, which shows the decay modes of ^{6}Be.[3] Provided the magnitude of the pairing energy ($V_{pair} < 0$) between the last two protons is greater than the Coulomb plus nuclear energy ($\epsilon_p > 0$) required to add a proton to the $A-2$ nucleus, but less than twice this energy ($0 < \epsilon_p < -V_{pair} < 2\epsilon_p$), then the nucleus of mass A will be stable with respect to decay to the $p+(A-1)$ system, but unstable with respect to two-proton decay. [For similar reasons, two-proton decay may be the only isospin allowed decay mode of the lowest $T=2$ state in $T_z=0$ nuclei. This is the situation in ^{8}Be.[4]]

While theoretical considerations of two-proton radioactivity have been published by several authors,[1,2,5] no experimental investigations of this decay mode have been reported. In part, this is due to the difficulty of populating relatively proton-rich nuclei. The only potential two-proton emitter readily accessible with direct-charged-particle reactions is ^{6}Be. However, the ^{6}Be decay may be complicated because of the large width (~1.5 MeV) of the ^{5}Li ground state (g.s.). The ^{6}Be g.s. is bound by only 0.6 MeV to decay to ^{5}Li$+p$, so that sequential decay through the tail of the ^{5}Li g.s. could be significant. The purpose of this work was to study the decay of the ^{6}Be g.s. and to determine the importance of the direct-two-proton decay mode.

EXPERIMENT

The ^{6}Be g.s. was populated via the ^{6}Li(^{3}He, t) reaction with 24 MeV ^{3}He ions from the Stony Brook FN tandem Van de Graaff. The targets were made by evaporating 200 μg/cm^2 of ^{6}Li on the 50 μg/cm^2 C backings; these were transferred under vacuum to the scattering chamber.

The tritons were detected at 50° laboratory angle with a ΔE-E Si telescope. Standard particle identification electronics were used to distinguish the tritons from other reaction products. α particles from ^{6}Be decay were measured at −46° in coincidence with the tritons. This angle corresponds to the direction of the recoiling ^{6}Be

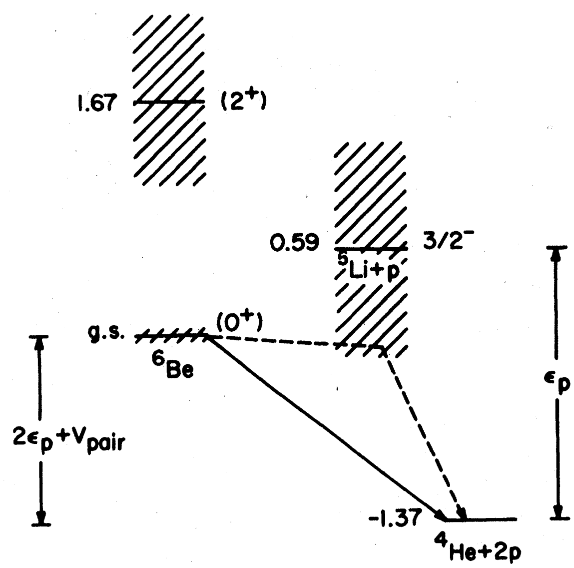

FIG. 1. Decay scheme of ^{6}Be to $\alpha+2p$ (Ref. 3). The two illustrated decay modes represent direct three-body breakup (two-proton decay) and the sequential decay ^{6}Be$\rightarrow$^{5}Li$+p\rightarrow\alpha+2p$ through the tail of the ^{5}Li ground state with $J^\pi=\frac{3}{2}^-$. Energies (MeV) of relevant states are given relative to the ^{6}Be ground state. The proton single particle energy and proton-proton pairing energy are denoted by ϵ_p and V_{pair}, respectively.

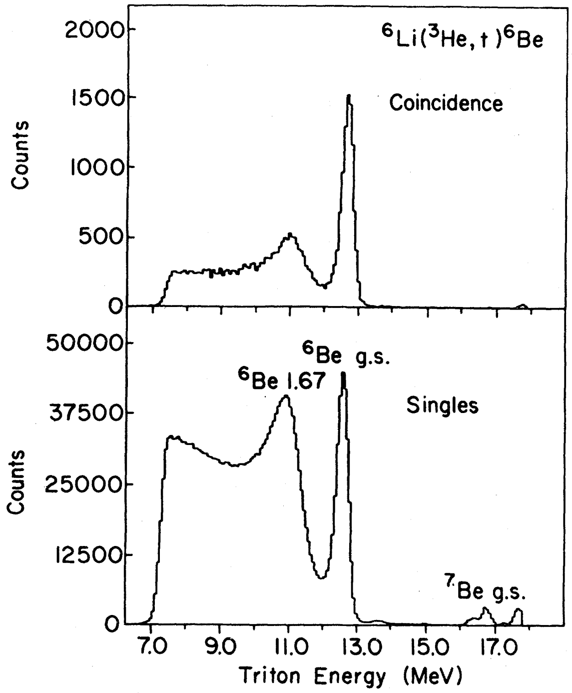

FIG. 2. Triton spectra from the ^{6}Li(^{3}He,t)^{6}Be reaction at 24 MeV bombarding energy. The lower spectrum is the triton singles spectrum. The upper spectrum shows tritons coincident with protons and α particles. In this spectrum the relative yield of the ^{6}Be g.s. is enhanced compared with the ^{6}Be 1.67 MeV state because of the kinematic focusing of the decay products. The ^{7}Be events are due to ^{7}Li target contamination.

g.s. Since the α particle c.m. velocity is always less than the laboratory velocity of the ^{6}Be g.s., there exist two α particle laboratory energies for a given c.m. energy. The laboratory α particle energies corresponding to the maximum and minimum c.m. energies (0.458 MeV and zero, respectively) are, respectively, 8.16 (or 2.26 MeV) and 4.75 MeV indicating a large kinematic "amplification" factor. The α particles were detected in a 64 μm Si detector. Protons (also in real coincidence with the tritons) lost less than 3.5 MeV in this detector. The coincidence data were stored on magnetic tape in event mode format. The energies of the triton and the α particle were recorded.

Typical triton singles and coincidence spectra are illustrated in Fig. 2. A spectrum of the α particles coincident with tritons populating the ^{6}Be g.s. is shown in Fig. 3. α particles emitted parallel to the ^{6}Be g.s. laboratory velocity populate the region of the spectrum from 4.75 to 8.16 MeV. This part of the spectrum was transformed into the ^{6}Be g.s. coordinate system for further analysis.

ANALYSIS

Since the mean lifetime of ^{6}Be g.s. is 7×10^{-21} s ($\Gamma=92$ keV),[3] it is assumed that the decay is delayed with respect to the ^{6}Li(^{3}He,t)^{6}Be production process. Thus, the tritons signal production of the ^{6}Be g.s., but do not complicate the decay. Decay products will be emitted isotropically in the ^{6}Be c.m. system since the g.s. has $J^\pi=0^+$. The solid line shown in Fig. 3 follows from the assumption that the g.s. decay is governed solely by the available three-body phase space. The phase space prediction was normalized by eye to the region of the spectrum from 6.5 to 8.0 MeV. Clearly the yield of α particles with energies ~4.7 MeV (zero energy in the c.m. system) is larger than the phase space estimate. The energies of events which correspond to the two protons being emitted with zero relative energy ($E_\alpha^{\text{c.m.}}$ = max) are also indicated in Fig. 3. The α particle spectrum after transformation into the ^{6}Be g.s. c.m. coordinate system is shown in Fig. 4. The solid curve illustrates the three-body phase space spectral shape $[E_\alpha(Q/3-E_\alpha)]^{1/2}$, where E_α is the

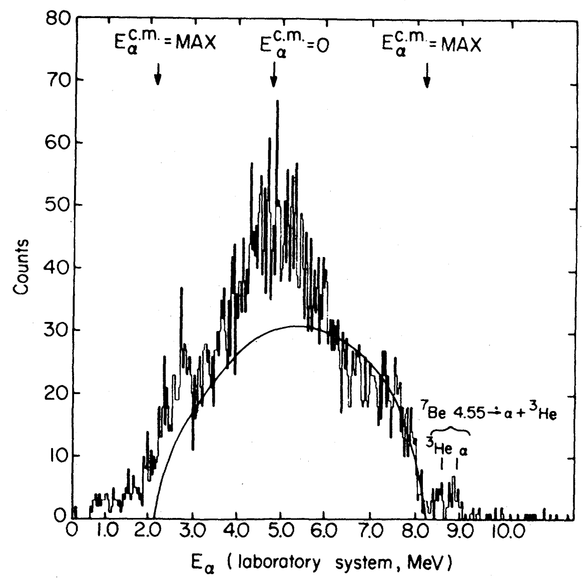

FIG. 3. Spectrum of α particles coincident with tritons which populate the ^{6}Be g.s. The solid line shows the three-body phase space spectrum normalized by eye to the region of the experimental spectrum from 6.5 to 8.0 MeV. The laboratory α particle energies corresponding to kinematic minimum (zero) and maximum (0.458 MeV) energies in the ^{6}Be c.m. system are indicated. Contaminant peaks due to ^{3}He + α decay of the ^{7}Be 4.55 MeV state are labeled; tritons from both the ^{7}Li(^{3}He,t)^{7}Be* and ^{6}Li(^{3}He,t)^{6}Be g.s. reactions have nearly equal energies. The peak at ~3 MeV is due to protons.

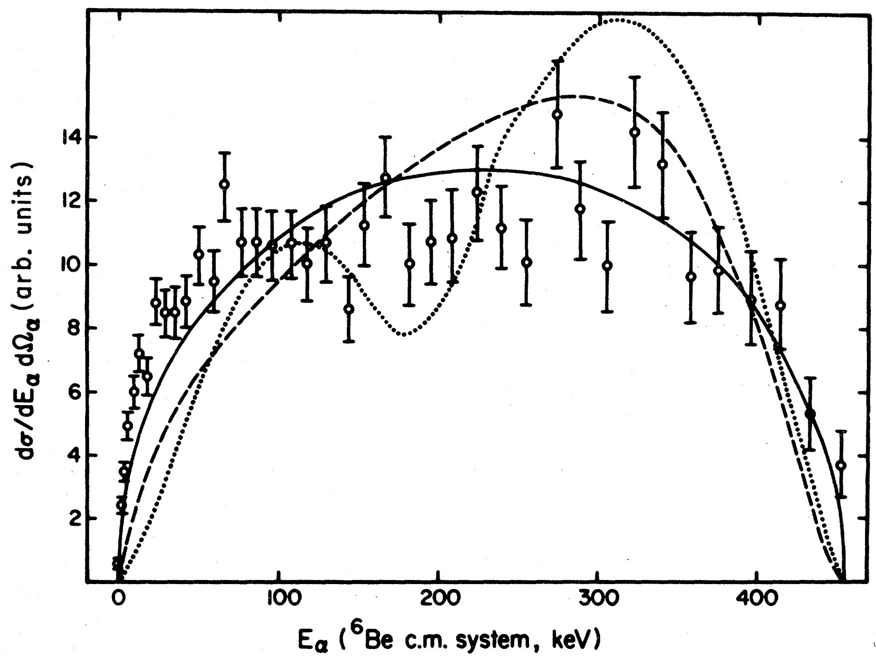

FIG. 4. Spectrum of α particles from the ^{6}Be g.s. decay in the center-of-mass coordinate system of the recoiling ^{6}Be. The solid curve is the three-body phase space spectrum. The p-p final state interaction modifies the phase space spectrum as indicated by the dashed curve. The dotted curve results from a sequential decay calculation of the ^{6}Be $\rightarrow {}^5\text{Li}+p \rightarrow \alpha+2p$ process. All three theoretical curves are normalized to have the same integrated yield as the experimental spectrum.

α particle energy and $Q=1.37$ MeV is the three-body decay energy. In this figure, the phase space prediction was normalized to have the same integrated yield as the experimental data.

Again, it is clear that the experimental yield in low energy ($\lesssim 100$ keV) part of the spectrum is enhanced compared with the available phase space. In what follows we discuss two attempts to put dynamics into the decay analysis.

An obvious distortion of the phase space spectrum is caused by final state interactions. The decay spectrum of the first excited state of ^{6}He clearly exhibited[6] the effect of the N-N interaction. Because the dineutron system is almost bound, the interaction produces a sharp peak near the kinematic maximum α particle energy. Coulomb repulsion makes the diproton system less localized, so that the effect of p-p final state interactions would not be expected to be as prominent. The distortion of the phase space spectral shape caused by the p-p interaction was computed using the method of Phillips.[7] The phase space shape is modified by the factor

$$B=\{[F(kR)\cos\delta+G(kR)\sin\delta]/kR\}^2 .$$

Here F and G are, respectively, the regular and irregular Coulomb wave functions, δ is the p-p scattering s-wave phase shift, and R is the matching radius. [The final state interaction effects are not sensitive to the particular choice of R.] The resulting α decay spectrum is given by the dashed curve in Fig. 4. While the enhancement at about 300 keV may give a slightly better fit to the data in this region, the overall quality of the fit is in even poorer agreement with experiment since the relative probability of low energy α particle emission is decreased compared with the phase space estimate.

Since the spectral shapes already discussed do not fit the data, the spectrum resulting from sequential decay through the ^{5}Li g.s. was computed. The transition matrix element was assumed to be

$$T=\frac{\langle {}^6\text{Be}\,|{}^5\text{Li}+p_1\rangle\langle {}^5\text{Li}\,|\,\alpha+p_2\rangle}{\frac{6}{5}E_{p_1}-E_r+\frac{1}{2}(i\Gamma)} - \frac{\langle {}^6\text{Be}\,|{}^5\text{Li}+p_2\rangle\langle {}^5\text{Li}\,|\,\alpha+p_1\rangle}{\frac{6}{5}E_{p_2}-E_r+\frac{1}{2}(i\Gamma)} .$$

Here E_r and Γ are the experimentally determined ^{5}Li g.s. values.[3] The ^{6}Be g.s. is assumed to have the $(\pi p_{3/2})_{J=0}{}^2$ configuration with respect to an inert α particle core. Both terms in the transition matrix element are required to insure antisymmetry with respect to interchange of the proton indices.

Each of the decay matrix elements was taken to be

$$\langle\psi_1|\psi_2+p\rangle \propto \left(\frac{1}{A_1^2}\right)^{1/2} \sum_{\substack{m_2 m\\ m_l m_s}} \langle J_2\, m_2 \tfrac{3}{2} m | J_1\, m_1\rangle \times \langle 1 m_l \tfrac{1}{2} m_s | \tfrac{3}{2} m\rangle Y_{1m_l} \delta_{m_s m_p}\,.$$

Here $A_1{}^2 = F_1{}^2(kR) + G_1{}^2(kR)$, Y_{1m_l} is a spherical harmonic of order 1, and m_p characterizes the spin of the outgoing proton. This ansatz ignores the energy dependence of the Coulomb and hard sphere phase shifts as well as the correct R-matrix treatment of the resonant denominator in terms of an energy dependent shift function Δ_l.[8] The angular factors are very important in determining the computed α particle spectrum. Summing over final m states results in an angular correlation pattern between the two protons of the form $(1+3\cos^2\theta_{12})$ for the direct term where θ_{12} is the angle between the proton momenta (the result is slightly more complicated for the exchange term). Thus, the decay probability is large when the angle between the protons is 0 or 180°. After integrating over the energy available to each proton the calculated α particle energy spectrum is double peaked as shown in Fig. 4. The height of the lower energy peak with $E_\alpha \sim 100$ keV is one-half that of the higher peak with $E_\alpha \sim 300$ keV. Again, the computed shape disagrees with the data.

SUMMARY

In summary, we have measured the α particle energy spectrum following the $\alpha+p+p$ decay of the ^{6}Be g.s. The yield of low energy α particles is enhanced compared with the available phase space. When the p-p final state interaction is included, the predicted probability of low energy α emission is further diminished. Thus our results contrast to earlier work on the $\alpha+N+N$ decay of the first excited state of ^{6}He where the effect of the N-N final state interaction is observed. The other intrinsically two-body interaction process considered here is sequential decay through the ^{5}Li g.s. The resulting α particle spectral shape is also in disagreement with experiment (although, the ^{6}Be g.s. model wave function used here may be unacceptably simplistic). Furthermore, no incoherent sum of the processes considered here will fit the data. Perhaps a full three-body computation is necessary to understand the energy spectrum. Unfortunately, while the ^{6}Be g.s. has a lifetime sufficient to guarantee a well-defined quantum state of the mass-6 system with angular momentum zero, the fact that the decay products are all charged makes solution of the Faddeev equations extremely difficult.[9]

To conclude more positively, we are intrigued by the similarities between the present data and those from the slow pion absorption reaction ^{6}Li$(\pi^+, 2p)\alpha$, in which the largest cross section occurs when the two protons are emitted ~180° from one another with nearly equal energies.[10] In the ^{6}Be decay measurement reported in this paper, an enhanced yield near $E_\alpha \sim 0$ implies the proton momenta are relatively likely to have the same configuration as in the pion experiments. Further calculations suggested by this comparison might be interesting.

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