WHAT CAN WE LEARN FROM THE DIRECT REACTIONS WITH ^{6}He AND ^{8}He SECONDARY BEAMS ON LIGHT TARGETS AT 25-32 MeV/n BEAM ENERGY?

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The study of ^{6}He and ^{8}He elastic scattering on a helium target and 2-neutron transfer reactions on protons are reported. The elastic scattering data are discussed in terms of the backward angle enhancement caused by structural effects. Abnormally large total reaction cross section for the ^{8}He+α system is found. The transfer reactions appear to be an important source of the information on neutron correlations in these nuclei.

INTRODUCTION

The recent interest in the drip-line nuclei was prompted by the discovery of various phenomena not observed for the stable nuclei. One can notice here the abnormally large radius, narrow internal momentum distribution of valence neutrons, soft dipole excitation, unusual nuclear shell occupation, see the recent review [1] and references therein. Among these so call exotic nuclei ^{6}He nucleus is the lightest system with a 2-neutron halo. Notable for its large N/Z =3 value, ^{8}He is considered as a candidate for a neutron skin nucleus. Direct reactions have been widely used in the past to study the properties of nuclei involved. A program to study the direct reaction with radioactive ^{6}He and ^{8}He beams has been launched at the Flerov Laboratory of Nuclear Reactions (JINR, Dubna). In the present paper we review the series of experiments aimed to investigate the elastic scattering and transfer reactions of these nuclei on helium and hydrogen targets. A brief presentation of experimental technique is given and the most important results are discussed.

EXPERIMENTAL TECHNIQUE

Beams of ^{6}He and ^{8}He were produced by bombarding a thick beryllium target with ^{7}Li, ^{11}B or ^{13}C primary beams having an energy of a few tens MeV/n. The ions of interest were selected from the main bulk of other products using the doubly achromatic magnetic separator ACCULINNA [2]. The average beam intensities amounted up to 10^{5} of ^{6}He or $4x10^{3}$ of ^{8}He particles per second in long-term irradiation. The separator ion optics restricted the energy spread of the secondary beam to a value of 5% (FWHM). In an experiment, where the beam energy resolution was important for the observation of the resonant state of ^{5}H nucleus, the energy of individual ^{6}He ions was measured with an accuracy of ~2% by the time-of-flight technique. Two MWPC provided track data for each bombarding particle. The products of nuclear reactions were identified by the two position sensitive, large solid angle telescopes, e.g., see [3]. To avoid the interference of false reaction products caused by beam impurities of other ions each individual incoming ion was identified by the beam monitoring system. The helium target was made as a gas cell closed on both sides with 20-μm stainless steel foils and coupled to a cryogenic generator. The cell diameter and thickness were 20 and 10 mm. At a helium gas pressure of 11atm the effective target thickness was 2.4×10^{21} atoms per cm^2. A polyethylene foil was used as hydrogen targets. Typically, the content of hydrogen atoms in these targets was $(1.5\text{-}3.0) \times 10^{21}$ per cm^2. The effective solid angle was estimated by Monte Carlo simulations, taking into account: the beam energy spread, detector energy thresholds, angular resolution of telescopes and the beam density pattern on the target surface.

DISCUSSION OF SELECTED RESULTS

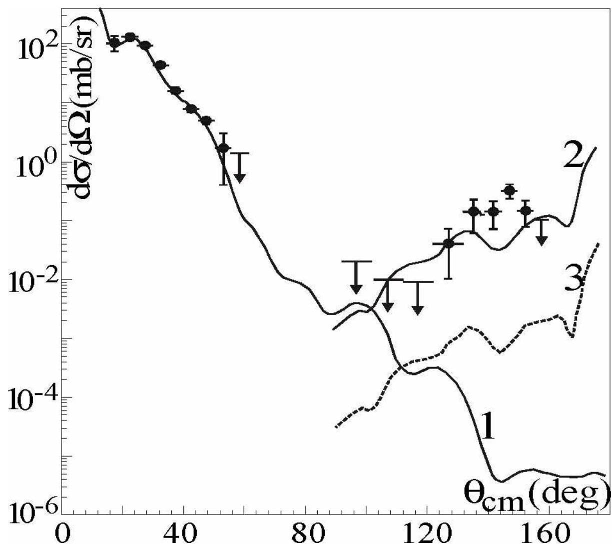

Fig.1.Differential cross section for elastic scattering of 151 MeV ^6He ions from a helium target. Curves: 1 – OM fit to the data obtained in the forward hemisphere, 2 – DWBA calculations with an approximation to the full 3-body wave function [6], 3 – the calculations taking only the "cigar"-like component of the wave function (see text).

We concentrated our attention on the transfer reactions occurring between ^6He and ^8He projectiles and helium and hydrogen target nuclei. In the case of a ^4He target. an exchange effect should be observed in the center-of-mass (CM) frame as a backward direction elastic scattering. The angular distributions for elastic scattering have been measured for the $^6He+^4He$ and $^8He+^4He$ systems at forward scattering angles and an attempt was undertaken to measure the cross-section at backward angles. The resulting differential cross section for the elastic scattering of 151MeV ^6He nuclei from ^4He [4] is shown in Fig. 1. A one-step, two-neutron exchange mechanism could account for the obtained distinct rise in the cross section at the CM backward angles. DWBA calculations were performed [4,5] with the use of a model wave function for ^6He derived from one given by the solution of the exact three-body problem [6]. The wave function assuming the presence of the two prominent configurations – the "di-neutron" and "cigar"-like ones - showed a good agreement with the experimental data obtained for the backward CM angles. This result indicates a dominance of the "di-neutron" configuration in this process.

For the case of the $^8He + ^4He$ scattering, in spite of rather low (around 1 μb/sr) cross-section limits attained at backward angles, the enhancement originated from transfer process was not observed, see Fig.2. In order to estimate the unobserved enhancement at the backward angles DWBA calculations with code FRESCO [7] were performed. It was assumed that one-step as well as two-step transitions contribute. For the one-step 4n transfer the internal ^8He wave function was taken as that of the two-cluster relative motion in 2S state with the binding energy equal to the ^8He four-neutron separation energy. The spectroscopic amplitude (SA) for α+4n clustering was set equal to 1.0. The calculated potential scattering with coherent inclusion of the one-step transfer is shown in Fig.2 as curve 2. The two-step processes were treated as sequential transfers of 2 pairs of neutrons through the two intermediate ^6He nuclei, both in their ground and first excited states. To simplify the task all absolute values of the relevant SA were taken to be equal 1.0, their signs were determined with the help of symmetry considerations [8]. Optical model (OM) parameters for all the $^6He+^6He$ pairs were taken from the $^6Li+^6Li$ elastic scattering at a 156 MeV lab energy [9]. In course of this qualitative analysis it was found that the intermediate system of two excited ^6He nuclei generates the largest contribution. The potential scattering with inclusion of the one-step and the main two-step contributions is shown in Fig.2 as curve 3. OM analysis of the experimental data at forward angles confirmed, that at the collision energy in question, due to predominance of the far-side component, the discrete ambiguities of OM potentials are removed. The analysis reveals a large value of the total reaction cross-section, see Fig.3 (open circle) for comparison with the α-

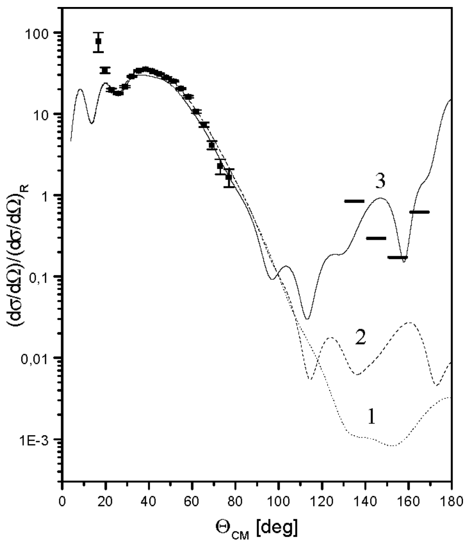

Fig.2. Experimental data for the elastic scattering of ^8He on ^4He. Symbols in the back hemisphere indicate upper limits only. Curves are for the calculations: curve 1 – OM, 2-one-step transfer, 3-two-step transfer processes, see text.

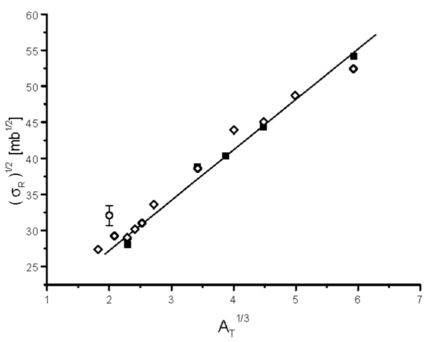

Fig.3. Square root of the total cross sections as a function of a target mass $A_t^{1/3}$ for 26 AMeV α-particles scattered on various targets. All σ_R were obtained by OM analysis of the elastic scattering angular distributions. Open diamonds correspond to the 6-parameter fit [10], black squares – microscopic model systematic [11], open circle with the error bar – the present case of ^8He + α. The line – is a linear fit to the double folding model calculations [11].

particle scattering data for various stable targets. The error bar corresponds to the calculated uncertainty of the total reaction cross-section caused by the limitation of ^{8}He + α angular distribution normalization. The evident disagreement with the systematic trend could be an indication of an anomaly structure of ^{8}He.

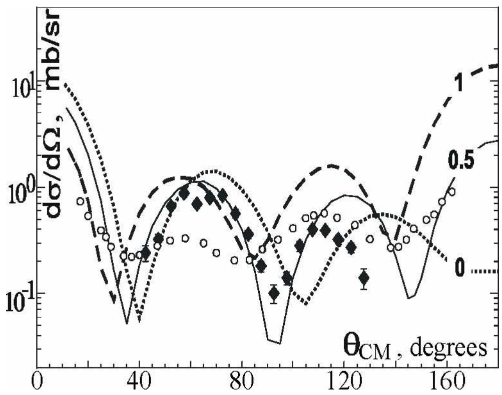

Fig.4: Solid symbols show our data on the cross section of $^{6}He+p\to\alpha+t$ reaction (E_{6He}=150 MeV). Open circles show similar data from Ref. [12] for $p+^{6}Le\to\alpha+^{3}He$ reaction (E_p=25 MeV). Curves: DWBA calculations assuming 1 – the full shell-model spectroscopic amplitude for two triton clusters in ^{6}He, 0.5 – this amplitude was reduced by a factor of two, 0 – the two-triton clustering of ^{6}He neglected.

To further look into the structure of ^{6}He and ^{8}He nuclei the transfer reaction on protons were investigated with these ions. We present here results of 2-neutron transfer reaction channels. In the case of the ^{6}He + p collision 2n and t transfers contribute coherently. Differential cross-section data for the reaction $^{6}He+p\to\alpha+t$ [3] are shown in Fig.4 together with analogous data for the reaction $p+^{6}Li\to\alpha+^{3}He$ [12]. The two measured oscillations for the ^{6}He+p reaction are more pronounced, and their relative magnitudes are reversed with respect to the $p+^{6}Li$ data. The analysis of the data, and comparison with the analogous reaction on ^{6}Li [12], see Fig.4, enabled us to make a conclusion that the t+t clustering in ^{6}He seems to be reduced in respect to the shell model prediction [8].

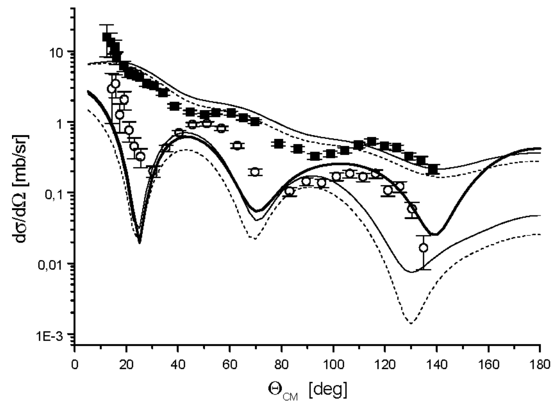

Fig.5. Experimental data (symbols) and DWBA calculations (lines) of differential cross-sections for 2n transfer reactions channels: $^{8}He+p\to^{6}He(0^{+})+t$ (circles), $^{8}He+p\to^{6}He(2^{+})+t$ (stars). The 1-step transfer calculations are shown by dashed lines, 2-step transfer, coherently added, by thin solid lines. The inclusion of 1-step transfer of ^{5}H cluster is shown by a thick solid line, see the text.

The 1n transfer reaction feeding the ^{7}He ground state and 2n transfer leading to the ^{6}He ground and $^{6}He(2^{+})$ excited states have been measured for the ^{8}He+p collision. One can see in Fig.5 the experimental results and relevant calculations for 2n transfer. The one-step 2n and sequential 2-step (though the ground state of ^{7}He) transfers were calculated. In this analysis the OM exit channel parameters were taken from elastic scattering data obtained for 45-MeV ^{3}He on ^{6}Li [13]. The shape of the $^{6}He(2^{+})$ angular distribution appeared to be quite sensitive to the geometry parameters of the binding potential. To calculate SA for the relevant transitions by method of Ref.[8] one should know the wave functions (WF) in LS coupling for all states in question.. Unlike ^{6}He(0^+) and ^{6}He(2 the ^{6}He(0^{++}) wave functions the ^{8}He one is less known. We assumed almost pure (90%) S wave function for the ground state of ^{8}He. The resulting ratio of spectroscopic factors (SF) was 1.4 in favor of ^{6}He(2^+) channel. One can see in Fig.5 that the calculation, which reproduces the angular distribution of the 2n one-step transition leading to ^{6}He(2^+) underestimates the 2n transition to ^{6}He(0^+) (dashed lines). It means that the ratio of SF is overestimated in present calculations. In order to investigate how much the effect of two-step processes could change the picture, the sequential 2n transfer through the ^{7}He ground state was calculated. The ^{6}He(0^+)+n internal wave functions was treated as a resonance. The resulting coherent sum of a one-step transfer and sequential 2n transfers is shown in Fig.5 with thin solid lines. One can see that sequential 2n transfer feeds both) and ^{6}He(2^+) exit channels The underestimation of ^{6}He(0^+) transition in respect to ^{6}He(2^+) one remains apparent especially at forward angles. It is known that the absolute value of a single SF extracted from an experiment is highly model dependent. However the ratio of SF is much more stable in respect to the freedom in choosing OM potential parameters. We believe that the performed analysis clearly recomends as a more proper ratio of SF to be rather in vicinity of 1.0. The shell model agebra of Ref. [8] yields SF ratio of ^{6}He(2^+) in respect to ^{6}He(0^+) to be close to 1.0 for the pure LS coupling, whereas for the pure jj coupling the ratio reaches a value of 2.4. The present discussion of experimental results suggests a week jj coupling of valence neutrons in ^{8}He. This important conclusion is at variance with the conjecture of $(p_{3/2})^4$ subshell closure for this nucleus.

There is one more one-step transfer which could contribute to the ^{6}He(0^+)+t exit channel. Namely, this is the transfer of a ^{5}H cluster. Very little is known about this system. Recently ^{5}H was observed for the first time. The p(^{6}He,2p)^{5}H reaction was chosen at 32MeV/n ^{6}He beam, hydrogen cryogenic target was applied and RIKEN annular detector telescope was used for the registration of 2 protons. Among triple p-p-t coincidences the ^{5}H ground state was identified as a resonance at 2 MeV above the 2n+t threshold [14]. The spin of the state was assumed to be $1/2^+$. With these spectroscopic parameters and SA of ^{8}He=^{5}H+^{3}H clustering taken to be equal to 1.0 the ^{5}H-cluster transfer was calculated and added coherently to that of 2n transfer. The process feeds only the ^{6}He ground state channel. The result is shown in Fig.5 as a thick solid line. One can see a better agreement with the experimantal data at backward angles. This result implies that the relevant clustering in ^{8}He can be not negligible.

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