7 May 1998

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 426 (1998) 251–256

Two-neutron exchange observed in the ^{6}He + ^{4}He reaction. Search for the ’’di-neutron’’ configuration of ^{6}He

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Received 4 November 1997; revised 19 February 1998
Editor: R.H. Siemssen

Abstract

Differential cross sections for the elastic scattering of ^{6}He exotic nuclei from a gaseous helium target has been measured in a wide angular range in the CM system at a ^{6}He beam energy of 151 MeV. The large cross-sections obtained at backward angles are discussed in terms of a two-neutron exchange process. The results of DWBA calculations show that this effect can account for the cross sections obtained between 120° and 160° assuming the spectroscopic factor to be about 1 for the di-neutron cluster as was predicted by theory for ^{6}He. © 1998 Published by Elsevier Science B.V. All rights reserved.

PACS: 29.25Rm; 29.30.-h; 25.45De; 24.10Ht; 25.10.+ s

For a long time the neutron rich nucleus of ^{6}He has attracted much attention both from the experimental and theoretical points of view. Among the other such nuclei [1] having two-neutron halo structure, ^{6}He is notable for its constituents, the ^{4}He core and the two neutrons, which can be treated as structureless to a great degree of confidence. Therefore, as this has been underlined repeatedly [2], the experimental study of the ^{6}He structure is especially interesting, since the theory describing it as a three-body system can give very accurate predictions. In particular, the ’’di-neutron’’ and ’’cigar’’-like configurations predicted for ^{6}He are waiting for experimental verification.

The available experimental data do not permit to draw with certainty conclusions about the details of the neutron halo structure in ^{6}He. The data on the total reaction cross section and the momentum distributions of alpha particles and neutrons obtained in fragmentation reactions (see Ref. [1] and references therein) point mainly to the long tail of the ^{6}He radial wave function. However, such a conclusion follows even from the fact that the neutron pair in ^{6}He is loosely bound. The study of the ^{6}He β^--decay led the authors of Ref. [3] to suggest a new mechanism for delayed deuteron emission which relies on the large overlap of ^{6}He with the alpha particle and the ’’di-neutron’’.

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PII S0370-2693(98)00233-0

It is well known that transfer reactions provide a good opportunity to study the structural parameters and spectroscopic factors of simple nuclear configurations. Therefore it appears to be natural to use such reactions for testing the ^{6}He internal wave function [2]. In the case of collision partners, which could be ^{6}He and ^{4}He, this could be two neutron transfer, i.e. an exchange effect which should be observed in the centre-of-mass frame as elastic scattering in the backward direction (see e.g. Ref. [4]). A helium gas target is necessary to carry out such a study, and this makes the problem more complicated from the experimental point of view. However, such a study appears to be quite promising as the two-neutron exchange occurring between identical core-nuclei could offer favourable conditions for a detailed test of the structure of the ^{6}He nucleus.

The choice of the ^{6}He projectile energy is essential for such experiments. In the case of low-energy collisions (up to 15 MeV/nucleon) potential scattering will make a sizeable contribution to the elastic cross section in the whole angular range, i.e. it will interfere with the searched for exchange effect. For the collision energy approaching (or even exceeding), in the CM frame, the Fermi energy in nuclei the probability of two neutron exchange becomes too small. Thus, for this effect to manifest itself clearly, the most favourable energy range for the ^{6}He projectile makes 20-30 MeV/nucleon. At this energy the elastic scattering, which is described by the optical model (OM) potential, will show a steep decrease in the cross section with increasing angle. Therefore, the contribution of the potential scattering to the cross section in the backward direction will be negligible, and one could observe the exchange effect without interference from the elastic scattering caused by the OM potential. An example of such an exchange reaction is the scattering of 166 MeV ^{4}He ions from ^{6}Li, in which case the backward angle elastic scattering has been described as the exchange of a deuteron cluster between two ^{4}He nuclei [5].

In the present paper we report the results of the study of the exchange effect in the reaction ^{6}He + ^{4}He in which a helium target was bombarded by a beam of ^{6}He nuclei. The searched reaction channel can be uniquely selected by the identification of both reaction participants. A possible contribution of inelastic scattering will be absent due to the fact that all the excited states in both partners, i.e. in ^{4}He and ^{6}He, are unstable with respect to the particle emission. Therefore, the requirement of a high energy resolution is not essential for this study.

A secondary beam of ^{6}He was produced by the fragmentation of a 32 MeV/nucleon ^{7}Li beam on a thick ^{9}Be target (225 mg/cm^2). The ions of ^{6}He were separated using the ACCULINNA facility [6] recently commissioned at the U-400M cyclotron. Some contamination in the separated ^{6}He beam arising from ^{3}H ions was reduced to a level of less than 10% with a 1.3 mm thick aluminium wedge located in the intermediate focal plane of ACCULINNA. The momentum acceptance of the spectrometer in this case was limited to $\pm 1.8\%$ by slits with dimensions of 22 and 10 mm in the horizontal and vertical position, respectively, positioned in the same intermediate focal plane. The secondary 151 MeV beam of ^{6}He ions was finally limited by a system of three carbon diaphragms, which fixed the diameter of the beam spot on the helium target at ~ 6.5 mm. The beam energy spread (FWHM) and transverse emittance made, respectively, $\pm 2\%$ and 30π mm · mrad. This relatively small transverse beam emittance was essential for carrying out the experiments without tracking individual bombarding ions. With this quality, the ^{6}He beam intensity amounted up to about $1 \cdot 10^5$ particles/s at an intensity of the primary ^{7}Li beam of $1 \cdot 10^{12}$ particles/s.

The helium gas target was enclosed in a cell of a cylindrical shape with a diameter of 25 mm and a length of 12 mm. The stainless steel entrance and exit windows (10 μm each) had dimensions of $24 \cdot 10$ mm^2 in the horizontal and vertical planes, respectively. The cell was cooled to 78K by liquid nitrogen and, at a pressure of 5 atm, the resulting thickness of the ^{4}He target was equal to $5.6 \cdot 10^{20}$ atoms/cm^2.

The experimental setup is shown in Fig. 1. It consisted of two silicon detector telescopes mounted on two independently movable arms (essential parameters are shown in Fig. 1 for both telescopes). The first ΔE-ΔE-E telescope was intended for the low energy ^{6}He nuclei corresponding to the backward angle scattering events. The veto counter E_{14} supplemented this telescope. The complementary high energy ^{4}He nuclei resulting from the backward scattering of the ^{6}He projectiles were detected by the second ΔE-ΔE-E telescope having at its front an

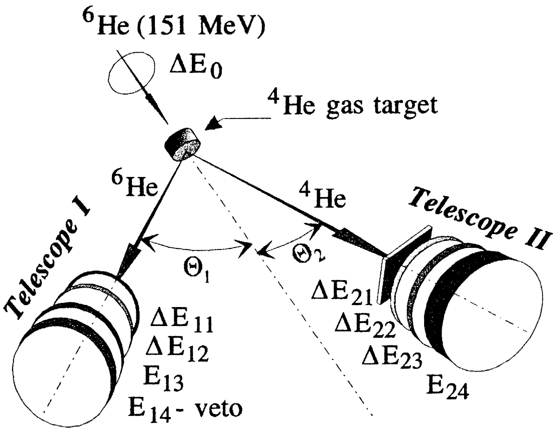

Fig. 1. Scheme of the experimental set up. ΔE_0 stands for the plastic scintillation detector used for the beam monitoring, ΔE_{21} is an array of position sensitive detectors (eight $64 \cdot 8$ mm^2, 0.3 mm thick Si strips). Dimensions of other telescope detectors (the two numbers that follow in parentheses the notation of each detector are, respectively, the detector diameter and thickness, both in mm): ΔE_{11} (16, 0.03), ΔE_{12} (20, 0.10), ΔE_{13} (48, 0.54), ΔE_{14} (50, 3.0), ΔE_{22} (55, 0.52), ΔE_{33} (68, 0.68), ΔE_{24} (66, 7.7).

array of position sensitive Si strips (detector ΔE_{21} in Fig. 1) for measuring the scattering angle. The second telescope also served for detecting the ^{6}He nuclei scattered in the forward direction from the helium target. The energy resolution of each detector used in the telescopes was better than 100 keV for the 5.5 MeV alpha line of ^{238}Pu. The solid angle of each of the two telescopes was ~ 75 msr in the laboratory system. Both telescopes were placed in a horizontal plane.

The backward angle elastic scattering cross-section was extracted from the coincident events when a $_6$He ion was recorded in the first telescope, and the corresponding high-energy ^{4}He - in the second one. The forward angle data were obtained from the single ^{6}He events in the second telescope. The position resolution of the strip detector array in the second telescope was 1 mm and 8 mm FWHM for the X and Y coordinates, respectively, and therefore the angle dependent angular resolution was on average close to $\pm 1°$ (in the lab. system). All together, the finite target length, beam emittance (the beam size and angular divergence on the target) and telescope position resolution led to the errors in the forward direction CM scattering angle estimations which did not exceed $\pm 3°$. For the coincident backward scattering events a better angular resolution ($\pm 2°$ in CM system) was achieved by taking the ratio of the energies deposited in the two telescopes.

The ^{6}He beam was monitored and the total projectile integral flux was measured by a thin scintillation detector. It consisted of a 150 μm thick plastic NE PILOT-U, a hollow light guide made as a cone from 27 μm Al foil and a R3082 Hamamatsu photomultiplier. The ΔE resolution of the detector allowed one to well separate the 6He projectiles from the ^{3}H ions.

Four separate runs were performed, in which the first telescope detected the reaction products emerging from the target in the laboratory system within the angular ranges of 35 ± 9, 35 ± 10, 34 ± 8.4 and 35 ± 10 degrees to which corresponded the angular ranges of 35 ± 8.5, 16.6 ± 6.3, 20 ± 10 and 10 ± 6.3 degrees covered by the second telescope. The integral flux amounted to $2.4 \cdot 10^9$ ions of ^{6}He in total in the four runs. The data acquisition system was triggered by the ''ΔE_{12} OR ΔE_{22}'' (see Fig. 1) condition in the first run and by the 2 μs coincidence condition ''ΔE_{22} AND ΔE_{23}'' in the other runs.

The ΔE-E (ΔE_{22} versus E_{24}) energy plot obtained for the geometry $\theta_1 = 35°$, $\theta_2 = 16.6°$ is shown in Fig. 2(a). The loci of the signals from ^{6}He and ^{4}He ions are well seen in this plot. It is apparent that the ^{4}He events extend to the energy range typical for the elastic scattering peak of ^{6}He ions clearly visible in the ^{6}He branch in Fig. 2(a). The ΔE-E (ΔE_{11} versus ΔE_{12}) plot shown in Fig. 2(b) involves the events detected by the first telescope in coincidence with the ^{4}He events of the second telescope (Fig. 2(a)). One can see in Fig. 2(b) ^{6}He events which, due to their coincidence with the ^{4}He ions detected in the second telescope and according to their energy range, can be identified as the back-scattering of ^{6}He. The validity of this conclusion in relation to the majority of such events is justified by the examination of Fig. 3, where the spectrum is shown for the sum of the energies deposited by the coinciding ^{6}He and ^{4}He ions in the first and second telescope, respectively.

In total, 24 ^{6}He-^{4}He coincidences were identified as backward direction elastic scattering events. In order to estimate the background originating from the scattering of the ^{6}He beam ions from the target

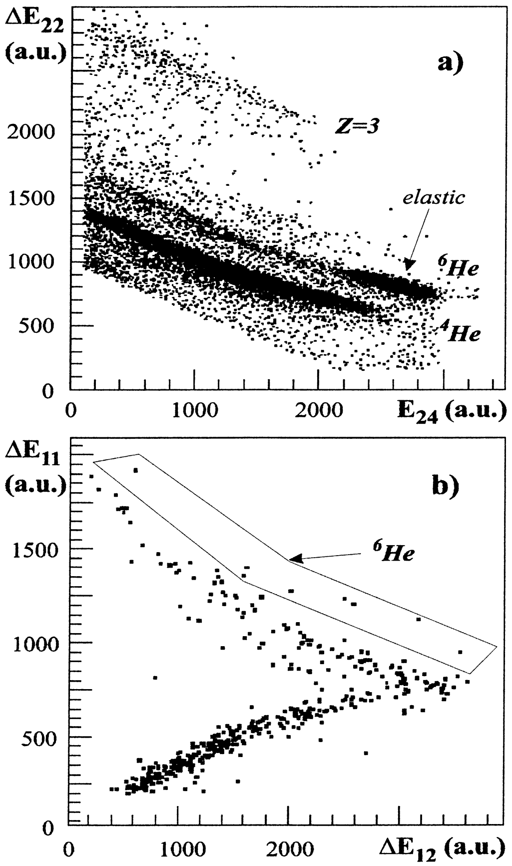

Fig. 2. Upper panel: Two-dimensional plot (ΔE_{22} versus ΔE_{24}) obtained with the second telescope. Lower panel: ΔE_{11} versus ΔE_{12} events observed in telescope 1 in coincidence with the ^{4}He events detected in telescope 2 (these ^{4}He events are seen in upper panel).

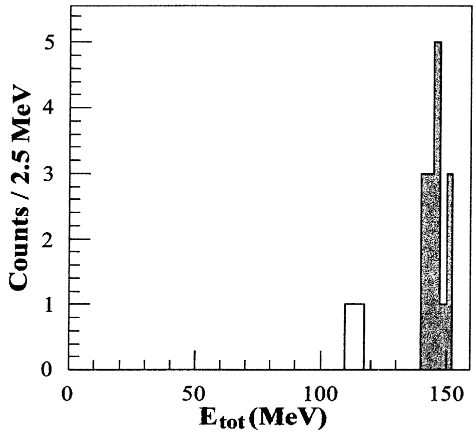

Fig. 3. Total kinetic energy spectrum for the ^{6}He - ^{4}He coincidences. The shaded peak corresponds to true events of backscattering.

windows and beam diaphragms, appropriate measurements were done when the helium was evacuated from the target cell and when the cell was removed from the beam axis. The estimated background for these events was negligible (< 0.1 events). In total, about 3,700 ^{6}He events originating from the elastic scattering to $\theta_{CM} = 15° - 55°$ were detected in these experiments, and the background was properly subtracted from these events.

Monte Carlo simulations of the experiment were performed to estimate the effective solid angles for all the angular bins. The resulting angular dependence of the differential elastic scattering cross section $d\sigma/d\Omega$ is presented in Fig. 4 : the closed circles stand for the estimated cross-section values, the horizontal bars with downward arrows - for the upper limits. The obtained absolute cross section values have error bars $\pm 15\%$ which originate from the uncertainties of the parameters used in Monte Carlo simulations and errors in the beam monitoring and target thickness. Only statistical errors are shown in Fig. 4.

To analyze our experimental results, we first described by OM the forward angle data. Taking into

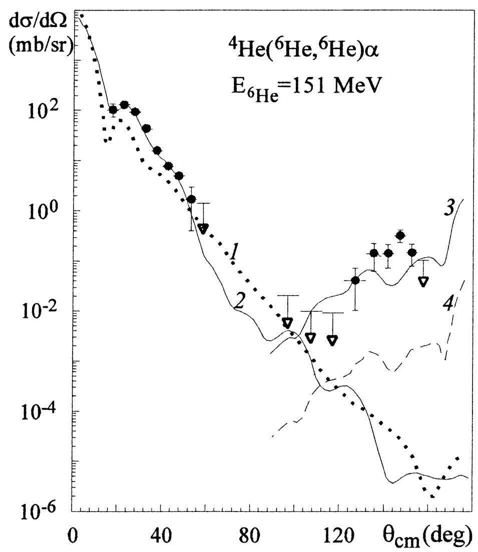

Fig. 4. Experimental data (symbols) and theoretical calculation (lines) for the elastic scattering ^{6}He(151 MeV) + ^{4}He.

account the quality of these data, we did not try to precisely fit these by varying the OM parameters. Instead, we took the OM potential that was found in [5] for the case of ^{4}He + ^{6}Li elastic scattering at E_{lab} = 166 MeV as a basis. The differential cross sections calculated for our ^{6}He + ^{4}He system with this OM potential are shown in Fig. 4 by the dotted line (curve 1). The deviation of this calculated curve from our forward angle experimental points is at most about 30%. By varying some of the OM potential parameters within 10% we were able to easily eliminate this discrepancy. Curve 2 in Fig. 4 was calculated with the following parameters of OM potential taken in WS-volume form with $R = r_0 \cdot (A_P^{1/3} + A_T^{1/3})$: $V_0 = -102.5$ MeV (102.5), $r_0^V = 0.522$ fm (0.522), $a_V = 0.920$ fm (0.820), $W_0 = -13.0$ MeV (-11.77), $r_0^W = 1.130$ fm (1.206), $a_W = 0.500$ fm (0.950) (the numbers given in parentheses are the parameter values used in [5] for the ^{6}Li + ^{4}He scattering). In view of the difference between ^{6}He and ^{6}Li, such variations of the OM parameters are reasonable.

Within the angular range of $122° \leq \theta_{CM} \leq 155°$ the calculated elastic scattering cross section varies between $5 \cdot 10^{-4}$ and $5 \cdot 10^{-6}$ mb/sr, whereas the experimental points lie in this range at a level which is by 10^2 - 10^4 times higher. As was expected, there is no reasonable set of OM parameters that can reproduce the yield of the ^{6}He nuclei observed in the backward direction. A change in the calculated $d\sigma/d\Omega$ values by a factor of three to five for some local angular intervals in the backward hemisphere is the maximum that one can achieve by varying the OM parameters. This definitely means that the ^{6}He scattering events observed in this angular region are in fact the result of two-neutron exchange. The authors of Ref. [5] came to a similar conclusion about the role of the deuteron cluster exchange in the α-particle scattering observed at the backward angles in the reaction ^{6}Li$(\alpha,\alpha)^6$Li.

Assuming that the exchange of the two-neutron cluster between ^{6}He and ^{4}He occurs via a direct one-step mechanism, one should calculate a 9-dimensional integral consisting of entrance and exit distorted waves and the two-neutron wave function of ^{6}He to accurately describe the backward angle yield of ^{6}He nuclei. The theoretical estimates done within the three-body model (α + n + n) predict two sufficiently distinct spatial components for the 6He ground state wave function: (1) - a ''di-neutron'' component in which the two neutrons are located close to each other ($r_{nn} \sim 2$ fm), with their centre of mass being rather far from the ^{4}He core ($R_{nn} \sim 3$ fm), and (2) - a ''cigar-like'' component ($r_{nn} \sim 4.5$ fm, $R_{nn} \sim 1$ fm) [2]. To calculate the cross-section of the direct two-neutron transfer process, we used a simplified approach in which the two neutrons in ^{6}He are treated as a cluster described by a wave function depending on the R_{nn}-coordinate only (we leave a more sophisticated calculation for the future). The transition amplitude was taken in the usual form

$$T^{DWBA}(\theta) = S_{2n}(^6\mathrm{He}) \cdot \langle \tilde{\chi}^{(-)}_{\mathbf{k}_f}(\mathbf{r}_f)\, \varphi^{mod}_{2n}(\mathbf{R}_f) | V_{(2n)\alpha} \times (R_i) | \varphi^{mod}_{2n}(\mathbf{R}_i)\, \tilde{\chi}^{(+)}_{\mathbf{k}_i}(\mathbf{r}_i) \rangle .$$

The normalized model 2n-cluster wave function was calculated within the Woods-Saxon potential $V_{(2n)\alpha}$ with the radius of 2 fm and diffuseness of 0.5 fm. The depth of this potential was adjusted to reproduce a 2s-state with the binding energy of 0.973 MeV. 2s-state bound wave function consists of two peaks at $R_{1,2}$ which can be easily confronted with the two components ('near' and 'far' located in R_{nn} space) of the total 3-body wave function of ^{6}He [2]. To make the reaction mechanism more clear we decomposed the wave function onto two items - $\varphi^{mod}_{2n}(R) = \varphi_1(R,R_1) - \varphi_2(R,R_2)$ - where the functions $\varphi_{1,2}(R)$ are peaked at $R_{1,2}$ and both have an appropriate asymptotic behavior at large distance. Of course, such decomposition is an identical transformation of the bound state wave function, but now we can estimate correctly the contributions to the transfer cross section coming from the short and large distances in R_{nn} space. We did not calculate a coherent sum of the elastic and transfer amplitudes (important at the angular region of 80° - 100°) because their values differ drastically at the backward angles.

Curve 3 in Fig. 4 shows the two-neutron transfer cross section calculated with the fully normalized model wave function. It is evident that the calculated cross section values are close to the experimental points in Fig. 4. Curve 4 in Fig. 4 shows the results of the calculation done with the model wave function from which the far- located ''di-neutron'' component was eliminated. One can see the deficit of two orders of magnitude in the cross-section values given by curve 4 showing that the contribution of the close located, ’’cigar-like’’ component of ^{6}He to the two-neutron transfer cross section is rather small. It means that it is the ’’di-neutron’’ configuration of ^{6}He that is mainly responsible for the two-neutron exchange (just reflecting the peripheral nature of transfer reaction). The fact that the calculated cross sections obtained with the fully normalized wave function are close to the experimental data implies that the spectroscopic factor of the two-neutron cluster in the ^{6}He nucleus is close to one.

To summarize, a high quality, intense secondary beam of exotic ^{6}He ions was produced. The measurements of the elastic scattering cross sections, for the first time carried out in a wide angular range with intermediate energy ^{6}He ions bombarding a helium target, disclosed a rise in the cross sections at the backward CM angles. To account for the obtained effect, a one-step, two-neutron exchange mechanism is proposed. The DWBA calculations were performed with the use of the ^{6}He model wave function derived from the one which is given by the solution of the exact three-body problem [2]. The wave function assuming the presence of two prominent configurations - ’’di-neutron’’ and ’’cigar’’-like ones - showed a good agreement with the experimental data obtained for the backward CM angles. This result can be interpreted as an experimental evidence in support of the theoretical wave function [2]. The calculations also showed that the ’’cigar’’-like configuration alone could contribute only negligibly to the obtained two-neutron exchange, which, thus, is by about 100% due to the ’’di-neutron’’ configuration.

The work was carried out at the Flerov Laboratory of Nuclear Reactions of JINR. The partial support of this work by the Russian Basic Research Foundation (grant No. 96-02-17382) is acknowledged. The authors are grateful to Drs. G. G. Gulbekian, B.N. Gikal and B.V. Kutner for the valuable contribution to the production of a high quality, intense beam of ^{7}Li ions. The useful discussions with Dr. D.D. Bogdanov as well as the illuminating discussions with Drs. B.V. Danilin, J. Vaagen and M.V. Zhukov are acknowledged.

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