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^{11}B(p,$\alpha\alpha$)^{4}He REACTION IN COLLINEARITY CONFIGURATIONS

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Dedicated to Professor Mladen Paić on the occasion of his 90$^{\mathbf{th}}$ birthday

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The ^{11}B(p,$\alpha\alpha$)^{4}He reaction was measured at eight incident proton energies, from 2 to 5.5 MeV, for the collinearity configurations (an α-particle at rest in the c.m. system). The results are compared with predictions of the Schäfer model. Involvement of the ^{12}C states with excitation energy between 17.8 and 21 MeV is discussed.

1. Introduction

Collinearity conditions have been used in the studies of three-body reactions, mainly of the nucleon induced deuteron break-up. This configuration corresponds to one of the outgoing particles being at rest in the centre of mass (c.m.) system. In the deuteron break-up experiments, it was expected that for these conditions some observables may be more sensitive to the three-nucleon forces [1]. However, some other three-body reactions have also been measured in these conditions but for other purposes. For example, in a study of the ^{12}C(^{16}O,^{12}C^{12}C)^{4}He reaction [2], the configuration with outgoing α-particles at rest in the c.m. system was chosen for the search of the ^{12}C-α-^{12}C linear chain states in ^{28}Si. Rae et al. [3] used similar configuration in the measurements of the ^{12}C(^{12}C,$\alpha\alpha$)^{16}O reaction for the determination of angular momentum of the ^{24}Mg states.

The ^{11}B(p,$\alpha\alpha$)^{4}He reaction has been extensively studied at low energies [4]. However, only two measurements were of the collinearity type. Gemeinhardt and Kamke [5] measured angular distributions of the ^{11}B(p,α_1)^{8}Be reaction at 1.39, 2 and 2.64 MeV by detecting two outgoing α-particles at several detection angles satisfying the condition $\theta_{12}^{c.m.} = \theta_1^{c.m.} - \theta_2^{c.m.} = 180^o$. Chanut et al. [6] measured the reaction at energies between 2.1 and 3 MeV with special emphasis on the kinematical condition of the zero c.m. energy of the undetected particle. The results of both measurements, which are of present interest, are:

i) For $E_p = 1.39$ and 2.64 MeV, in the part of the spectra corresponding to the contributions of the ^{8}Be first excited state (^{8}Be$_1$), a minimum is observed at $E_3^{c.m.} \approx$ 0 MeV for all angles satisfying $\theta_{12}^{c.m.} = 180^o$.

ii) The minimum at $E_p = 2.6$ MeV transforms into a maximum when $\theta_{12}^{c.m.}$ changes from 180^o by only 8^o.

iii) The maximum is observed at $E_p = 2$ and 3 MeV in the same region of the spectrum and for $E_3^{c.m.} \approx 0$ MeV.

There have been different attempts to explain this behaviour. It can be stated that gross features of the spectra are now well understood and they can be correlated with the parities and spins of different states of the compound system, ^{12}C, through which this process passes at low energies. The negative parity states (1^- and 3^-) are responsible for the minima in the collinearity configuration for $E_p = 1.4$ and 2.6 MeV, while maxima at $E_p = 2$ and 3 MeV are due to the positive parity states 0^+ and 2^+.

The aim of present experiment was to measure the ^{11}B(p,$\alpha\alpha$)^{4}He reaction in different kinematical conditions (but with the emphasis on the collinearity) with better angular resolution and in a wider range of energies in order to learn more about the ^{12}C states with excitation energy from 17.8 to 21 MeV, as well as about the process itself. Only a part of the collinearity data is discussed here.

2. *Experiment*

The experiment was carried out by bombarding a ^{11}B target (70 μg/cm^2) by a 50–100 nA proton beam from the EN Tandem Van de Graaff accelerator of the Ruder Bošković Institute. Two coincidence α-particles were detected on opposite sides with respect to the beam direction ($\Delta\phi = 180^o$) by rectangular position sensitive detectors. Angular openings of the detectors were 14^o in the horizontal and 1.5^o in the vertical direction. The angular resolution was better than 0.5^o in the horizontal direction. α-particles from the ^{11}B(p,α_0)^{8}Be reaction were monitored in a separate detector. The data, together with previously measured cross–sections for the reaction [7], were used for the determination of the absolute value of the cross–section for the three-body process. The energy, position and time pulses from the detectors were sent through standard electronics and recorded by a data acquisition system [8] for subsequent analysis.

Figure 1 shows schematically the kinematical conditions of the collinearity measurements. Vertical lines in E_p represent incident proton energies (2, 2.6, 3.2, 3.76, 4.2, 4.6, 5.1 and 5.5 MeV). Most of them correspond to the established α-decaying states in ^{12}C with the excitation energy $17.8 < E_x < 21.0$ MeV (vertical lines in $E_x(^{12}\mathrm{C})$) and/or to the maxima in the excitation functions for the ^{11}B(p,α)^{8}Be reactions. For the collinearity conditions ($E_3^{c.m.} = 0$ MeV) both relative energies, E_{13} and E_{23}, are equal and they change by a factor of four slower than $E_x(^{12}\mathrm{C})$. For these incident energies they range from 2.6 to 3.6 MeV, i.e. they are inside the width of $^8\mathrm{Be}_1$ ($E_x = 3.04$ MeV, $\Gamma = 1.5$ MeV). Because of that, one can expect the interferences in the part of spectra around the collinearity condition.

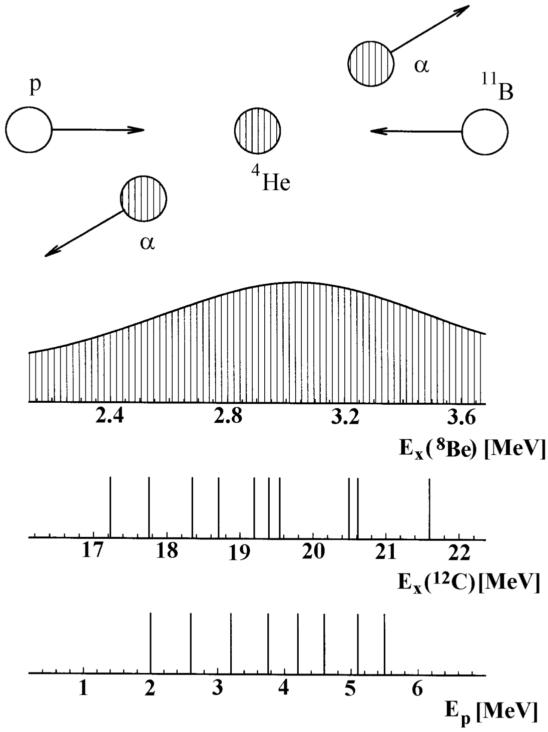

Fig. 1. Kinematical conditions of the experiment (see text).

3. Results and discussion

Figure 2a shows a typical coincidence α-α energy spectrum shown as a projection on the energy axis of one of detected α-particles. It was measured at $E_p = 3.76$ MeV and $\theta_1 = \theta_2 = 82.5^o$. Only the events falling in a range of $\pm 1.5^o$ around the setting angle are included in this display. The peaks at 2.5 and 8.2 MeV correspond to the sequential process through the ground state of ^{8}Be. The structure around 6.2 MeV (at the collinearity condition) is the result of the $^8\mathrm{Be}_1$ contributions.

Figure 2b shows only this part of the spectrum. For illustration are also given the calculations with only one Breit-Wigner term (dashed line) and with two terms added incoherently (full line) with E_x = 3.04 MeV and Γ = 1.5 MeV. These calculations correspond to the sequential processes involving the 2-3 α-α pair only and both 1-3 and 2-3 pairs, respectively. It is seen that measured peak is narrower ($\Gamma \approx 1$ MeV) than those calculated indicating the presence of interference effects. In the following we concentrate only on this part of the coincidence spectra.

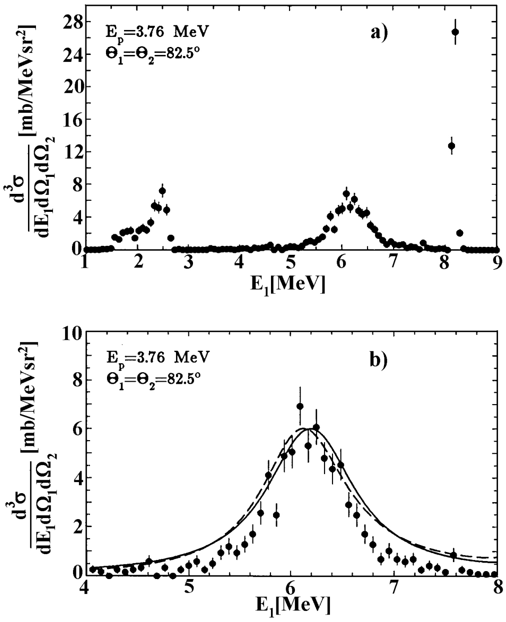

Fig. 2. a) The α-α coincidence spectrum from the ^{11}B*(p,$\alpha\alpha$)*^{4}He *reaction, measured at* E_p = 3.76 MeV, *shown as a projection on the E_1 axis. b) A part of the spectrum with the contribution from the* ^{8}Be *first excited state. The curves represent the calculations with one (dashed line) and two incoherently added Breit-Wigner terms (full line).*

With the help of the recorded positions of the detected particles and fine angular resolution of the detectors it is possible in the off-line analysis to select from the large body of data only those events satisfying a given requirement, e.g. collinearity.

Figure 3 shows the data measured at eight incident proton energies. The data were collected at symmetrical setting angles satisfying collinearity condition. In this way the central line, connecting three α-particles in the c.m. system, is perpendicular to the incident beam. From all the data collected at these setting angles only those events are selected having the scattering angles which satisfy the collinearity condition (allowing for an angular spread of $\pm 0.5^o$ in both detectors). The experimental results are shown as the projection on the energy axis E_{23} (relative energy between the α-particle detected in the detector D_2 and the undetected α-particle).

It can be seen that with the change of incident energy the peak due to the $^8Be_1$ contributions changes its position, magnitude, as well as the shape. A minimum is observed only for $E_p = 2.6$ MeV.

The results are compared with the predictions of the theory given by Schäfer [9]. In the theory several approximations were made, the most important being the following:

i) The reaction goes via a resonance in ^{12}C of definite spin and parity.

ii) The resonance decays sequentially through the states of ^8Be.

iii) The dynamics is described by the coherently added Breit-Wigner terms.

In the calculations presented here some additional assumptions are made, similar to those in Ref. 10 :

a) Only the lowest possible value of the orbital angular momentum, λ, contributes in the entrance channel.

b) The contributions from the sequential process involving the pair of detected α-particles (1-2 pair) could be neglected. This assumption can be justified by low c.m. energy of the undetected particle in the collinearity region.

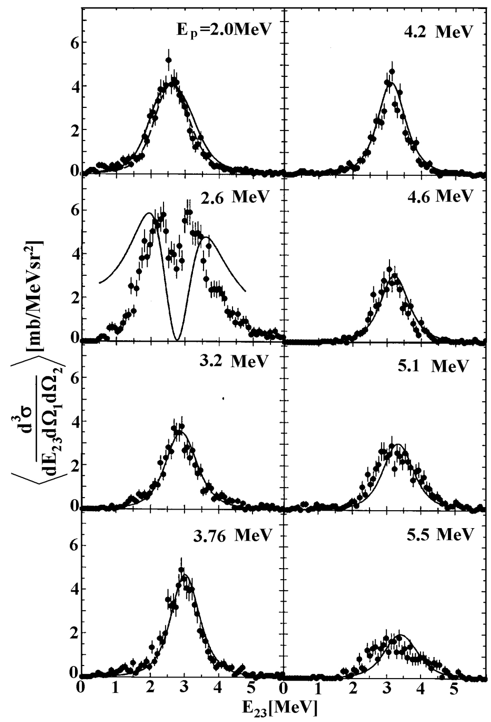

Fig. 3. The α-α coincidence spectra, measured at eight incident energies in the collinearity conditions at symmetric angle settings, shown as the projection on the E_{23} relative energy axis. The curves are the Schäfer model calculations.

In the calculations of this particular part of the spectra, the orbital angular momenta in the 1-3 and 2-3 α-α pairs, l, were fixed to 2, because that is the value of the $^8Be_1$ spin. The calculated curves, shown on Fig. 3, have been normalized separately to the experimental results at the peak.

Many calculations have been performed in this analysis corresponding to different combinations of λ, s (entrance channel spin), L (orbital angular momentum of a particle with respect to the c.m. of the other two) and J^π (spin and parity of the ^{12}C states). However, from all of them only three are shown here for illustration.

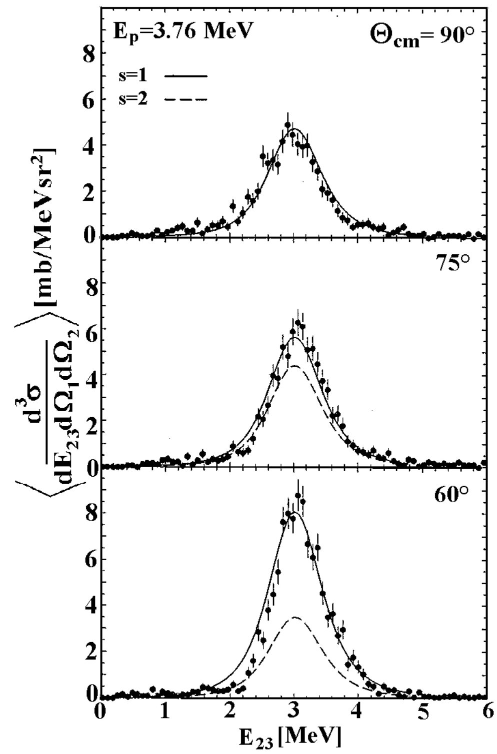

Fig. 4. The α-α coincidence spectra, measured at $E_p = 3.76$ MeV in the collinearity conditions. $\theta_{c.m.}$ is the c.m. system angle between the incident proton beam and the line connecting three α-particles. The curves are the Schäfer model calculations with $J = 2$, $s = 1$, $L = 0$ (full line) and with $J = 2$, $s = 2$, $L = 0$ (dashed line).

The curves at 2 MeV are calculated with $\lambda = 1$, $s = 1$ and $L = 2$. This combination is uniquely fixed by the spin and parity of the 17.8 MeV state of ^{12}C (0^+). They correspond to two values for the excitation energy and width of $^8Be_1$: $E_x = 3.04$ MeV, $\Gamma = 1.5$ MeV (full line) and $E_x = 2.9$ MeV, $\Gamma = 1.45$ MeV (dashed line). It is seen that the curve calculated with the later values, which were previously used, better fits the data than the one with the values from newer compilations. For the other energies the difference is less pronounced.

There seems to be at least two states in ^{12}C around 18.35 MeV, with assignments 2^- and 3^- [4] (there have also been some claims that one of the states is 2^+, see e.g. Ref. 11). Because a strong resonance was observed in the ^{11}B(p,α_0)^{8}Be reaction at E_p = 2.6 MeV [7], this state should have natural parity. However, the minimum observed in old and present data supports negative parity assignment. Because of that the results of the calculation with $\lambda = 2$, $s = 1$, $L = 1$ and $J = 3$ are shown. It is seen that the theory predicts only the general features of the data. One should add that the integrated cross–section for the contribution is the highest at this energy indicating also a strong resonance in the ^{11}B(p,α_1)^{8}Be reaction.

The data at other energies all have similar behaviour and because of that only the results of a combination with $\lambda = 1$, $s = 1$, $L = 0$ and $J = 2$ are shown here. This combination could be justified by the finding from the study of the charged particle emission from ^{11}B+p processes [12], that a strong 2^+ background is present at these energies and even dominating except at those energies where strong compound resonances occur. It was speculated that this 2^+ background is due to the low-energy tail of the giant quadrupole resonance. In the ^{12}C excitation energy region from 18.8 to 21 MeV ($3.2 < E_p < 5.5$ MeV) there are two groups of α-decaying states, listed in Ref. 4, grouped around 19.4 and 20.6 MeV. In a recent study of the decay of the ^{12}C high-lying states [13] it was concluded that one of the states at 19.55 MeV has spin and parity 2^-, but for the lower one no assignment could be given. At least one state in this region decays by the α_0 emission, which implies its natural parity. Both assignments 2^+ and 3^- were claimed in earlier studies (see e.g. Refs. 7 and 14). Our data support the 2^+ assignment. Although there has been evidence for states with the assignments 3^- and 3^+ at about 20.6 MeV, present data could not confirm this. It should be mentioned that in the study of the decay of the ^{12}C states produced in the ^{11}B(d,n)^{12}C reactions a very broad α-decaying region was found at these excitations in contrast to the claimed relatively narrow widths of these two states.

Figure 4 shows the data collected at E_p = 3.76 MeV for three setting angles, which correspond to the collinearity conditions with three α-particles in the c.m. system being on the line inclined by 90^o, 75^o and 60^o with respect to incident proton beam. The curves represent the Schäfer model calculations with $\lambda = 1$, $s = 1$, $L = 0$ (full line) and $\lambda = 1$, $s = 2$, $L = 0$ (dashed line). The curves for a given s are normalized to the data with the same factor for all three angles. From the data and calculations one would conclude that the channel spin $s = 2$ gives no significant contribution to the resonance. Good agreement with the data for all three spectra additionally supports 2^+ assignment for the 19.4 MeV state.

4. *Conclusion*

The present study of the ^{11}B(p,$\alpha\alpha$)^{4}He reaction in the collinearity condition illustrates a possible use of these special kinematical conditions, together with its limitations, for the spin and parity assignments of a compound system decaying sequentially into three particles. It can be at present used only to determine the parity of a strongly resonating state, and in a very special case also its spin. In present case the results support the following assignments of the ^{12}C states: 0^+ (17.8 MeV), 3^- (18.4 MeV) and 2^+ (19.4 MeV), while neither one of the tentative assignments of the states around 20.6 MeV (3^- and 3^+) could be confirmed. One also hopes that these data may be used in the future for testing different three-body theories the same way as the nucleon-deuteron break-up data in these conditions are now used for the three-nucleon theories.

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REAKCIJA $^{11}B(p,\alpha\alpha)^4He$ U UVJETIMA KOLINEARNOSTI

Mjerena je reakcija $^{11}B(p,\alpha\alpha)^4He$ za osam upadnih energija protona, od 2 do 5.5 MeV, u uvjetima kolinearnosti (jedna α-čestica miruje u sustavu centra masa). Rezultati su uspoređeni s predvidanjima Schäferovog modela. Diskutirana je uloga stanja jezgre ^{12}C s energijama pobudenja izmedu 17.8 i 21 MeV.