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Understanding the $^{11}B(p,\alpha)\alpha\alpha$ reaction at the 0.675 MeV resonance

S. Stave [a,b,*], M.W. Ahmed [a,b], R.H. France III [c], S.S. Henshaw [a,b], B. Müller [a], B.A. Perdue [a,b], R.M. Prior [d], M.C. Spraker [d], H.R. Weller [a,b]

[a] Department of Physics, Duke University, Durham, NC 27708, USA
[b] Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA
[c] Department of Chemistry, Physics & Astronomy, Georgia College and State University, Milledgeville, GA 31061, USA
[d] Department of Physics, North Georgia College and State University, Dahlonega, GA 30597, USA

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ABSTRACT

The $^{11}B(p,\alpha)\alpha\alpha$ reaction at energies between 200 keV and a few MeV has a very long history, dating back to studies by Lord Rutherford and Dee and Gilbert in the 1930s. It is shown that the modern view of this reaction, established in 1987, is incorrect. This model viewed the reaction as a two-step process with a primary high energy α-particle having $\ell = 1$ going to the first excited state of ^{8}Be, with the subsequent emission of two low energy secondary α-particles. We have found that an earlier result (1969) which showed that the primary α-particle must have $\ell = 3$ does, as originally noted, account for the data. Our simulations show that this view leads to the prediction of two high energy α-particles (of almost equal energy), as originally proposed in 1936, one being the primary α-particle and the other a secondary α-particle. Coincidence data verify the existence of these two high energy α-particles. The implications of this result on astrophysics and fusion energy production are noted.

1. Introduction

The history of the study of the $^{11}B(p,\alpha)\alpha\alpha$ reaction is almost as long as the history of nuclear physics itself. The reaction was studied and discussed in some detail by M.L.E. Oliphant and Lord Rutherford over 75 years ago for proton energies in the vicinity of 200 keV [1]. At that time there was a considerable controversy as to whether the most probable mode of emission of the three α-particles was with equal energies at 120° with respect to each other, or with two particles which are emitted at angles close to 180° relative to one another, while the third particle remained almost at rest. Three years after the paper by Oliphant and Rutherford, who subscribed to the first interpretation, Dee and Gilbert, also of the Cavendish Laboratory, published the results of their expansion chamber studies and concluded that, at their proton energy of about 300 keV, "the common mode of disintegration is into two [alpha] particles which proceed at angles of 150° to 180° relatively to one another, the third particle receiving very little energy" [2].

Since that time there have been numerous theoretical and experimental studies of this reaction at these and higher energies continuing to the present time [3]. The modern view of this reaction is contained in Ref. [4] which contains references to many previous studies. This study, which covered the energy range of E_{cm} from 22 to 1100 keV, claimed that the reaction proceeded predominantly by a sequential decay through the ground and first excited states of ^{8}Be over the entire energy range. The study of Ref. [4] maintained that the 2^- resonance at $E_p = 0.675$ MeV decayed via a two-step sequential process which proceeded via $\ell = 1$ α-particles leading to the 2^+ first excited state of ^{8}Be. The subsequent decay of this state produced two secondary α-particles. According to their simulation, the α-particle yield consisted of one high energy (≈ 4 MeV) primary α-particle and a secondary α-particle yield peaked at an energy just below 1 MeV with an intensity about equal to the primary α-particle yield.

The present data and simulations disagree with the conclusions of Ref. [4] in the case of the 2^- resonance at 0.675 MeV. A previous interpretation (Ref. [5]), not discussed in Ref. [4], also found that the two-step model with $\ell = 1$ primary α-particles failed to describe the data at the 2^- resonance. However, they found that they could describe the data by assuming that the primary α-particle decayed with $\ell = 3$.

It will be shown that the present results confirm the findings of Ref. [5]: the two-step model gives a good description of the data at the 2^- $E_p = 0.675$ MeV resonance if the primary α-particle is taken to have $\ell = 3$. It will also be shown that this assumption leads to one high energy (≈ 4 MeV) and one low energy ($\lesssim 1$ MeV) secondary α-particle. Since the primary α-particle also is found to have an energy of ≈ 4 MeV, this result implies the ex-

* Corresponding author at: Department of Physics, Duke University, Durham, NC 27708, USA.
E-mail address: stave@tunl.duke.edu (S. Stave).

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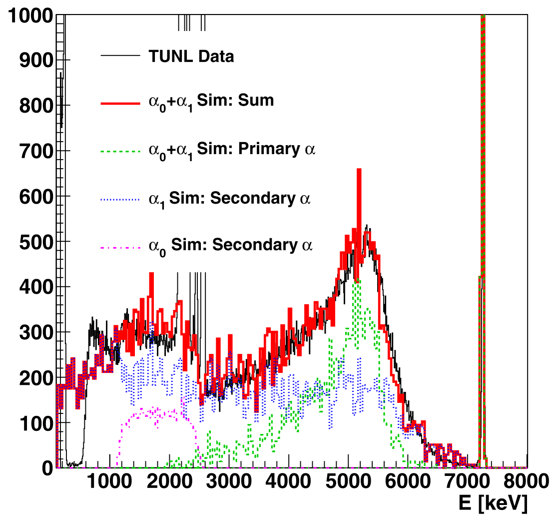

Fig. 1. (Color online.) Comparison of the two-step reaction simulation with data at $\theta_\alpha^{\rm lab} = 90°$ and $E_p = 2.64$ MeV. The sharp peak at 7.26 MeV corresponds to the α_0 channel.

istence of two *high-energy* α-particles. The existence of these two high-energy particles is confirmed by coincidence measurements. Data and simulations show that these two particles are primarily emitted with an opening angle of about 155°, reminiscent of the mechanism first proposed by Dee and Gilbert [2] in 1936.

One of the reasons for the intense interest in this reaction is the possibility of using it as an aneutronic source of energy in an advanced fusion reactor [6]. Clearly, the design of such a reactor requires a detailed knowledge of the α-particle yields as a function of energy and angle. One purpose of the present study is to provide this information at the strong 2^- resonance ($\Gamma = 300$ keV) located at $E_p = 0.675$ MeV which dominates the low energy cross section of this reaction and which plays a key role in a possible fusion reactor.

2. Experiment

We began our experiments at the 3^- $E_p(\text{lab}) = 2.64$ MeV ($\Gamma = 400$ keV) resonance, using a target of 56 ± 2 µg/cm^2 of isotopically pure ($\sim 99\%$) ^{11}B (ground-state $J^\pi = 3/2^-$) deposited on a 9 µg/cm^2 carbon backing. Proton beams of 50–100 nA were provided by the TUNL FN-tandem accelerator. The scattered particles were detected using an array of eight silicon surface barrier detectors at angles between 20° and 160°. The data obtained at $E_p = 2.64$ MeV in a detector placed at 90° in the scattering chamber are shown along with the results of our simulation, normalized to the data, in Fig. 1.

The results of the simulation shown in Fig. 1 assumed that the two-step process as described in Ref. [4] is appropriate at the $E_p = 2.64$ MeV resonance. In this model the primary α-particle (α_1) is assumed to have $\ell = 1$ (p-wave) when decaying to the first excited state of ^{8}Be, and $\ell = 3$ when transitioning to the 0^+ ground state. Two secondary α-particles are subsequently emitted when the ground and first excited states of ^{8}Be decay.

Our simulation began by choosing the direction of the primary α-particle at random in the center of mass (cm) system. Next, the excitation energy of the outgoing ^{8}Be nucleus in its first excited state was chosen randomly with a weighting factor based upon data which describe the shape of this excitation curve. These data were in the form of elastic scattering phase shifts for α-particle energies corresponding to excitation of the $\Gamma = 1.5$ MeV 2^+ state at 3 MeV in ^{8}Be [7]. The single level approximation allowed us to correct these phase shifts for potential scattering using hard-sphere phase shifts [8], resulting in an energy dependent resonance line shape for the 2^+ first-excited state of ^{8}Be. This shape was convoluted with the p-wave penetrability factor of the primary α-particles being emitted from the resonance state in ^{12}C to produce the final weighting function. Once the excitation energy was randomly chosen, the remaining kinematics were calculated. The direction of the primary α-particles and the ^{8}Be, fully determined in the cm system, were then transformed into the lab system for comparison to the data. The shapes of the angular distributions of the primary and secondary α's were calculated using standard angular momentum coupling algebra [9,10] by assuming that the 3^- state is formed via $\ell = 2$ protons and decays via $\ell = 1$ primary α's to the 2^+ state of ^{8}Be, which then decays into two secondary α's. The result of this calculation indicated that the primary α-particles had an angular distribution of the form: $\sigma(\theta) = C[1.0 + \frac{3}{7}P_2(\cos\theta)]$, where $P_2(\cos\theta)$ is the second Legendre polynomial. The secondary α-particles also have an internal angular distribution with respect to the axis defined by the primary α (and the recoiling ^{8}Be* nucleus). The $\overline{Z}$ formalism was used to determine the distribution of the secondary α's by considering the 3^- resonance to emit an $\ell = 1$ α-particle while forming the 2^+ state of ^{8}Be* which then decays into two secondary α-particles having $\ell' = 2$. The result indicated that the angular distribution of the secondary α-particles with respect to the direction of the 2^+ ^{8}Be* was $\sigma(\theta) = C[1 + \frac{2}{7}P_2(\cos\theta)]$. The outgoing α's in the lab were examined to see if they would enter any of the detectors. If so, their energy was logged for the event, leading to an energy distribution for each detector. Finally, it was possible to identify each α-particle in the simulation as a primary or secondary type particle.

The results of the simulation were compared with our data across a range of angles and it was found that the simulation was in good qualitative agreement with the data and a previously observed angular distribution [11]. The simulated results for the separated primary and secondary α-particles at 90° are shown in Fig. 1. As can be seen, the simulation succeeds well in describing the shape of the measured spectrum providing us with confidence in both the model and our simulation. Even the secondary α-particles from the α_0 channel are observed, lying just below the elastic proton peak in Fig. 1. Note that the assumption of $\ell = 1$ primary α-particles in the case of the transition to the first excited state of ^{8}Be, as assumed in Ref. [4], works well here. This was also confirmed in Ref. [5] which explicitly showed that the other two allowed ℓ values of 3 and 5 failed to describe the data.

According to our simulation two secondary α-particles are generated and detected for every primary one. This indicates that the total measured α-yield should be divided by a factor of 3 when determining the absolute cross section assuming that all α-particles down to zero energy are detected. The authors of Ref. [4] argued that the sequential reaction mechanism implied that the total α-particle yield measured in a finite solid angle should be divided by 2 instead of 3 when determining the absolute cross section. This result has been adopted by the NACRE (Nuclear Astrophysics Compilation of REaction rates) group in their compilation of astrophysical S-factors [12] and should be corrected.

We next present data measured for a proton energy of 0.675 MeV, which corresponds to the 2^- state in ^{12}C with a width of $\Gamma = 300$ keV. The measured angular distribution was found to be isotropic, as expected since this state is formed via s-wave protons. Indeed the angular distribution $\overline{Z}$ formalism gave, with $\ell = 0$, an isotropic distribution for the primary α-particles coming from this 2^- resonance. The form of the angular distribution of the secondary α-particles was calculated by considering the 2^- resonance to emit an $\ell = 1$ α-particle (as assumed in Ref. [4])

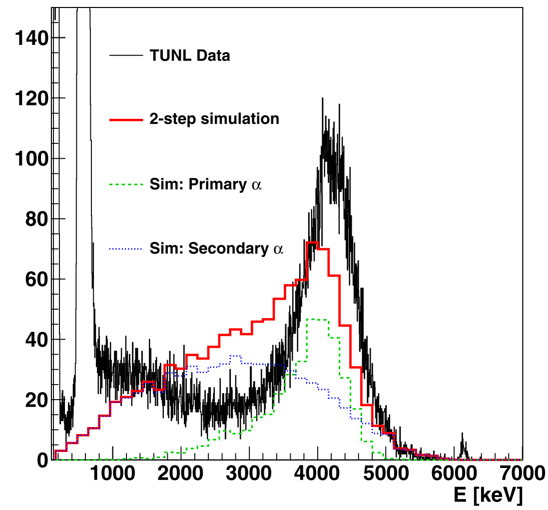

Fig. 2. (Color online.) Comparison of the two-step reaction simulation using $\ell = 1$ with data at $\theta_\alpha^{\mathrm{lab}} = 90°$ and $E_p = 0.675$ MeV.

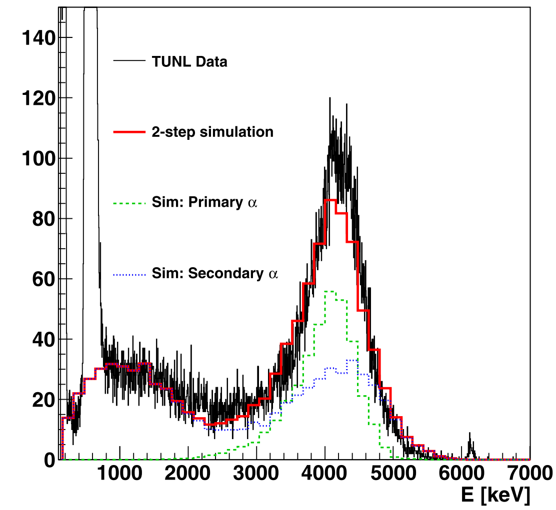

Fig. 3. (Color online.) Comparison of the two-step simulation using $\ell = 3$ with data at $\theta_\alpha^{\mathrm{lab}} = 90°$ and $E_p = 0.675$ MeV.

while forming the 2^+ state of ^{8}Be* which then decays into two α-particles having $\ell' = 2$. This led to an angular distribution with respect to the axis defined by the direction of the ^{8}Be* having the form $\sigma(\theta) = C[1 - P_2(\cos\theta)] = C' \sin^2\theta$. This functional form was used in our simulation. Note that this is an internal angular distribution – the final outgoing α-particles remain isotropic in agreement with the measurement. However, the internal angular distribution can affect the energy distribution of the outgoing α-particles which is why it must be included. The data at 90° are compared to the result of our two-step simulation in Fig. 2. Note that the α_0 peak is negligible here due to the unnatural parity of the state.

The data and the simulation shown in Fig. 2 clearly indicate that the two-step process with the assumption of $\ell = 1$ primary α-particles is not appropriate at the $E_p = 0.675$ MeV resonance. The results of the study of Ref. [5] have previously shown that this was true, but went on to show that these data could be described by the two-step model by assuming that the primary α-particle had $\ell = 3$. (Note that $\ell = 1$ and $\ell = 3$ are both allowed from angular momentum conservation.) We therefore ran our simulation under this assumption. This required two changes: first, while the angular distribution of the primary α-particles remains isotropic, the internal angular distribution of the secondary α-particles is now given by $\sigma(\theta) = C[1 + \frac{2}{7}P_2(\cos\theta) - \frac{9}{7}P_4(\cos\theta)]$. And second, the shape of the excitation curve for the first excited state of ^{8}Be is now convoluted with f-wave penetrabilities instead of the p-wave ones used before. The results of this simulation are shown in Fig. 3.

This "no free parameters" model of the reaction describes the data very well, in agreement with the findings of Ref. [5]. It was particularly impressive to observe that the use of f-wave penetrabilities produced a narrowing of the main peak in the spectrum in comparison with that obtained using p-waves and in very good agreement with the data of Fig. 3. Furthermore, as seen in Fig. 3, the secondary α-particles are emitted in two main groups: one centered near 4 MeV, and the other centered near 1 MeV. This detailed insight was not noted in Ref. [5], but leads to the conclusion that the two-step model with $\ell = 3$ primary α-particles produces two high energy α-particles at the 2^- resonance, and one low energy one.

In order to gain more insight into the nature of the reaction at this energy, we performed a coincidence experiment using two large area position-sensitive silicon detectors. The active areas of these rectangular detectors measured 47 mm wide × 8 mm high.

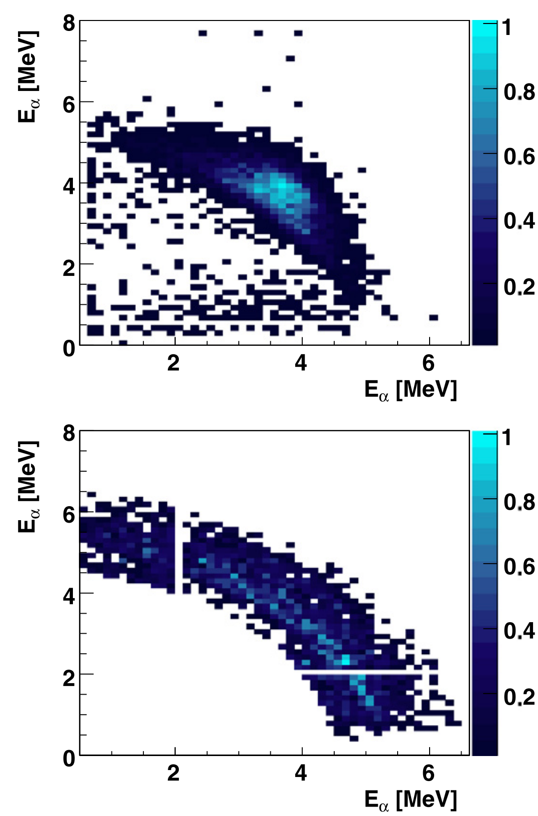

Fig. 4. (Color online.) Coincidence spectra for $E_p = 0.675$ MeV (top) and 2.64 MeV (bottom) at the same lab α–α opening angle of 150°. The spectra have been normalized so that the maximum in the z direction is 1.0. The vertical and horizontal slices in the lower figure removed the elastic events.

Each detector subtended an angular range of ±8°, with a measured angular resolution of 0.2°. The detectors were placed symmetrically on the left and right sides of the beams. Data were taken at eight settings covering an opening angle range of 100°–180°. A simulation was used to correct the data for angular dependent geometrical acceptances.

Two-dimensional coincidence spectra obtained at $E_p = 0.675$ and 2.64 MeV at an opening angle of $150° \pm 8°$ are shown in Fig. 4. These results show a dramatic difference at these two ener-

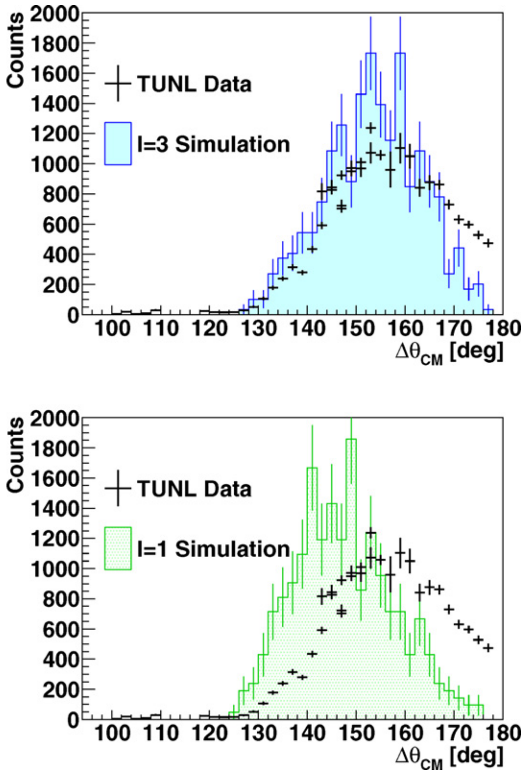

Fig. 5. (Color online.) Coincidence data as a function of the opening angle in the center-of-mass frame are compared to the results of the simulation assuming that the primary α-particle has $\ell = 3$ (top) and $\ell = 1$ (bottom). The simulations were normalized to the total number of counts in the data.

gies and indicate that while the coincidence spectrum at 2.64 MeV is rather spread out, as expected for the two-step process with $\ell = 1$ primary α-particles, a distinct peak is present in which both α-particles have an energy of about 4 MeV for the 0.675 MeV case. This observation of two high energy α's confirms the $\ell = 3$ assumption and is reminiscent of the mechanism first proposed by Dee and Gilbert [2].

As a further check on the validity of our model and our simulation, the simulation was run to generate the coincidence count rate as a function of opening angle with the requirement that both α-particles had energies greater than 3 MeV. The results, shown as a histogram in the top panel of Fig. 5, indicate a peaking in the coincidence rate in the vicinity of an opening angle of 155°. The results of the simulation for the $\ell = 1$ assumption are shown in the bottom panel of Fig. 5.

The coincidence data taken at $E_p = 0.675$ MeV were processed for opening angles ranging from 100° to 180°, with the results shown in Fig. 5. The excellent agreement with our simulation confirms the model and leads us to conclude that at this energy the reaction proceeds via a two-step process with $\ell = 3$ primary α-particles leading to the emission of two almost equal in energy high energy α-particles having an opening angle centered at 155° as shown in Fig. 5 – as originally proposed by Dee and Gilbert [2].

3. Conclusion

In summary, we have measured the α-particle singles and coincidence spectra and angular distributions for the $^{11}B(p,\alpha)\alpha\alpha$ reaction at two different resonance energies and compared our measurements with simulations.

We found that the two-step sequential model with $\ell = 1$ primary α-particles describes the data at the 2.64 MeV 3^- resonance quite well, but that $\ell = 3$ primary α-particles are required to describe the data at the 0.675 MeV 2^- state as originally discovered in Ref. [5]. Our results show that the $\ell = 3$ assumption predicts the existence of two high energy α-particles at an opening angle centered at 155° – as originally proposed by Dee and Gilbert [2]. Our coincidence data confirm this finding. We note that additional measurements down to 200 keV have shown that this behavior persists at these lower energies.

An immediate consequence of our results is that the astrophysical rates for the $^{11}B(p,\alpha)\alpha\alpha$ reaction must be revised [12]. Our results also will have a pronounced impact on the design of a possible aneutronic fusion reactor. A more microscopic theoretical treatment of the $^{11}B(p,\alpha)\alpha\alpha$ reaction valid over the energy range of our experiments would be very desirable.

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