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CLUSTER STRUCTURE OF ^{9}Be

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Лукьянов С. М. и др. E7-2017-65
Кластерная структура ^{9}Be

Измерены угловые распределения протонов, дейтронов, тритонов и альфа-частиц, полученных в реакции $^2\mathrm{H} + {}^9\mathrm{Be}$ при энергии $E_{\text{лаб}} = 19{,}5$ МэВ, с целью изучения внутренней кластерной структуры ^{9}Be и возможной передачи ^{5}He-кластера. Анализ предполагает значительный вклад пятинуклонной передачи в канал реакции $^9\mathrm{Be}(d, {}^4\mathrm{He})^7\mathrm{Li}$.

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Cluster Structure of ^{9}Be

Angular distributions of protons, deuterons, tritons, and alpha particles emitted in the reaction $^2\mathrm{H} + {}^9\mathrm{Be}$ at $E_{\mathrm{lab}} = 19.5$ MeV were measured to shed light on the internal cluster structure of ^{9}Be and to study possible cluster transfer of ^{5}He. The analyses suggest a significant contribution of a five-nucleon transfer in the $^9\mathrm{Be}(d, {}^4\mathrm{He})^7\mathrm{Li}$ reaction channel.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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INTRODUCTION

Due to the Borromean structure, a special attention has been focused on the ^{9}Be nucleus, the breakup of which can occur directly into two alpha particles and a neutron or via one of two unstable intermediate nuclei such as ^{8}Be or ^{5}He [1, 2]. Scattering of a projectile on a target, such as ^{1,2}H or ^{3,4}He, is a standard tool to study the structure of nuclei. This method involves the angular distribution measurement of elastic and inelastic scattering. Energy distribution of the products gives information about internal structure of the interacting nuclei. The angular distributions of the ^{9}Be(^{3}He, ^{3}He)^{9}Be, ^{9}Be(^{3}He, ^{5}He)^{7}Be, ^{9}Be(^{3}He, ^{5}Li)^{7}Li, ^{9}Be(^{3}He, ^{6}Be)^{6}He, and ^{9}Be(^{3}He, ^{6}Li)^{6}Li reaction channels were measured in [3, 4] and described within the optical model, the coupled-channel approach, and the distorted-wave Born approximation. The performed analysis of the experimental data shows that the potential parameters are quite sensitive to the exit channel and hence to the cluster structure of the populated states, which allows one to make general observations and conclusions regarding the internal structure of the target and product nuclei. The experiment [3, 4] was designed to study the breakup of ^{9}Be in an attempt to determine the contribution of the $^8\mathrm{Be} + n$ and $^5\mathrm{He} + \alpha$ channels in the inclusive measurements. We have found that the ratio about 2.7:1 may be assigned to the contributions of these two channels, respectively. The determined value justifies that the $^5\mathrm{He} + \alpha$ breakup channel plays an important role.

Another aspect is an attempt to find not only the cluster structure (for instance, ^{5}He) but also clarify how the cluster structure is involved into nuclear reaction mechanism. Indeed, starting from Détraz [5, 6] multiparticle–multihole structures were expected to occur at rather low excitation energies in nuclei. Four-nucleon transfer reactions are being extensively studied. One may hope that their major features, in spite of the *a priori* complexity of such a transfer, can be understood assuming that the nucleons are transferred as a whole, strongly correlated in a cluster, which has the internal quantum numbers of a free particle.

1. EXPERIMENTAL METHOD

The experiment was performed using 19.5-MeV beam energy of ^{2}H ions on the cyclotron of INP (Řež, Czech Republic). The average beam current during the experiment was maintained at 10 nA. The self-supporting Be target was prepared

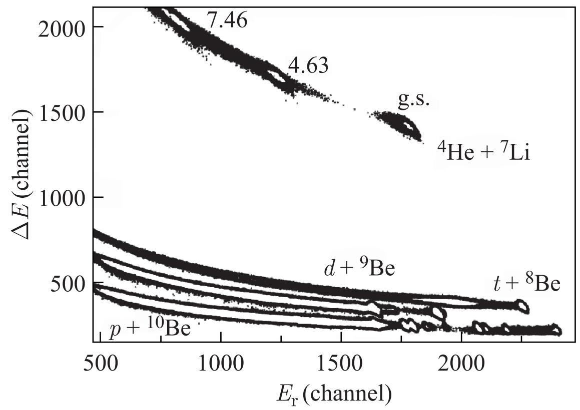

Fig. 1. Particle identification plots for the products of the $^2H + {}^9Be$ reaction: p, d, t, and ^4He. ΔE is the energy loss and E_r is the residual energy. Excited states for the ^7Li reaction channel $^7Li + \alpha$ are indicated

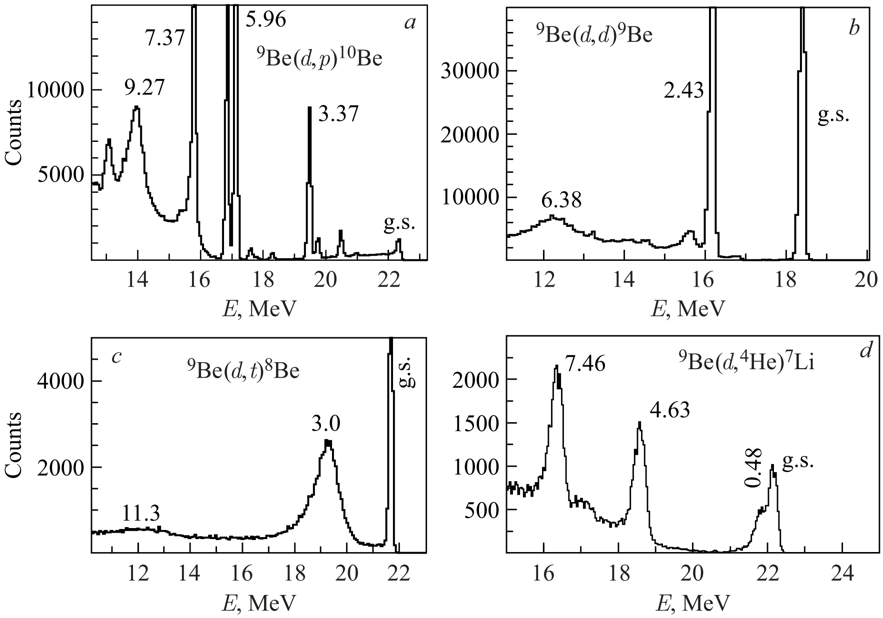

Fig. 2. Total deposited energy spectra measured at $\theta_{lab} = 32^\circ$ for the detected p (a), d (b), t (c), and ^4He (d). The ground and excited states of ^7Li for the case of detected complementary product ^4He, as well as the ground and excited states for ^8Be, ^9Be, and ^{10}Be in the case of detected t, d, and p, as complementary products, respectively, were unambiguously identified

from a thin beryllium foil of 99% purity. To measure (in)elastically scattered ions, a set of four telescopes, each consisting of ΔE_0, ΔE, E_r detectors with thicknesses of 12 μm, 100 μm and 3 mm, respectively, were used. The telescopes were mounted at a distance of about 19 cm from the target in the reaction chamber. Particle identification was performed based on the energy-loss measurements of ΔE and residual energy E_r, i.e., by the so-called $\Delta E - E$ method. An example of two-dimensional plots (yield vs. energy loss ΔE and residual energy E_r) is shown in Fig. 1.

This experimental technique allows us to identify the particles p, d, t, and ^{4}He and determine their total deposited energies. The spectra of total deposited energy are shown in Fig. 2. All peaks, which can be observed in the histograms in Fig. 2, were identified and found to belong to the ground and excited states of ^{10}Be, ^{9}Be, ^{8}Be, and ^{7}Li, as the complementary products to the detected particles p, d, t, and ^{4}He, respectively.

2. RESULTS AND DATA ANALYSIS

The differential cross sections for the elastic, inelastic, and transfer reaction channels are presented in Fig. 3. All calculations and fitting of the experimental data have been performed using the FRESCO code [7] within the CC method.

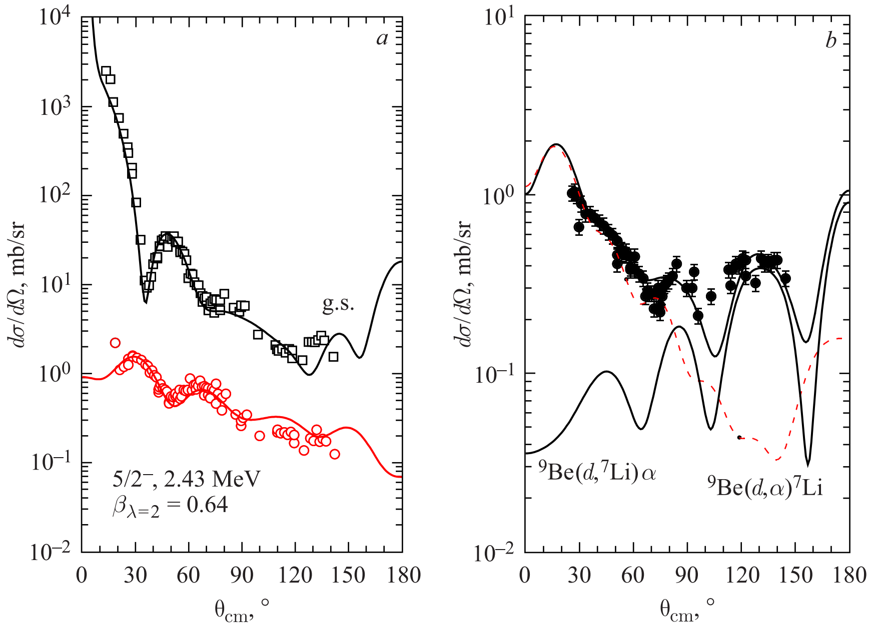

Fig. 3. *a*) Experimental angular distribution for elastic (□) and inelastic (○) scattering of 19.5-MeV deuterons from ^{9}Be target compared with the calculations. The curves are the results of the optical-model and coupled-channel calculations. *b*) Experimental angular distribution (•) for ^{4}He + ^{7}Li reaction channel (see details in the text)

The calculation for (in)elastic scattering (Fig. 3, a) was performed using the method of strong channel coupling in the adiabatic rotational model. It is assumed that the 2.43-MeV state is the first excited state in the rotational band of ^{9}Be. The quadrupole deformation parameter of the target nucleus found from the performed analysis of the data is $\beta_2 = 0.64$, which perfectly coincides with the previous analysis of inelastic scattering of ^{4}He nuclei on the same target [3]. The optical potential parameters used for the calculation are similar to those obtained in [8]. Good agreement between experimental data and calculations is observed (see Fig. 3, a)

A special attention was paid to the $^4\mathrm{He} + {}^7\mathrm{Li}$ reaction channel, which can proceed through two different mechanisms: either transfer of d (dashed line in Fig. 3, b) or transfer of ^{5}He (solid line in Fig. 3, b) from the target to the projectile. In the exit channel both mechanisms are indistinguishable from each other. However, in the former case the ^{4}He nuclei are expected to fly in the forward direction in the center of mass system, whereas in the latter case the alpha particles should preferably fly at the backward angles in the center of mass system. The calculations carried out within the DWBA method for these two mechanisms are shown as the dashed and solid curves in Fig. 3, b. Their coherent sum shown as the black curve is in good agreement with the experimental points. It is interesting to note that for the correct description of the data it is necessary to set the sufficiently large values of the spectroscopic factors for the systems $^9\mathrm{Be} = \alpha + {}^5\mathrm{He}$ ($S = 1.2$) and $^7\mathrm{Li} = d + {}^5\mathrm{He}$ ($S = 1.0$). In addition, to describe the structure of the angular distributions it is also necessary to assume a 30% admixture of the d-state in the structure of ^{7}Li.

In summary, angular distributions for the $^9\mathrm{Be}(d,d)^9\mathrm{Be}^*$, $^9\mathrm{Be}(d,p)^{10}\mathrm{Be}$, $^9\mathrm{Be}(d,t)^8\mathrm{Be}$, and $^9\mathrm{Be}(d,{}^4\mathrm{He})^7\mathrm{Li}$ channels were measured. Experimental angular distributions were described within the optical model, the coupled-channel approach, and the distorted-wave Born approximation. The optical model provides good agreement with the elastic scattering. The DWBA calculations agree well with the transfer reaction data. The spectroscopic factors for the systems $^9\mathrm{Be} = \alpha + {}^5\mathrm{He}$ and $^7\mathrm{Li} = d + {}^5\mathrm{He}$ are close to unity, which confirms significant contribution of the considered cluster configurations to the structure of ground states. The analysis shows that the contribution of the compound nucleus mechanism is negligible. In the $(d, {}^4\mathrm{He})$ channel (see Fig. 3), the deuteron transfer provides only a small contribution, whereas a relatively large contribution of ^{5}He transfer was found in agreement with the result [8]. This demonstrates that the specific structure of the ^{9}Be nucleus as a weakly bound system of two alpha particles and a neutron strongly favors the five-nucleon transfer compared to the deuteron transfer.

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REFERENCES

1. *T. A. D. Brown, P. Papka, B. R. Fulton et al.,* Phys. Rev. C **76**, 054605 (2007).
2. *P. Papka, T. A. D. Brown, B. R. Fulton et al.,* Phys. Rev. C **75**, 045803 (2007).
3. *S. M. Lukyanov, A. S. Denikin, E. I. Voskoboynik et al.,* J. Phys. G **41**, 035103 (2014).
4. *S. M. Lukyanov, M. Harakeh, M. A. Naumenko et al.,* World J. Nucl. Sci. Technol. **5** 265 (2015). doi: 10.4236/wjnst.2015.54026.
5. *C. Détraz, H. H. Duhm, H. Hafner*, Nucl. Phys. A **147**, 488 (1970).
6. *C. Détraz, F. Pougheon, M. Bernas et al.,* Nucl. Phys. A **228**, 39 (1974).
7. http://www.ianthompson.org/surrey; http://nrv.jinr.ru
8. *A. Szczurek, K. Bodek, J. Krug et al.,* Z. Physik A At. Nucl. **333**, 271 (1989).

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