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Abstract

The Binary Cluster Model (BCM) has been employed with the single particle harmonic oscillator and Gaussian wave functions to study the ground state density distributions and the elastic form factors of proton rich ^8B and ^{17}Ne halo nuclei. The Glauber model with an optical limit approximation has been used to study the reaction cross sections for these nuclei in the low and high energy regions. The calculated results of reaction cross sections of these nuclei at both low and high energy give good agreement with experimental data.

Keywords: Reaction cross sections, Glauber model, Proton-rich halo nuclei, Binary Cluster Model.

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المقاطع العرضية للتفاعل وتوزيعات الكثافة لنوى الهالة ^8B و ^{17}Ne

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الخلاصة

تم استخدام الأنموذج العنقودي الثنائي مع الدوال الموجية للجسيمة المفردة لجهد المتذبذب التوافقي وجهد جاوس لدراسة توزيعات الكثافة للحالة الأرضية وعوامل التشكل المرنة لنوى الهالة الغنية بالبروتونات ^8B و ^{17}Ne . تم استخدام نموذج جلوبر لدراسة المقاطع العرضية للتفاعل لهذه النوى عند الطاقات الواطئة و العالية. ان حسابات المقاطع العرضية للتفاعل لهذه النوى عند الطاقات الواطئة و العالية تعطي تطابق جيد مع القيم العملية.

الكلمات المفتاحية: المقاطع العرضية للتفاعل، نموذج جلوبر، نوى الهالة الغنية بالبروتونات، الانموذج العنقودي الثنائي.

Introduction

The development of the experiments using radioactive nuclear beams allowed us to study nuclei far from the valley of stability [1 and 2], which led to the discovery of halo phenomena. Halo phenomena is a quantum effect explained as a result of the combined impact of small binding energy of the valence particle(s) and their low angular momentum ($l = 0, 1$) [3].

The experiments with exotic (halo) nuclei are challenging because of the specific techniques required due to the low intensity with which the nuclei are produced and their short lifetime. It is impossible to make a target of short-lived nuclei; therefore, the experiments must be performed in inverse kinematics. In this case a beam of radioactive nuclei is produced and it interacts with a stable target [4].

One of the most important variables characterizing the features of nuclear reaction is the reaction cross section. It is can provide us fundamental information such as the nuclear

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structure, the size of nucleus and nucleon density distribution of nucleus. Glauber model is one of the widely used models to study the reaction and interaction cross sections of nucleus-nucleus scattering [5].

The proton-rich ^8B nucleus has been received much attention from both experimental and theoretical points of view. ^8B is the most likely candidate for having a proton halo structure due to the small proton separation energy of 0.138 MeV.

Although the existence of the centrifugal and Coulomb barriers, ^8B nucleus is assumed to be a proton halo nucleus at present. Several experiments through measurements of the interaction (reaction) cross section have been used to deduce the matter root mean square (rms) radius of ^8B [6-11]. Korolev *et al.* [12] have measured the absolute differential cross section of small-angle proton elastic scattering on the proton drip-line ^8B nucleus in inverse kinematics for the first time.

The only nucleus has a two-proton halo structure in the sd-shell region is ^{17}Ne , although the neutron halo structure is found in many nuclei. Oishi *et al.* [13] have used the three-body model along with Woods-Saxon potential to study the ground state properties of ^{17}Ne . Tanaka *et al.* [14] have used the transmission method to measure the reaction cross sections (σ_R) for the proton rich ^{17}Ne nucleus on ^9Be , ^{12}C , and ^{27}Al targets at 64 and 42 MeV / nucleon.

The density distribution of ^{17}Ne was deduced from the energy dependence of the σ_R using Glauber model. Abdullah [15] has used the few-body model of core + valence nucleon (s) along with Woods-Saxon potential to study the ground state properties of ^8B and ^{17}Ne .

In the present work, the Binary Cluster Model (BCM) will adopt with the single particle harmonic oscillator and Gaussian wave functions to study the ground state densities and the elastic form factors of proton rich ^8B and ^{17}Ne halo nuclei. The Glauber model with an optical limit approximation will be used to study the reaction cross sections for these nuclei at low and high energy regions.

Theory

In the case of halo nuclei, it is reasonable to parameterize the core and halo densities separately. In BCM [16], the halo nuclei are considered as composite projectiles of mass A_p and described, in figure 1, as core and valence clusters, of masses A_c and A_v bounded with a state of relative motion. It is assumed that $A_c \geq A_v$. The matter density of the composite projectile is given by [17]:

$$\rho_m(r) = \rho_c(r) + \rho_v(r), \quad (1)$$

where $\rho_c(r)$ and $\rho_v(r)$ are the core and valence (halo) densities, respectively.

In this study, we have used two methods to study the ground state densities of halo nuclei, these are HO + HO (Harmonic Oscillator- Harmonic Oscillator) and G + G (Gaussian – Gaussian). In the HO + HO method, the core and valence densities are given by the harmonic oscillator wave functions as [18].

$$\rho_c(r) = \frac{1}{4\pi} \sum_{n\ell} X_c^{n\ell} |R_{n\ell}(r, \hat{b}_c)|^2 \quad (2)$$

$$\rho_v(r) = \frac{1}{4\pi} \sum_{n\ell} X_v^{n\ell} |R_{n\ell}(r, \hat{b}_v)|^2 \quad (3)$$

Whereas in the G + G method, the core and valence densities are given by the Gaussian wave functions as [16]

$$\rho_m(r) = A_c g^{(3)}(\hat{\alpha}_c, r) + A_v g^{(3)}(\hat{\alpha}_v, r) \quad (4)$$

Where $g^{(3)}$ is the normalized 3-dimensional Gaussian function

$$g^{(3)}(\hat{\alpha}_{c(v)}, r) = \frac{1}{\pi^{3/2} \hat{\alpha}_{c(v)}^3} e^{-r^2/\hat{\alpha}_{c(v)}^2}, \quad \int g^{(3)}(\alpha_{c(v)}, r) d\vec{r} = 1 \quad (5)$$

The size parameters of the harmonic oscillator $(\hat{b}_c^2, \hat{b}_v^2)$ and Gaussian $(\hat{\alpha}_c^2, \hat{\alpha}_v^2)$ wave functions are given by [16,17]:

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$$\hat{g}_c^2 = g_c^2 + \left(\frac{A_v g}{A_v + A_c}\right)^2, \quad \hat{g}_v^2 = g_v^2 + \left(\frac{A_c g}{A_v + A_c}\right)^2, \quad g \equiv \alpha, b \quad (6)$$

The matter density of Eq. (1) can be written as [19]:

$$\rho_m(r) = \rho^n(r) + \rho^p(r) \quad (7)$$

Where $\rho^n(r)$ and $\rho^p(r)$ are the neutron and proton densities, respectively written as [19]:

$$\rho^n(r) = \rho_c^n(r) + \rho_v^n(r) \quad (8)$$

and

$$\rho^p(r) = \rho_c^p(r) + \rho_v^p(r) \quad (9)$$

Figure 1: The coordinates of the target and two-cluster projectile [16]

The elastic form factors for considered nuclei are studied by the plane wave Born approximation (PWBA) within the proton density distribution obtained by HO + HO method. In the PWBA, the elastic form factors are written as [20]:

$$F(q) = \frac{4\pi}{Z} \int_0^\infty \rho_p(r) j_0(qr) r^2 dr \quad (10)$$

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Where $j_0(qr)$ is the zero-order spherical Bessel function and q is the momentum transfer from the incident electron to the target nucleus. Inclusion the corrections of the finite nucleon size $F_{fs}(q) = \exp(-0.43q^2/4)$ and the center of mass $F_{cm}(q) = \exp(b^2q^2/4A)$ in the calculations needs multiplying the form factor of Eq. (10) by these corrections.

The reaction cross section of considered nuclei is studied by the Glauber model within an optical limit (OL) approximation which can be expressed as [21]:

$$\sigma_R = 2\pi \int [1 - T(b)] b db \left(1 - \frac{B_c}{E_{cm}}\right) \quad (11)$$

Where E_{cm} is the kinetic energy in the center of mass system, B_c is Coulomb barrier and $T(b)$ is the transparency function at impact parameter b .

In the optical limit (OL) approximation the $T(b)$ is written as [16]

$$T(b) = |S_{el}^{OL}(b)|^2 \quad (12)$$

Where $S_{el}^{OL}(b)$ is the elastic S -matrix for the target-projectile system given as [16]:

$$S_{el}^{OL}(b) = \exp[iO_{PT}(b)] \quad (13)$$

$$O_{PT}(b) = \int_{-\infty}^{\infty} d\vec{R}_3 \int d\vec{r}_1 \int d\vec{r}_2 \rho_P(r_1) \rho_T(r_2) f_{NN}(|\vec{R} + \vec{r}_1 - \vec{r}_2|) \quad (14)$$

is the overlap of the ground state densities of projectile and target (ρ_P and ρ_T , respectively)

Results and discussion

The BCM has been employed with the harmonic oscillator and Gaussian wave functions to study the ground state neutron, proton and matter densities and the elastic charge form factors of proton rich ^8B and ^{17}Ne halo nuclei. The Glauber model with an optical limit approximation has been used to study the reaction cross sections for these nuclei at low and high energy regions.

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A structure of the core ^7Be [^{15}O] plus one halo proton [two halo protons] is assumed for ^8B [^{17}Ne] nucleus. In HO + HO method the core and valence densities are described by the harmonic oscillator wave functions. The configurations $\{(1s_{1/2})^4, (1p_{3/2})^3\}$ and $\{(1s_{1/2})^4, (1p_{3/2})^8, (1p_{1/2})^3\}$ are assumed for core nuclei ^7Be and ^{15}O , respectively.

The last one proton of ^8B assumed occupies $1p_{1/2}$ level, while the last two protons of ^{17}Ne occupy $2s_{1/2}$ level. In G + G method the core and valence densities are described by the Gaussian wave functions.

Table 1 shows some properties of halo ^8B and ^{17}Ne nuclei. The harmonic oscillator and Gaussian size parameters are calculated using Eq. 6 and shown in table 2.

Table 1: Some properties of the selected nuclei

Halo nucleus	J^π [22]	Type of halo nucleus	Half-life time ($\tau_{1/2}$) [22]	Separation energy (MeV) [23]
^8B	2^+	One proton halo	770 ms	$S_p = 0.136$
^{17}Ne	$1/2^-$	Two-proton halo	109.2 ms	$S_{2p} = 0.933$

Table 2: The harmonic oscillator and Gaussian size parameters employed in our calculations

Halo nucleus	Core nucleus	HO+HO		G+G	
		$\hat{b}_c$ (fm)	$\hat{b}_v$ (fm)	$\hat{a}_c$ (fm)	$\hat{a}_v$ (fm)
^8B	^7Be	1.573	2.779	1.777	3.788
^{17}Ne	^{15}O	1.745	2.909	1.886	4.393

Figure 2 shows the theoretical matter density profiles for ^8B (two upper figures) and ^{17}Ne (two lower figures) obtained by the HO + HO figures (2a and 2c) and G + G figures (2b and 2d) methods as well as the experimental matter densities taken from Refs.[12 and 24] for ^8B and ^{17}Ne , respectively. Therein, the black, blue and dashed-red curves refer to core, valence and matter densities, respectively. The long tail manner (the distinctive property of halo nucleus) is revealed in all dashed-red curves of figure 2 which agree nicely with the experimental data.

Figure 3 exhibits the neutron, proton and matter densities displayed as black, blue and dashed-red curves, respectively. It is clearly shown that a long tail exists in the proton density distributions of ^8B and ^{17}Ne , which supports the proton halo structure for these nuclei.

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Figure 4 illustrates the proton densities of $^{10,8}\text{B}$ (the top panel) and $^{20,17}\text{Ne}$ (the bottom panel). Therein, the blue distributions corresponding to the proton densities unstable nuclei ^8B and ^{17}Ne whereas the red distributions refer to those of their stable isotopes ^{10}B and ^{20}Ne . It is clear from figures (4a and 4b) figures (4c and 4d) that the blue distributions have a longer tail than that of the red distributions due to the weak binding of the last one proton [last two-proton] in ^8B [^{17}Ne].

The elastic form factors for the unstable proton-rich nuclei ^8B and ^{17}Ne (dashed-blue curves) and those of their stable isotopes ^{10}B and ^{20}Ne (red curves) are calculated through combining the proton densities calculated by HO + HO method with PWBA and presented in figure 5 compared with the experimental data (dotted symbols) of the stable nuclei ^{10}B [25] and ^{20}Ne [26]. According to these results there is a major difference between red curves and dashed-blue curves. It is obvious from figure 5, that each of the red curve and the dashed-blue curve has only one diffraction minimum.

The minima of ^8B and ^{17}Ne shift outward and downward with an increasing neutron number. This trend change is caused by the variation in the proton density distributions, especially the details of the outer parts.

The Glauber model within OL approximation has been used to calculate the reaction cross section (σ_R) of ^8B and ^{17}Ne on ^{12}C target at low and high energy regions. Figure 6 shows the calculated (open circle symbols) and experimental (filled circle symbols) σ_R of ^8B Figure 6a and ^{17}Ne Figure 6b as a function of energy, which are tabulated in table 3. The calculated results of σ_R are consistent with experimental results at both low and high energy within quoted error.

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Figure 2: Core, valence (halo) and matter density distributions for ^8B and ^{17}Ne halo nuclei

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Figure 3: Neutron, proton and matter density distributions for ^8B and ^{17}Ne halo nuclei

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Figure 4: Proton density distributions for $^{10,8}\text{B}$ and $^{20,17}\text{Ne}$

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Figure 5: Elastic form factors for ^{10}B and ^{20}Ne

Figure 6: The calculated reaction cross section of (a) ^8B and (b) ^{17}Ne

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Table 3: Calculated reaction cross sections for ^8B and ^{17}Ne halo nuclei

Halo nuclei	Calculated σ_R (mb)	Experimental σ_R (mb) [14,27]	Energy (MeV) [14,27]
^8B	788	784 ± 14	790
	760	763 ± 5	285
	828	823 ± 3	142
	1109	1103 ± 18	60
	1280	1274 ± 12	38
^{17}Ne	1099	1090 ± 76	680
	1051	1044 ± 31	620
	1345	1331 ± 27	64
	1588	1541 ± 31	42

Summary and Conclusions

The Binary Cluster Model (BCM) has been employed with the single particle harmonic oscillator and Gaussian wave functions to study the ground state densities and the elastic form factors of proton rich ^8B and ^{17}Ne halo nuclei. The last one proton of ^8B is assumed to occupy $1p_{1/2}$ level while the last two protons of ^{17}Ne occupy $2s_{1/2}$ level. From the calculated densities, it is found that ^8B and ^{17}Ne have a long tail in proton and matter densities which is consistent with the experimental data. The Glauber model with an optical limit approximation has been used to study the reaction cross sections for these nuclei in the low and high energy regions. The calculated results of reaction cross sections of these nuclei at both low and high energy give good agreement with experimental data.

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