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1 GeV proton elastic scattering on ^{9}Be nuclei in the α-cluster model with dispersion

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Abstract. The polarization observables for the elastic p-^{9}Be scattering at 1 GeV are calculated on the basis of the multiple-diffraction scattering theory and the α-cluster model with dispersion. The ^{9}Be nucleus is considered as composed of two α-clusters and a neutron arranged at the vertices of an isosceles triangle. The results obtained are in agreement with existing experimental data.

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1 Introduction

In the recent few years the interaction of intermediate-energy protons with odd nuclei was intensively investigated. Theoretical analysis of these processes is an important test for studying scattering dynamics, nuclear structure and nucleon-nucleon (NN) interaction. Various approaches were used to describe intermediate-energy proton elastic scattering on spin-$\frac{1}{2}$ polarized nuclei. In [1–5] calculations based on relativistic and nonrelativistic dynamical models were published. In [1] the nonrelativistic impulse approximation with density-dependent NN amplitude was used. In [2–5] calculations of p-^{13}C scattering were performed in the framework of the relativistic impulse approximation and relativistic distorted-wave Born approximation (DWBA). In these calculations the optical potential has been obtained from fitting the p-^{12}C scattering data, and then it was used for making DWBA predictions for p-^{13}C scattering. In [6] the solution of the p-^{13}C Lippmann-Schwinger equation was employed. In these papers quantitative agreement with experimental data was obtained. A good agreement between the calculated and measured observables was obtained in [3] by means of the relativistic DWBA based on Dirac phenomenology.

In [7] the p-^{13}C scattering was analyzed on the basis of the multiple-diffraction scattering theory (MDST) and the independent nucleon model. In these calculations, the NN amplitude with parameters obtained from the phase-shift analysis was used. The results of calculations of the differential cross-section and analyzing power were in agreement with experimental data. Unfortunately, the authors of this paper had no possibility to compare the results of their calculations with experimentally measured observables for the p-^{13}C scattering that appeared later. Such a comparison shows, for example, that the behavior of the analyzing powers for the recoil target nuclei calculated in [7] is not correct.

One of the most intesively studied odd nuclei is the ^{9}Be nucleus. To describe the observables in the elastic p-^{9}Be scattering, the optical model [8–10], macroscopic DWIA [9–11] and the coupled channel approximation [9] were used.

In many light nuclei the α-cluster structure is often manifested. In [12] and [13] the $2\alpha n$ model and MDST with using three-particle wave functions of the ^{9}Be nucleus calculated in [14] were employed to describe the polarization observables in the elastic p-^{9}Be scattering at 220 and 1000 MeV. The results obtained in [12,13] are in agreement with experimental data. In [12,13] the ^{9}Be ground-state wave function was presented as an expansion in Gaussians, and the NN amplitude was taken as a sum of the central and spin-orbital interactions. In [12,13] differential cross-sections and analyzing powers were calculated. However, the nuclear spin dynamics in the interaction of two nonzero-spin nuclei is more variable and intricate than that for scattering of protons on zero-spin nuclei [15]. Therefore, to properly describe the interaction of two nonzero-spin nuclei properly it is necessary to calculate more than one polarization observable.

To describe the polarization observables in the elastic scattering of intermediate-energy protons on even nuclei

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(^{12}C, ^{16}O, ^{20}Ne), the α-cluster model with dispersion has been proposed [16–18]. According to this model the carbon and oxygen nuclei are considered as made up of three and four α-clusters arranged at the vertices of an equilateral triangle and a tetrahedron, respectively. These α-clusters can be displaced from their most probable equilibrium positions. The ^{20}Ne nucleus is considered as composed of the deformed core (^{16}O nucleus) and an additional α-cluster situated with the highest probability inside the core, *i.e.* oscillating around the most probable position of equilibrium in the center of mass of the core.

In this paper the α-cluster model with dispersion is developed for the case of ^{9}Be nuclei. In sect. 2 the model used is described and in sect. 3 the calculations of the p-^{9}Be elastic-scattering observables are presented.

2 Three-particle density of the ^{9}Be nucleus

The ^{9}Be nucleus is one of the most investigated odd nuclei. The three-particle wave functions of the ^{9}Be nucleus in the $2\alpha n$ model with different pair potentials were calculated, for example, in [14]. The ^{9}Be ground-state wave function in [14] was presented as an expansion in Gaussians. In this paper we also suppose the $2\alpha n$ configuration for the ^{9}Be nucleus. We consider the ^{9}Be nucleus as made up of two α-clusters and a neutron arranged with the highest probability at the vertices of an isosceles triangle (boomerang). In this approach the density of the ^{9}Be nucleus can be presented in the form

$$\rho(\boldsymbol{\xi},\boldsymbol{\eta}) = \int \mathrm{d}^3\xi'\mathrm{d}^3\eta'\rho_0(\boldsymbol{\xi}',\boldsymbol{\eta}')\Phi_\Delta(\boldsymbol{\xi}-\boldsymbol{\xi}',\boldsymbol{\eta}-\boldsymbol{\eta}'), \quad (1)$$

where the density $\rho_0(\boldsymbol{\xi},\boldsymbol{\eta})$ and the smearing function $\Phi(\boldsymbol{\xi},\boldsymbol{\eta})$ are

$$\rho_0(\boldsymbol{\xi},\boldsymbol{\eta}) = \frac{1}{8\pi^2 d_1 d_2}\delta(\xi-d_1)\delta(\eta-d_2)\delta(\boldsymbol{\xi\eta}), \quad (2)$$

$$\Phi(\xi,\eta) = \frac{1}{(2\pi\Delta_1\Delta_2)^3}\exp\left(-\frac{\xi^2}{2\Delta_1^2}-\frac{\eta^2}{2\Delta_2^2}\right). \quad (3)$$

In these formulae parameters d_1, d_2 and Δ_1, Δ_2 characterize the distance between the α-clusters, the distance between the neutron and the center of mass of two α-clusters and the probabilities of the α-clusters and neutron displacement from their most probable positions at the vertices of an isosceles triangle, respectively.

The coordinates of the α-clusters, $\mathbf{r}_2$, $\mathbf{r}_3$, and of the neutron, $\mathbf{r}_1$, are related to the Jacobi coordinates $\boldsymbol{\xi}$ and $\boldsymbol{\eta}$ through

$$\mathbf{r}_1 = \frac{8}{9}\boldsymbol{\eta}, \quad \mathbf{r}_2 = -\frac{1}{9}\boldsymbol{\eta}+\frac{1}{2}\boldsymbol{\xi}, \quad \mathbf{r}_3 = -\frac{1}{9}\boldsymbol{\eta}-\frac{1}{2}\boldsymbol{\xi}. \quad (4)$$

The density parameters d_1, d_2 and Δ_1, Δ_2 can be determined from the comparison of the calculated and measured charge form factors of the ^{9}Be nucleus. It is well known that the charge form factor of the neutron is practically equal to zero. Therefore, we present the elastic-scattering charge form factor of the ^{9}Be nucleus in the form

$$F^{\mathrm{Be}}(q) = F_\alpha(q)\int \exp\left(i\mathbf{q}\left(-\frac{1}{9}\boldsymbol{\eta}+\frac{1}{2}\boldsymbol{\xi}\right)\right)\rho(\boldsymbol{\xi},\boldsymbol{\eta})\mathrm{d}^3\xi\,\mathrm{d}^3\eta. \quad (5)$$

In this formula the α-particle form factor $F_\alpha(q)$ has the form

$$F_\alpha(q) = \exp\left(-\frac{1}{6}q^2\langle r^2\rangle_\alpha\right), \quad (6)$$

where $\langle r^2\rangle_\alpha^{1/2} = 1.61\,\mathrm{fm}$ is the root-mean-square radius of the α-cluster, $\mathbf{q}$ is the transferred momentum.

Integrating (5), we have

$$F^{\mathrm{Be}}(q) = \exp\left(-\frac{1}{6}q^2\langle r^2\rangle_\alpha - \frac{1}{8}q^2\Delta_1^2 - \frac{1}{162}q^2\Delta_2^2\right)j_0 \times\left(q\sqrt{\frac{1}{4}d_1^2+\frac{1}{81}d_2^2}\right), \quad (7)$$

where $j_0(x)$ is the spherical Bessel function.

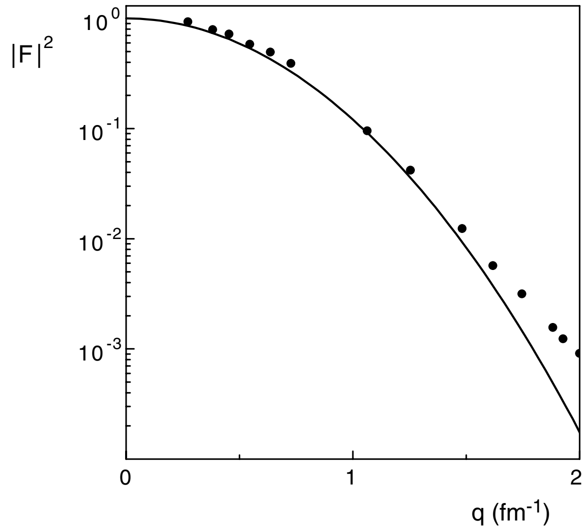

Fig. 1. The ^{9}Be form factor as a function of the momentum transferred. The experimental data are from [19,20].

Figure 1 shows the calculated ^{9}Be elastic-scattering charge form factor together with the experimental data taken from [19,20]. As can be seen from fig. 1, the calculated and measured form factors are in agreement up to the values of transferred momentum $q \le 2\,\mathrm{fm}^{-1}$. The distinctions between the calculated and measured charge form factors in the region of the largest transferred momenta are due to the fact that the quadrupole electrical form factor should be used to describe the existing experimental data.

From the comparison of the calculated and measured form factors we have obtained the following values of the ^{9}Be density parameters: $d_1 = 2.0\,\mathrm{fm}$, $\Delta_1 = 1.892\,\mathrm{fm}$, $d_2 = 1.232\,\mathrm{fm}$, $\Delta_2 = 0.00012\,\mathrm{fm}$.

The root-mean-square radius of the ^{9}Be nucleus is determined by

$$\langle r^2\rangle_{\mathrm{Be}} = \langle r^2\rangle_\alpha + \frac{1}{4}d_1^2 + \frac{3}{4}\Delta_1^2 + \frac{1}{81}d_2^2 + \frac{1}{27}\Delta_2^2. \quad (8)$$

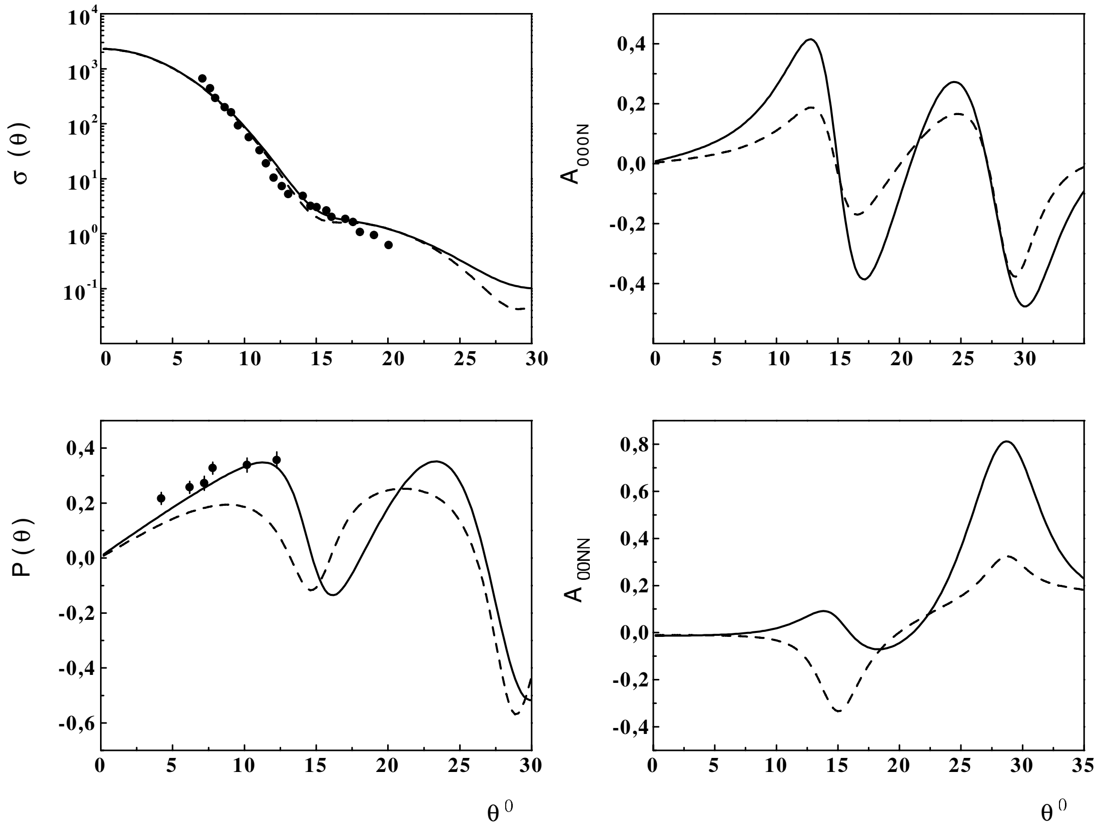

Fig. 2. Differential cross-section $\sigma(\theta)$, polarization $P(\theta)$, target analyzing power $A_{000\mathrm{N}}(\theta)$ and spin correlation parameter $A_{00\mathrm{NN}}(\theta)$ of the elastic p-^{9}Be scattering at 1 GeV as functions of the scattering angle. Experimental data are from [26,27].

The obtained values of density parameters d_1, d_2 and Δ_1, Δ_2 for the ^{9}Be nucleus yield the root-mean-square radius $\langle r^2\rangle^{1/2}_{\mathrm{Be}} = 2.509\,\mathrm{fm}$, which is in agreement with the experimentally measured value [21] $\langle r^2\rangle^{1/2}_{\mathrm{Be\,exp}} = 2.519\,\mathrm{fm}$.

3 Scattering of protons on ^{9}Be nuclei

According to MDST, the p-^{9}Be elastic-scattering amplitude has the form

$$T^{\mathrm{Be}}(\mathbf{q}) = \frac{ik}{2\pi}\int \mathrm{d}^2b\,\mathrm{d}^3\xi\,\mathrm{d}^3\eta e^{i\mathbf{qb}}\rho^{(^9\mathrm{Be})}(\boldsymbol{\xi},\boldsymbol{\eta})\Omega(\mathbf{b},\mathbf{r}_j), \quad (9)$$

$$\Omega(\mathbf{b},\mathbf{r}_j) = 1 - \prod_{j=1}^{3}\left[1 - \frac{1}{2\pi ik}\int \mathrm{d}^2q e^{-i\mathbf{q}(\mathbf{b}-\mathbf{r}_j)}\tilde{f}(\mathbf{q})\right], \quad (10)$$

where $\mathbf{b}$ is the impact parameter, $\mathbf{r}_j$ are the cluster coordinates of the ^{9}Be nucleus, $\mathbf{k}$ is the wave vector of the incident proton, $\tilde{f}(\mathbf{q}) = f_{\mathrm{NN}}(q)$, $f_{\mathrm{p}\alpha}(\mathbf{q})$ are the "elementary" proton elastic-scattering amplitudes on the clusters of the ^{9}Be nucleus. Notice that in this approach we also consider the neutron as a cluster.

In the general case, the NN amplitude $f_{\mathrm{NN}}(q)$ is an operator in the spin-isospin space. The amplitude $f_{\mathrm{NN}}(q)$ can be written in the most general form as

$$f_{\mathrm{NN}}(q) = f_1(\mathbf{q}) + qf_2(\mathbf{q})(\boldsymbol{\sigma}_0\mathbf{n}+\boldsymbol{\sigma}_1\mathbf{n}) + f_3(\mathbf{q})(\boldsymbol{\sigma}_0\boldsymbol{\sigma}_1) + f_4(\mathbf{q})(\boldsymbol{\sigma}_0\mathbf{q})(\boldsymbol{\sigma}_1\mathbf{q}) + f_5(\mathbf{q})(\boldsymbol{\sigma}_0\mathbf{p})(\boldsymbol{\sigma}_1\mathbf{p}), \quad (11)$$

where $\boldsymbol{\sigma}_0$ and $\boldsymbol{\sigma}_1$ are the spin operators of the incident proton and additional neutron of the target nucleus, $\mathbf{n} = [\mathbf{k},\mathbf{k}']/|[\mathbf{k},\mathbf{k}']|$, $\mathbf{q} = \mathbf{k}-\mathbf{k}'$, $\mathbf{p} = (\mathbf{k}+\mathbf{k}')/(|\mathbf{k}+\mathbf{k}'|)$, $\mathbf{k}$ and $\mathbf{k}'$ are the wave vectors of the incident and scattered protons. The vectors $\mathbf{n}$, $\mathbf{p}$ and $-\mathbf{q}$ form the right-hand orthogonal coordinate system. Neglecting the isospin part of the NN interaction we choose the amplitudes $f_i(\mathbf{q})$ in the form

$$f_i(\mathbf{q}) = kH_i\exp(-\gamma_i q^2), \quad 1 \le i \le 5. \quad (12)$$

The numerical values of parameters H_i, γ_i obtained from the solutions of the phase-shift analysis are presented in [7].

The elementary proton-α amplitude can be chosen in the form [17]

$$f_{\mathrm{p}\alpha}(\mathbf{q}) = k\sum_{i=1}^{2}\big(G_{ci}\exp(-\beta_{ci}q^2) + qG_{si}\exp(-\beta_{si}q^2)(\boldsymbol{\sigma}_0\mathbf{n})\big). \quad (13)$$

The parameters G_{c1}, β_{c1}, G_{s1} and β_{s1} are the fitting ones, and the parameters G_{c2}, β_{c2}, G_{s1} and β_{s1} are related with G_{c1}, β_{c1}, G_{s1} and β_{s1} through [17]

$$G_{c2} = \frac{3iG_{c1}^2}{32\beta_{c1}}, \qquad \beta_{c2} = \frac{1}{2}\beta_{c1}, \quad (14)$$

$$G_{s2} = \frac{3iG_{c1}G_{s1}\beta_{c1}}{8(\beta_{c1}+\beta_{s1})^2}, \qquad \beta_{s2} = \frac{\beta_{c1}\beta_{s1}}{\beta_{c1}+\beta_{s1}}. \quad (15)$$

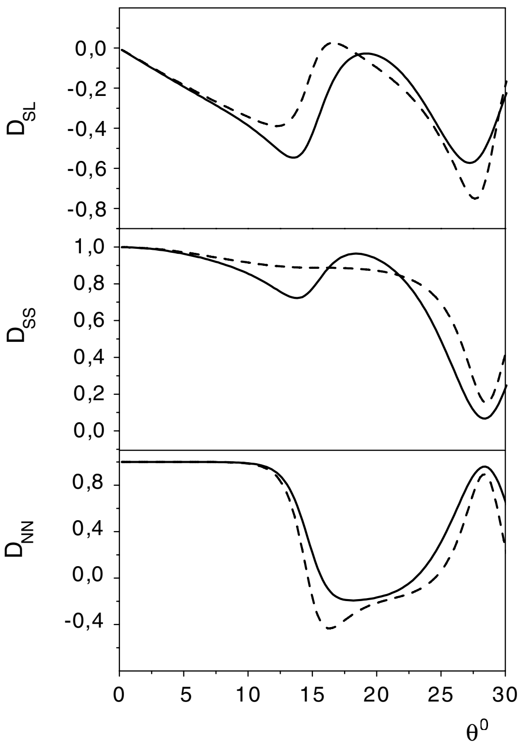

Fig. 3. Spin-rotation-depolarization parameters $D_{LS}(\theta)$, $D_{SS}(\theta)$ and $D_{\rm NN}(\theta)$ of the elastic p-^{9}Be scattering at 1 GeV as functions of the scattering angle.

The values of the parameters G_{c1}, β_{c1}, G_{s1} and β_{s1} obtained from the comparison of the calculated and measured [22] elastic p-^{4}He scattering observables at 1 GeV are: $G_{c1} = 0.336 + i1.277\,({\rm fm}^2)$, $\beta_{c1} = 0.435 - i0.029\,({\rm fm}^2)$, $G_{s1} = 0.179 + i0.215\,({\rm fm}^3)$ and $\beta_{s1} = 0.476 + i0.013\,({\rm fm}^2)$.

Substituting (11)–(14) into (10) and integrating (10) over variables, we can present the amplitude $T^{\rm Be}(\mathbf{q})$ in the form

$$T^{\rm Be}(\mathbf{q}) = A + E(\boldsymbol{\sigma}_0\mathbf{n}) + F(\boldsymbol{\sigma}_1\mathbf{n}) + B(\boldsymbol{\sigma}_0\mathbf{n})(\boldsymbol{\sigma}_1\mathbf{n}) + C(\boldsymbol{\sigma}_0\mathbf{q})(\boldsymbol{\sigma}_1\mathbf{q}) + D(\boldsymbol{\sigma}_0\mathbf{p})(\boldsymbol{\sigma}_1\mathbf{p}) \quad (16)$$

A complete description of the elastic proton scattering on a zero-spin nucleus requires the measurement of three independent observables as functions of the scattering angle [23]. To describe the elastic scattering of two spin-$\frac{1}{2}$ particles in the intermediate-energy region, it is necessary to measure eleven independent observables [7]. The ^{9}Be nucleus in the ground state has the spin $I = \frac{3}{2}^-$. Therefore, the number of independent observables that form the complete set must essentially increase.

Unfortunately, at present the complete experimental data concerning the elastic scattering of protons on odd nuclei are absent. Relatively more complete experimental data for these processes exist for the elastic p-^{13}C scattering at 500 MeV [3,24,25]. In these papers the measured differential cross-section $\sigma(\theta) \equiv \frac{{\rm d}\sigma}{{\rm d}\Omega}$ (mb/sr), polarization (asymmetry) $P(\theta)$, spin-rotation-depolarization parameters $D_{LS}(\theta)$, $D_{SS}(\theta)$, $D_{\rm NN}(\theta)$, target nucleus analyzing power $A_{000\rm N}(\theta)$ and spin correlation $A_{00\rm NN}(\theta)$ are presented.

In this paper we have calculated only these seven observables. The definitions of these observables are given in [23]. In the calculations we have used the p-α amplitude parameters determined in the present paper and the parameters of nucleon-nucleon amplitude determined in [7] at 800 MeV. The results of calculations of the observables for the 1 GeV proton elastic scattering by ^{9}Be nuclei along with the experimental data from [26,27] are presented in figs. 2, 3 (dashed curves). As can be seen from figs. 2, 3, the calculated differential cross-section is in agreement with the experimental data, and the analyzing power (polarization) is in quantitative agreement with the existing data.

4 Discussion

In the model proposed the ^{9}Be nucleus is considered as an isosceles triangle (boomerang) formed by two α-clusters and an additional neutron. For this nucleus it is an unusual enough configuration. However, it is well known that the same configurations exist in molecules. For example, the molecules of water (H_2O) and ozone (O_3) have the form of a boomerang [28]. In [29] the structure of odd-even isotopes of Li and Be nuclei was studied systematically with antisymmetrized molecular dynamics. It was shown that clear evidence of an isosceles triangle strucrure is observed in the density of ^{9}Be nuclei. It is difficult to explain the reasons why Nature chooses these configurations for stable states of some simple quantum systems. The results obtained allow us to conclude that this configuration is presented with a great probability in the wave function of the ^{9}Be nucleus.

As has been mentioned above, the polarization observables can give more information about the structure of target nuclei and mechanisms of nuclear reactions as compared with the total, reaction or even differential cross-sections. For example, analyzing power (polarization) can be used to determine the imaginary part of spin-orbital nucleon-nucleus amplitude [23]. To describe the existing data (see the solid curves in figs. 2, 3) we have changed the imaginary part of spin-orbital NN amplitude (from ${\rm Im}\,H_2 = -4.51\ ({\rm GeV}/c)^{-3}$ in [7] to ${\rm Im}\,H_2 = -10.51\ ({\rm GeV}/c)^{-3}$ in the present paper). As can be seen from figs. 2, 3 (the solid curves), the behavior of the calculated observables for the elastic p-^{9}Be scattering is similar to that for the p-^{13}C scattering. Moreover, the behavior of the spin correlation parameters $A_{00\rm NN}$ calculated with and without changing the imaginary part of spin-orbital NN amplitude differs significantly.

Therefore, we conclude that the assumption about the model in which the ^{9}Be nucleus is considered as made up of two α-clusters and neutron arranged at the vertices of isosceles triangle allows us to agree the calculated and measured charge form factors up to the values of transferred momentum $q \leq 2\,{\rm fm}^{-1}$, root-mean-square radii of the ^{9}Be nucleus and observables in the elastic 1 GeV proton scattering on these nuclei. Experimental measurements of the maximally possible number of independent observables in maximally wide angular range could serve as a more critical verification of the models which describe nucleon-nucleus interactions and it would provide more information about the nuclear structure and nature of the nuclear forces.

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