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Reactions with weakly-bound exotic nuclei using deformed two-body models

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The ^{11}Be halo nucleus has been studied using different deformed two-body models, the Nilsson model and the semi-microscopic PAMD model. Electric transition probabilities have been calculated with both models and found to be compatible with those extracted from Coulomb dissociation data. The calculated $B(E1)$ and $B(E2)$ are applied to the calculation of ^{11}Be+^{208}Pb Coulomb dissociation cross section. Both models reproduce reasonably well the experimental data. It is also shown that quadrupole resonances are relevant for this agreement, being PAMD model more accurate in the energy of such resonances.

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1. Introduction

Due to advances in radioactive beam facilities, the study of reactions involving weakly bound exotic nuclei has been an active field in nuclear physics over the past decades. The cases of nuclei that exhibit a halo nature are especially relevant, ^{11}Be being a clear example of neutron halo nucleus.

In this contribution, we present the application of different deformed two-body models (neutron+*core*) to ^{11}Be. The purpose is to have a model that, being manageable for reaction calculations, provides a sufficiently realistic description of the ^{11}Be structure. To study these reactions, weakly bound nuclei are usually described with few-body models that ignore possible deformation of the fragments. However, for some nuclei, *core deformation* is significant and must be taken into account. Therefore, they are described using deformed two-body models such as the particle-rotor (PRM) or the particle-vibrator (PVM) models. The PRM has been successfully applied to the study of the structure and resonant breakup of ^{11}Be [1–4].

In the present contribution, Coulomb excitations of ^{11}Be are studied using the Nilsson and PAMD models from [5]. Being a reference halo nucleus, the electric dipole transition probability $B(E1)$ of ^{11}Be is especially relevant. In particular, the transition between its two bound states shows the largest measured $B(E1)$ between bound states [6]. The $B(E1)$ and $B(E2)$ distributions extracted from these models are tested by applying them to ^{11}Be+^{208}Pb Coulomb dissociation experiments.

2. Structure models

We consider a composite nucleus, described as a two-body system, comprising a weakly bound neutron coupled to a core. The Hamiltonian of the system can be written as

$$\mathcal{H} = T(\vec{r}) + V_{\ell s}(r)(\vec{\ell} \cdot \vec{s}) + V_{vc}(\vec{r}, \xi) + h_{core}(\xi), \tag{1}$$

where $h_{core}(\xi)$ is the Hamiltonian of the core. $V_{vc}(\vec{r}, \xi)$ is the effective valence-core interaction, which depends on the relative motion between the valence and the core, but also on the core degrees of freedom ξ.

Two different models have been used to describe the ^{11}Be system according to the limits of the coupling strength. For the strong-coupling, the Nilsson model from Ref. [5] was used. For the weak-coupling case, we employ the semi-microscopic particle-plus-AMD (PAMD) model proposed in Ref. [7]. This model obtains the coupling potential $V_{vc}(\vec{r}, \xi)$ convoluting an effective nucleon-nucleon interaction with microscopic transition densities of the core nucleus calculated with Antisymmetrized Molecular Dynamics (AMD) [8].

The low-lying energy spectra and wave functions obtained with these two models have been compared in Ref. [5]. These wave functions have also been applied to the study of the transfer reaction ^{11}Be$(p,d)^{10}$Be, comparing the results of our calculation with experimental data [9, 10]. Although the PAMD model turns out to be more suitable for the description of ^{11}Be, both models provide reasonable results.

3. Electric transition probabilities

The dipole $B(E1)$ and quadrupole $B(E2)$ electric transition probabilities are calculated as explained in Ref. [1]. In the case of $E1$ transitions from the ground state $(1/2^+)$, $1/2^-$ and $3/2^-$ states

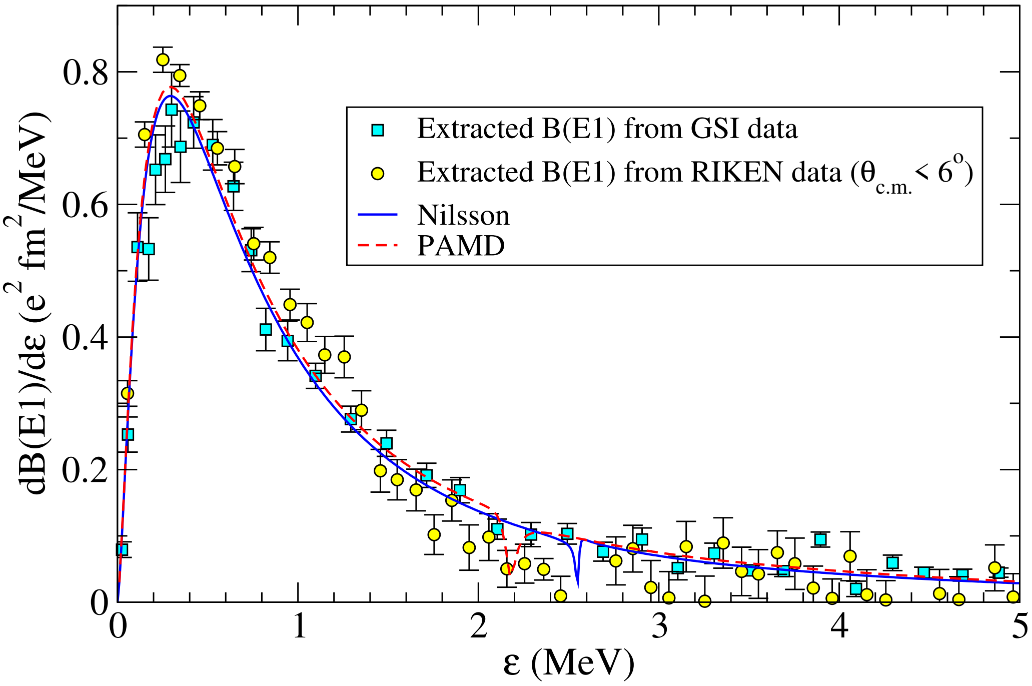

Figure 1: $B(E1)$ distributions obtained with the Nilsson and PAMD models. They are compared with the distributions from Ref. [4] extracted from the ^{11}Be+^{208}Pb breakup data at 520 MeV/nucleon in GSI [11] and 69 MeV/nucleon in RIKEN [12].

are populated via single-particle excitations. Between the bound states, the resulting $B(E1)$ are 0.116 and 0.110 e^2fm^2 for the Nilsson and PAMD models, respectively. These values are consistent, but slightly higher than the experimental one: $B(E1; 1/2^+ \to 1/2^-) = 0.102 \pm 0.002$ e^2fm^2 [6]. Regarding the transition to the continuum, the obtained distributions are shown in Fig. 1. They can be compared with the distributions extracted from the ^{11}Be+^{208}Pb breakup data at 520 MeV/nucleon in GSI [11] and 69 MeV/nucleon in RIKEN[12]. We note that the lack of agreement between of the $B(E1)$ distributions extracted from these two measurements has been a long-standing controversy over the last decade. Recently, a novel method for extracting the $B(E1)$ strength has been applied to these data sets [4], obtaining compatible distributions and hence reconciling the two datasets. In Fig. 1, good agreement can be observed between these distributions and the results of both models.

In the case of quadruple transitions, in addition to single-particle excitations, there is a more dominant contribution due to the $E2$ transition of the core. This contribution is calculated assuming a rotor model reproducing the experimental $B(E2)$ value between the ground state and the first excited state of ^{10}Be: $B(E2;\ 2^+ \to 0^+) = (10.5 \pm 1.0)$ e^2fm^4 [13]. The calculations for both models are shown in Fig. 2, in which the contribution from $3/2^+$ or $5/2^+$ continuum states are presented separately. For both models, we find contributions of the first $5/2^+$ and $3/2^+$ resonances, but with significant differences in the predicted energies and the widths of the resonances. As discussed in [5], one of the advantages of the PAMD model over the Nilsson model is the improved description of these resonances.

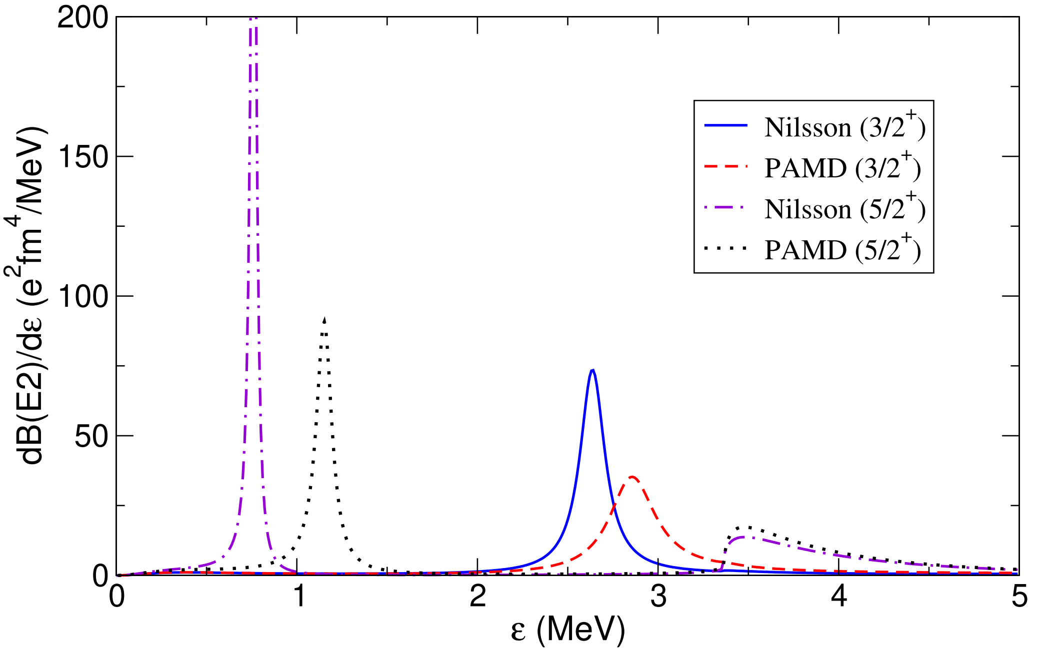

Figure 2: $B(E2)$ distributions obtained with the Nilsson and PAMD models. Contributions populating $3/2^{+}$ and $5/2^{+}$ states are shown separately, revealing their corresponding resonances.

4. Application to ^{11}Be+^{208}Pb breakup

The semi-classical equivalent photon method (EPM) [14] is used to calculate the differential cross section for ^{11}Be+^{208}Pb breakup, taking the obtained $B(E1)$ and $B(E2)$ distributions as input. To compare with the experimental data from RIKEN [12], we consider an incident energy of 69 MeV/nucleon and the calculated double differential cross section is integrated up to $\theta_{\text{c.m.}} = 6°$. The grazing angle (3.8°) and the experimental resolution are also taken from [12]. The results of the calculation are compared with the experimental data in Fig. 3. The $E1$ and $E2$ contributions are calculated separately and then summed incoherently, so we show the sum and also the $E1$ contribution. As expected, the $E1$ contribution is a good first approximation and the results are very similar for both models. By adding the $E2$ contribution, the agreement generally improves, but is better in the case of the PAMD model. This is mainly due to the differences in energies of the resonances that have already been discussed. Although the agreement with the data is quite good, we must take into account that there is a contribution from nuclear interaction that is not being considered. It is known that this interaction could slightly increase the cross section predicted by the models. However, the grazing angle used may be too large by underestimating the nuclear radius of ^{11}Be, and a more realistic one could slightly decrease the cross section. At the end of the day, if we want greater reliability at the expense of larger computational difficulty, we could perform XCDCC calculations with the models as done in [4].

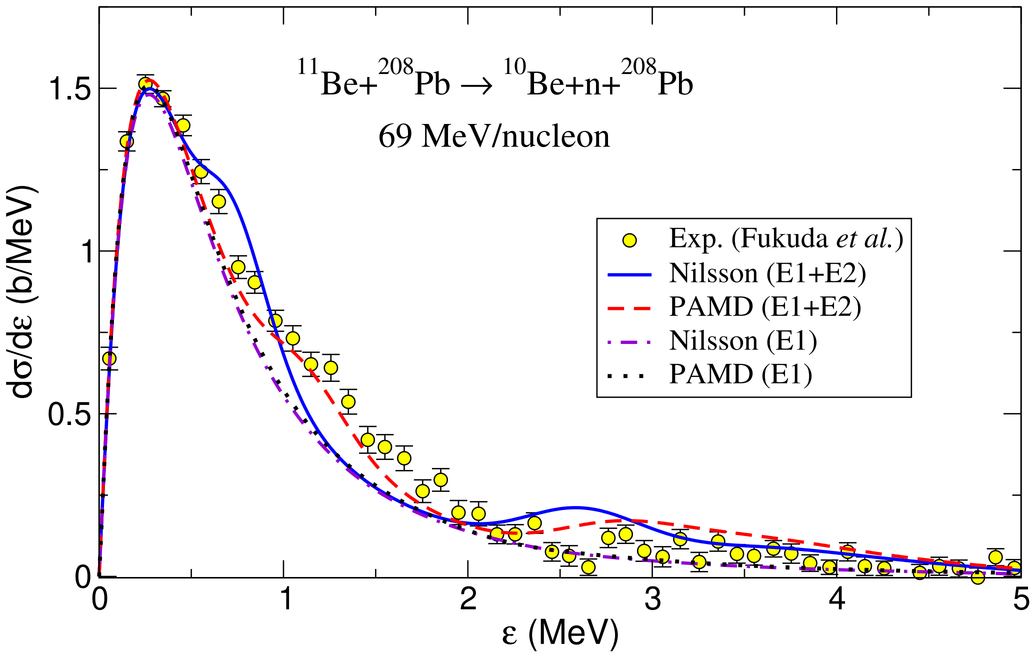

Figure 3: Energy distribution of the exclusive breakup for the reaction ^{11}Be+^{208}Pb at 69 MeV/nucleon up to $\theta_{c.m.} = 6^\circ$. The experimental data from Ref. [12] are compared with the results of the EPM calculations using the Nilsson and PAMD models. The sum of the $E1$ and $E2$ contributions are shown, but also the $E1$ separately. All theoretical results have been convoluted with the experimental energy resolution Ref. [12].

5. Conclusions

The structure of ^{11}Be halo nucleus has been studied using Nilsson and PAMD models. $B(E1)$ distributions have been calculated, and they show a good agreement with the $B(E1)$ extracted from the experimental data [4]. The $B(E2)$ has also been obtained and both distributions have been tested applying them to the calculation of ^{11}Be+^{208}Pb Coulomb dissociation cross section using the EPM method. The cross section obtained is compatible with the RIKEN data [12].

The results show that the PAMD model provides a more realistic description of ^{11}Be than the Nilsson model, but the latter still gives a reasonable description of the Coulomb excitations in ^{11}Be. We expect that the description of Coulomb excitations will be better using the Nilsson model than the PAMD for other nuclei such as ^{17}C, in which the former provides a better overall description [5].

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