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## Some Evidence of the Cluster Structure Inside of $^9\text{Be}$

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# Some Evidence of the Cluster Structure Inside of ${}^9\text{Be}$

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

## 1. Introduction

Due to its Borromean structure, a special attention has been focused on the  ${}^9\text{Be}$  nucleus, the breakup of which can occur directly to two particles and a neutron or via one of two unstable intermediate nuclei such as  ${}^8\text{Be}$  or  ${}^5\text{He}$  [1, 2]. Scattering of a projectile, such as  ${}^{1,2}\text{H}$  or  ${}^{3,4}\text{He}$ , on a target is a standard tool to study the structure of nuclei. This method involves an angular distribution measurement of elastic and inelastic scattering of projectile-like products. Energy distribution of these products is bearing information about internal structure of the interacting and forthcoming nuclei. The angular distributions of the  ${}^9\text{Be}({}^3\text{He}, {}^3\text{He}){}^9\text{Be}$ ,  ${}^9\text{Be}({}^3\text{He}, {}^5\text{He}){}^7\text{Be}$ ,  ${}^9\text{Be}({}^3\text{He}, {}^5\text{Li}){}^7\text{Li}$ ,  ${}^9\text{Be}({}^3\text{He}, {}^6\text{Be}){}^6\text{He}$  and  ${}^9\text{Be}({}^3\text{He}, {}^6\text{Li}){}^6\text{Li}$  reaction channels were measured [3, 4] and described within the framework of 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 to make general observations and conclusions regarding the internal structure of the target and residual nuclei. The experiment [3, 4] was designed to study the breakup of  ${}^9\text{Be}$  in an attempt to determine the contribution of the  ${}^8\text{Be}+n$  and  ${}^5\text{He}+\alpha$  channels in the inclusive measurements. We found that the ratio about 2.7:1 may be assigned for the contributions of these two channels, respectively. The determined value ratifies that the  ${}^5\text{He}+\alpha$  breakup channel plays an important role.

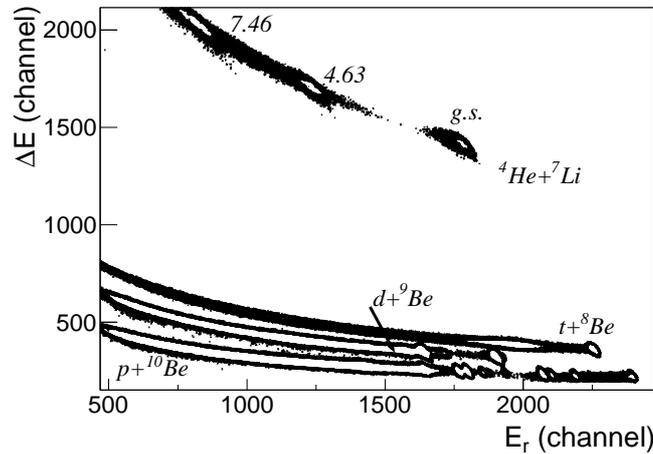
An other aspect is an attempt to find not only the cluster structure (for instance,  ${}^5\text{He}$ ) but also clarify how the cluster structure transfer is involved into nuclear reaction mechanism. Indeed, starting from Detraz [5, 6] multi particle-multi hole structures were expected to occur at rather low excitation energies in nuclei. Four-nucleon transfer reactions continue 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.

## 2. Experimental Method

The experiment was performed using beam energy of a  $^2\text{H}$  ions at 19.5 MeV using the cyclotron of the INP (Rez, Czech Republic). The average beam current during the experiment was maintained at 10 nA. The self-supporting Be target is prepared from a thin beryllium foil of 99 % purity. To measure (in)elastically scattered ions, a set of four telescopes each consisting of  $\Delta E_0$ ,  $\Delta E$ ,  $E_r$  detectors with thicknesses of 12, 100  $\mu\text{m}$  and 3 mm, respectively, were used. The telescopes were mounted at a distance of about 19 cm from the target in a reaction chamber. Particle identification is performed based on the energy-loss measurements of  $\Delta E$  and residual energy  $E_r$ , i.e. by the so-called  $\Delta E$ - $E_r$  method. An example of two-dimensional plots (yield versus energy loss  $\Delta E$  and residual energy  $E_r$ ) are shown in Fig.1.



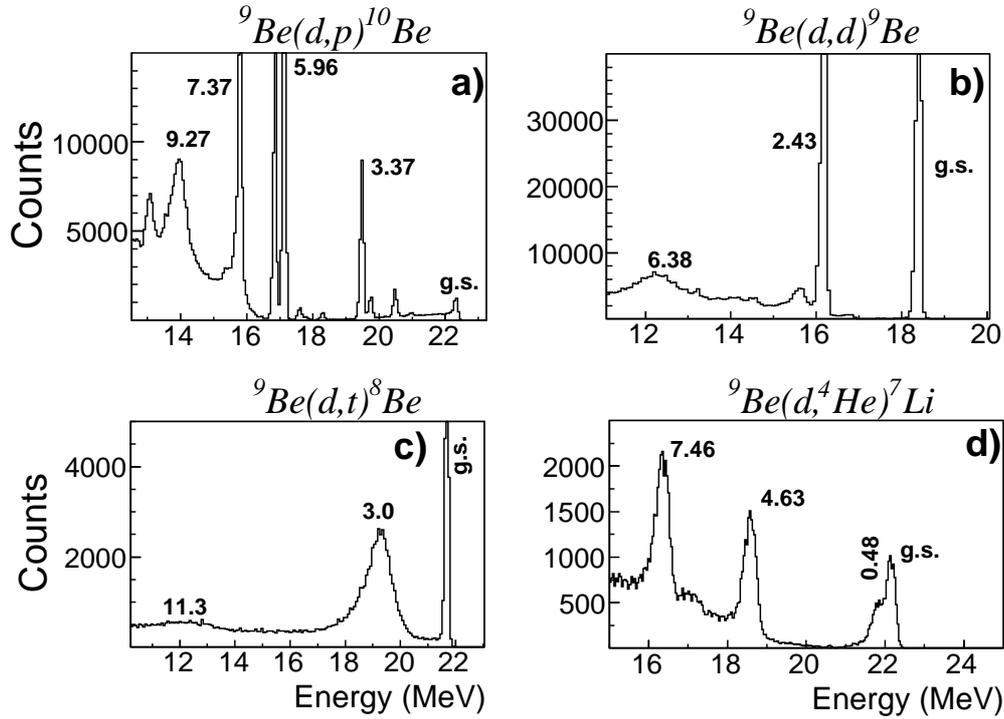
**Figure 1.** Particle identification plots for the products of the  $^2\text{H}+^9\text{Be}$  reaction:  $p$ ,  $d$ ,  $t$  and  $^4\text{He}$ .  $\Delta E$  is the energy loss and  $E_r$  is the residual energy. Excited states for  $^7\text{Li}$  the reaction channel  $^7\text{Li}+\alpha$  are indicated.

This experimental technique allows for identifying the particles  $p$ ,  $d$ ,  $t$ , and  $^4\text{He}$  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  $^{10}\text{Be}$ ,  $^9\text{Be}$ ,  $^8\text{Be}$  and  $^7\text{Li}$ , as the complementary products to detected particles  $p$ ,  $d$ ,  $t$  and  $^4\text{He}$  respectively.

## 3. Results and Data Analysis

The differential cross section 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 FRESKO[7] code in the framework of the CC method.

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

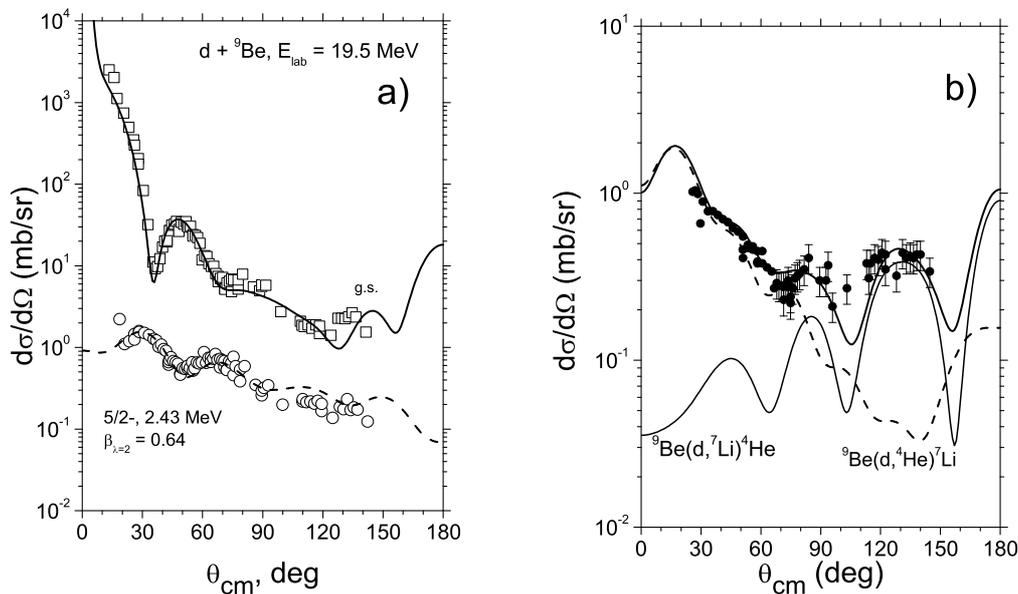


**Figure 2.** Total deposited energy spectra measured at  $\theta_{lab}=32^\circ$  for the detected  $p$  (panel a),  $d$  (panel b),  $t$  (panel c) and  ${}^4\text{He}$  (panel d). The ground and excited states of  ${}^7\text{Li}$  for the case of detected complementary product  ${}^4\text{He}$  as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

Good agreement between experimental data and experimental fitting is observed, as it's shown in Fig. 3a.

A special attention was paid to the  ${}^4\text{He}+{}^7\text{Li}$  reaction channel, which can proceed through two different channels: either with transfer of  $d$  (dashed line in Fig.3b) or transfer of  ${}^5\text{He}$  (solid line in Fig.3b) from the target to the projectile. In the exit channel both these reactions are indistinguishable from each other. However, in the former case the  ${}^4\text{He}$  nuclei are expected to fly "forward" 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 channels are shown in Fig. 3b as the dashed and solid curves in Fig.3b. Their coherent sum is shown as the black curve which is in good agreement with the experimental points. It is interesting to note that for the correct description of the data amplitude it is necessary to set the sufficiently large values of the spectroscopic factors for the systems  ${}^9\text{Be} = \alpha + {}^5\text{He}$  ( $S=1.2$ ) and  ${}^7\text{Li} = d + {}^5\text{He}$  ( $S=1.0$ ). 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  ${}^7\text{Li}$ .

In summary, angular distributions of the differential cross sections for the  ${}^9\text{Be}(d,d){}^9\text{Be}^*$ ,  ${}^9\text{Be}(d,p){}^{10}\text{Be}$ ,  ${}^9\text{Be}(d,t){}^8\text{Be}$  and  ${}^9\text{Be}(d,{}^4\text{He}){}^7\text{Li}$  reactions were measured. Experimental angular distributions were described within the optical model, coupled channel approach and distorted wave Born approximation. The optical potential provides good fit of the elastic scattering in the entrance and exit channels. The DWBA calculations are well agreed with the transfer reaction



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

data. The spectroscopic factors of both reactions are close to unit that confirm significant contribution of the considered cluster configurations into the structure of ground states. The analysis shows that the contribution of the compound nucleus mechanism is neglectable. In the  $(d, ^4\text{He})$  channels, see Fig. 3, the deuteron transfer gives only a small contribution, while a relatively large contribution of  $^5\text{He}$  transfer was found in agreement to result [8]. This demonstrates that the specific structure of the  $^9\text{Be}$  nucleus as a weakly bound system of two alpha particles and a neutron strongly favors the five-nucleon transfer compared to deuteron transfer.

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