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DINEUTRON CONFIGURATIONS IN NEUTRON-RICH EXOTIC NUCLEI

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The analysis, carried out in the framework of the diffractive approach, of a number of experiments on interaction of the neutron-rich exotic nuclei ^6He and ^{11}Li with nuclei allows one to make the conclusion about the presence of a dineutron configuration (dineutron) in ^6He and the absence of that in ^{11}Li.

1. During the last years, exotic unstable nuclei, overloaded with neutrons [1 - 11], are intensively studied both experimentally and theoretically hopefully to obtain the new information on structure of such nuclei and, in particular, about the possible existence in them of dineutron configurations (dineutron). Obtaining in a number of nuclear centres of beams of unstable neutron-rich nuclei and investigating their interaction with various nuclear targets facilitate this first of all.

At present, there are no reliable data on the existence of dineutrons in neutron halo nuclei. Therefore, there is a great deal of interest in the theoretical analysis of the performed experiments on the interaction of beams of neutron-rich nuclei with various nuclei. In this study, on the basis of diffractive nuclear model the analysis of results of experimental works [9, 10] on the interaction with nuclear targets of the incident exotic nuclei ^6He and ^{11}Li, having considerable neutron halo, is made for the purpose to obtain the conclusions about an opportunity of the presence or the absence of dineutron configurations in the nuclei ^6He and ^{11}Li.

In refs. [9, 10] the integrated total cross section of all reactions σ_R and the cross section σ_{-2n} for removal of two neutrons from ^6He and ^{11}Li were measured. We treat the nuclei ^6He and ^{11}Li within the two-cluster model ($^6He \to 2n + {}^4He$, $^{11}Li \to 2n + {}^9Li$), and the first cluster in each of these two nuclei is considered as supposed dineutron (2n), the interaction range R_1 of which with the nuclear target differs from the interaction range R_2 with the same nuclear target of the second clusters (^4He and ^9Li) of the projectiles.

Further we use the model of strongly absorbing (black) target nucleus, so the profile function $\omega_j(\rho)$ for the $j-$ th cluster of the incident nucleus ($j = 1,2$) takes the form

$$\omega_j(\rho) = \begin{cases} 1, & \rho \le R_j, \\ 0, & \rho > R_j, \end{cases} \tag{1}$$

where ρ is the impact parameter, and

$$R_j = r_0 (A_j^{1/3} + A^{1/3}) \tag{2}$$

is the range of interaction between the $j-$th cluster, consisting of A_j nucleons and a target nucleus with the mass number A.

2. We shall write down, first of all, in the diffractive approximation the formula for each of mentioned above integrated cross sections σ_R and σ_{-2n}, measuring in experiments. These sections can be divided into the nuclear (N) and the Coulomb (C) parts:

$$\sigma_R = \sigma_R^N + \sigma_R^C, \qquad \sigma_{-2n} = \sigma_{-2n}^N + \sigma_{-2n}^C \tag{3}$$

The nuclear part of the total cross section for all possible reactions σ_R^N is equal to the sum of the integrated cross sections for all inelastic processes in the considered two-cluster diffractive model, namely, the cross section σ_d^N for diffractive dissociation of the projectile into two clusters, one of which is a dineutron (2n), the stripping cross section of dineutron with its absorption by target nucleus $\sigma_S^{(1)} = \sigma_S^{(2n)}$ and the second cluster with its absorption $\sigma_S^{(2)}$, and the absorption cross section of the whole incident nucleus σ_a. The cross section σ_R^N can be also written down as the difference between the total cross section of all processes σ_t and the integrated cross section for elastic scattering of the incident nucleus σ_e. Thus, it is possible to present the cross section σ_R^N in the following way

$$\sigma_R^N = \sigma_t - 2\pi \int_0^\infty dqq \cdot \left| \frac{R_1 J_1(qR_1)}{q} \cdot \Phi(-\beta_2 q) + \frac{R_2 J_1(qR_2)}{q} \cdot \Phi(\beta_1 q) - \right.$$

$$\left. - \frac{R_1 R_2}{2\pi} \cdot \int d^{(2)}\vec{q}\,' \cdot \Phi(q') \cdot \frac{J_1(|\beta_1\vec{q} - \vec{q}\,'|R_1)}{|\beta_1\vec{q} - \vec{q}\,'|} \cdot \frac{J_1(|\beta_2\vec{q} + \vec{q}\,'|R_2)}{|\beta_2\vec{q} + \vec{q}\,'|} \right|^2, \tag{4}$$

$$\sigma_t = 2\pi \cdot (R_1^2 + R_2^2) - 4\pi R_1 R_2 \cdot \int_0^\infty \frac{dq}{q} \cdot \Phi(q) J_1(qR_1) J_1(qR_2), \tag{5}$$

where $\Phi(q)$ is the structural form factor of the incident nucleus

$$\Phi(q) = \int d\vec{r} \cdot \exp(-i\vec{q}\vec{r}) \cdot \varphi^2(r), \qquad \Phi(0) = 1 \tag{6}$$

$\varphi(r)$ is the projectile wave function of the bound state for the relative motion of two clusters, $\beta_1 = 1 - \beta_2 = \dfrac{M_1}{M_1 + M_2}$, M_1 and M_2 are the masses of clusters.

The nuclear part of the cross section of the first cluster (dineutron) removal from an incident nucleus is equal to $\sigma_{-2n}^N = \sigma_d^N + \sigma_S^{(1)} = \sigma_R^N - (\sigma_a + \sigma_S^{(2)})$, where for a black target nucleus

$$\sigma_S^{(j)} = \pi R_j^2 - 2\pi R_1 R_2 \cdot \int_0^\infty \frac{dq}{q} \cdot \Phi(q) J_1(qR_1) J_1(qR_2) =$$

$$= \frac{1}{2}\sigma_t - \pi(R_1^2 + R_2^2 - R_j^2), \; j = 1,2. \tag{7}$$

In this case $\sigma_a = \frac{1}{2}\sigma_t - \sigma_S^{(1)} - \sigma_S^{(2)}$, so for the cross section σ_{-2n}^N we have

$$\sigma_{-2n}^N = \sigma_R^N - (\frac{1}{2}\sigma_t - \sigma_S^{(1)}) = \sigma_R^N - \pi R_2^2. \tag{8}$$

The Coulomb part σ_R^C of the total reaction cross section σ_R is equal, obviously, to the Coulomb part σ_{-2n}^C of the two neutron (2n) removal cross section σ_{-2n}, and both these parts are equal to the sum of the integrated cross section for the Coulomb dissociation of the incident nucleus into two fragment-clusters σ_d^C and the additional term σ_{int}, connected with the interference between the Coulomb and nuclear processes of dissociation. Taking into account the first cluster (dineutron) is not charged, we get

$$\sigma_R^C = \sigma_{-2n}^C = \sigma_d^C + \sigma_{\text{int}} =$$

$$= \sigma_d^C - 8\pi n \cdot \int_0^\infty \frac{dq}{q^2} \cdot \Big\{ R_2 J_1(qR_2) \cdot \left[1 - \Phi^2(\beta_1 q)\right] + R_1 J_1(qR_1) \cdot \left[\Phi(q) - \Phi(\beta_1 q)\Phi(\beta_2 q)\right] -$$

$$- \frac{qR_1R_2}{2\pi} \cdot \int d^{(2)}\vec{q}\,' \frac{J_1(|\beta_1\vec{q} - \vec{q}\,'|R_1)}{|\beta_1\vec{q} - \vec{q}\,'|} \cdot \frac{J_1(|\beta_2\vec{q} + \vec{q}\,'|R_2)}{|\beta_2\vec{q} + \vec{q}\,'|} \cdot \left[\Phi(|\beta_1\vec{q} - \vec{q}\,'|) - \Phi(q')\Phi(\beta_1 q)\right]\Big\} \times$$

$$\times \operatorname{Im}\left[\left(\frac{2}{qR_2}\right)^{2in} \cdot \frac{\Gamma(1+in)}{\Gamma(1-in)} - qR_2 \cdot \int_0^1 d\varsigma \cdot J_1(qR_2\varsigma)\varsigma^{2in}\right], \tag{9}$$

$$\sigma_d^C = 8\pi n^2 R_2^2 \cdot \int_{q_{\min}}^\infty \frac{dq}{q} \cdot \left[1 - \Phi^2(\beta_1 q)\right] \cdot \left|\int_1^\infty d\varsigma \cdot J_1(qR_2\varsigma)\varsigma^{2in}\right|^2, \tag{10}$$

where $n = \dfrac{Z'Ze^2}{\hbar v}$; v is the relative velocity of the projectile with the charge $Z'e$ and the target nucleus with the charge Ze, $q_{\min} = \dfrac{\varepsilon}{\hbar v}\left(1 - \dfrac{v^2}{c^2}\right)^{1/2} \cdot \max(1, 4n)$ is the minimal momentum transfer [12,13], ε is the separation energy of dineutron from the projectile. According to (3), the sum of the cross sections (4) and (9) gives the cross section σ_R, and the sum (8) and (9) gives the cross section σ_{-2n}. At specific calculations of the cross sections, as the wave function of the bound state for the relative motion of two cluster system n the projectile the Hulthen wave function $\varphi(r)$ was used

$$\varphi(r) = \sqrt{\frac{\alpha\beta(\alpha+\beta)}{2\pi(\beta-\alpha)^2}} \cdot \frac{\exp(-\alpha r) - \exp(-\beta r)}{r}, \quad \alpha = \sqrt{\frac{2M_1M_2\varepsilon}{\hbar^2(M_1 + M_2)}}. \tag{11}$$

In our model the nuclear parts of the cross sections σ_R^N and σ_{-2n}^N, as it is seen from the formulas, do not depend on the projectile energy E, however, the Coulomb part of σ_R^C and σ_{-2n}^C depend on E through n and $q_{\min}$, so the cross sections σ_R and σ_{-2n} will also depend on E. In the corresponding experiments [9, 10] the cross sections σ_R and σ_{-2n} were measured as the energy-averaged values in several finite intervals $\Delta E_k = E_2^k - E_1^k$ of the energy E ÌeV/nucleon, where E_1^k and E_2^k are the minimal and maximal energies for each interval of energy ($k = 1, 2 \ldots$).

According to this, the theoretical values for the cross sections σ_R and σ_{-2n} were calculated for the average values of energy, equal $\overline{E}_k = \frac{1}{2}(E_1^k + E_2^k)$ ÌeV/nucleon.

3. Let us first consider the results of our calculations of the cross sections σ_R and σ_{-2n} for the incident nucleus ^6He and analysis of the corresponding experiments [9, 10] for the ^6He interaction with the nuclei ^{28}Si in the energy range E from 13,7 to 55,6 ÌeV/nucleon. The binding energy of the nucleus ^6He with respect to its dissociation into two clusters, (2n) and α - particle, according to [14], is equal to $\varepsilon = 0{,}975 \pm 0{,}040$ ÌeV, and the parameter β in (11) is assumed to be equal $\beta = 7\alpha \approx 1{,}75\ \text{fm}^{-1}$. The parameter r_0 in (2) is taken to be equal $r_0 = 1{,}3$ fm.

In Table 1 the calculated cross sections σ_R and σ_{-2n} and the corresponding experimental cross sections $\sigma_R^{\exp}$ and $\sigma_{-2n}^{\exp}$ with errors (all in barns) are given for four average values of energy $E = \overline{E}_k$ in ÌeV/nucleon ($k = 1 \div 4$). Extreme values of energies E_1^k and E_2^k in ÌeV/nucleon for each of four energy intervals are shown together with $\overline{E}_k$. It is seen, that within experimental errors the observable cross sections $\sigma_R^{\exp}$ and $\sigma_{-2n}^{\exp}$ simultaneously are well described theoretically using the two-cluster (dineutron) model for ^6He with the common set of parameters, that is the weighty argument in favor of the existence of a dineutron in the ground state ^6He.

Table 1. **Comparison of the integrated cross sections σ_R and σ_{-2n}, calculated within the dineutron model for ^6He, with the experimental data for this nucleus [9, 10]**

k	E_1^k	E_2^k	$\overline{E}_k$	σ_R	$\sigma_R^{\exp}$	σ_{-2n}	$\sigma_{-2n}^{\exp}$
1	13,7	29,0	21,35	1,63	1.59 ±0.06	0.49	0.47 ±0.06
2	29,0	39,5	34,25	1,60	1,62 ± 0.06	0,46	0,47 ±0,05
3	39,5	48,1	43,80	1,58	1,54 ± 0,06	0,44	0,40 ±0,04
4	48,1	55,6	51,85	1,57	1,67 ± 0,10	0,43	0,35 ±0,15

The confirmation of this conclusion is also the analysis performed within the same model of the cross section $\sigma_{-2n}^{\exp} = 0{,}189 \pm 0{,}014$ b measured in [15] for the two neutron (2n) removal from ^6He in collision with the nucleus ^{12}C already at relativistic energy $E = 800$ ÌeV/nucleon. The calculated cross section $\sigma_{-2n} = 0{,}196$ b is in a good agreement with the experimental one. The relativistic effects, leading to the noticeable reduction of the linear sizes of nuclear interaction range in the direction of the projectile motion, are qualitatively taken into account. In this connection, the calculations were carried out at $r_0 = 1{,}15$ fm in (2) and $\beta = \infty$ in (11), that corresponds to the assumption of zero-range ($\beta^{-1} = 0$) nuclear forces between two clusters in ^6He.

The similar analysis of experiments [9] on measurement of the cross sections σ_R and σ_{-2n} on ^{28}Si of the neutron-rich nuclei ^{11}Li with the energy E from 22,7 to 57,1 ÌeV/nucleon was carried out as well. The cross sections $\sigma_R^{\exp}$ and $\sigma_{-2n}^{\exp}$ in [9] were measured in three finite intervals of the energy E ($k = 1 \div 3$). According to this, the calculations of the cross sections were performed for three average values of the energy $E = \overline{E}_k = \frac{1}{2}(E_1^k + E_2^k)$ using the value of the binding energy $\varepsilon = 0{,}25 \pm 0{,}08$ ÌeV for two clusters ($2n$ and ^9Li) in ^{11}Li [16, 17]. All corresponding data (the cross sections in barns, energies in ÌeV/nucleon) are presented in Table 2 for $\varepsilon = 0{,}25$ ÌeV, $r_0 = 1{,}3$ fm, $\beta = \infty$ (1-st row) and $\beta = 7\alpha$ (2-nd row). At such values of parameters the calculated values of the cross sections σ_R are the most close to $\sigma_R^{\exp}$.

Table 2. **The integrated cross sections σ_R and σ_{-2n}, calculated within the dineutron model for ^{11}Li, with the experimental data [9] for this nucleus**

k	E_1^k	E_2^k	$\overline{E}_k$	σ_R	$\sigma_R^{\exp}$	σ_{-2n}	$\sigma_{-2n}^{\exp}$
1	22,7	37,1	29,9	2,14 2,45	2,55 ±0,10	0,74 1,06	0,47 ±0.04
2	37,1	47,9	42,5	2,06 2,34	2,37 ± 0,10	0,67 0,95	0,39 ± 0.04
3	47,9	57,1	52,5	2,02 2,28	1,97 ± 0.10	0,63 0,89	0,38 ± 0,06

Thus, as it is seen from Table 2, the agreement between the calculated cross section σ_{-2n} and experimental one $\sigma_{-2n}^{\exp}$ is not reached at any of three values of the energy $E = \overline{E}_k$ (the difference in value almost twice).The variation of the parameters r_0, ε and β within reasonable limits (from $\beta \approx \alpha$ to $\beta = \infty$) does not improve the general picture of deviations of the calculated cross sections σ_R and σ_{-2n} from observable ones in comparison to the data of Table 2.

Thus, it is not possible to describe simultaneously the observable cross sections $\sigma_R^{\exp}$ and $\sigma_{-2n}^{\exp}$ in the framework of the two-cluster dineutron model of ^{11}Li that testifies, apparently, against of dineutron configuration (dineutron) in ^{11}Li.

Our conclusions about the structure of neutron halo in the nuclei ^6He and ^{11}Li agree with results of a number of both experimental and theoretical works, carried out recently on the theme in question [3, 4, 6, 7, 11].

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ДИНЕЙТРОННІ КОНФІГУРАЦІЇ У НЕЙТРОНОНАДЛИШКОВИХ ЕКЗОТИЧНИХ ЯДРАХ

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Виконаний у рамках дифракційного підходу аналіз ряду експериментів із взаємодії падаючих ядер ^{6}He і ^{11}Li з атомними ядрами дозволяє зробити висновок щодо наявності динейтронної конфігурації (динейтрона) в ядрі ^{6}He і її відсутності в ядрі ^{11}Li.

ДИНЕЙТРОННЫЕ КОНФИГУРАЦИИ В НЕЙТРОННОИЗБЫТОЧНЫХ ЭКЗОТИЧЕСКИХ ЯДРАХ

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Выполненный в рамках дифракционного подхода анализ ряда экспериментов по взаимодействию падающих ядер ^{6}He и ^{11}Li с атомными ядрами позволяет сделать вывод о наличии динейтронной конфигурации (динейтрона) в ядре ^{6}He и отсутствии таковой в ядре ^{11}Li.