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Unbound exotic nuclei studied via projectile fragmentation reactions

A. Bonaccorso[a]

INFN, Sezione di Pisa and Dipartimento di Fisica, Università di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy

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Abstract. We present a time-dependent model for the excitation of a nucleon from a bound state to a continuum resonant state in the neutron-core potential. The final state is described by an optical model S-matrix so that overlapping resonances of any energy as well as deeply bound initial states can be considered. Due to the coupling between initial and final states the neutron-core free particle phase shifts are modified, in the exit channel, by a small additional phase. The model allows to extract structure information from data obtained in projectile fragmentation reactions of a borromean nucleus on a light target. Some results relative to the study of ^{13}Be are presented.

PACS. 25.60.-t Reactions induced by unstable nuclei – 21.60.-n Nuclear structure models and methods

1 Introduction and reaction model

Light unbound nuclei have recently attracted much attention [1,2] in connection with exotic halo nuclei. A precise understanding of unbound nuclei is essential to determine the position of the driplines in the nuclear mass chart. A fundamental question to answer, in order to understand the structure of matter, is indeed what makes a certain number of neutrons and protons to bound together, while adding an extra neutron would lead to an unbound nucleus. Sometimes adding instead two neutrons leads to bound nuclei. Those are two-neutron halo nuclei such as ^{6}He, ^{11}Li, ^{14}Be, in which the two neutron pair is bound, although weakly, while each single extra neutron is unbound in the field of the core. In a three-body model these nuclei are described as a core plus two neutrons. The properties of core plus one neutron system are essential and structure models rely on the knowledge of angular momentum, parity, energies and spectroscopic strength for neutron resonances in the field of the core and the corresponding neutron-core effective potential. The neutron elastic scattering at very low energies on the "core" nuclei is not feasible as such cores, like ^{9}Li, ^{12}Be or ^{15}B are themselves unstable and cannot be used as targets. Indirect methods like projectile fragmentation, following which the neutron-core relative energy spectrum is reconstructed [2] have been used so far.

Our model describes one neutron breakup probability from a halo projectile due to the interaction with the target and including final-state interaction with the original core nucleus. It is appropriate to describe coincidence measurements in which the neutron-core relative energy spectrum is reconstructed. For two-nucleon breakup the complete process including the second nucleon breakup will be discussed elsewhere [3]. According to eq. (2.15) of [4] inelastic-like excitations can be described by a first-order time-dependent perturbation theory amplitude

$$A_{fi} = \frac{1}{i\hbar}\int_{-\infty}^{\infty} \mathrm{d}t \langle \psi_f(\mathbf{r},t)|V_2(\mathbf{r}-\mathbf{R}(t))|\psi_i(\mathbf{r},t)\rangle, \qquad (1)$$

for a transition from an occupied nucleon bound state ψ_i to an unoccupied final state ψ_f. Here V_2 is the interaction responsible for the neutron transition. The wave function $\psi_i(\mathbf{r})$ for the initial state is calculated in a potential $V_1(\mathbf{r})$ which is fixed in space. The final-state wave function $\psi_f(\mathbf{r})$ can be a bound state or a continuum state. The potential $V_2(\mathbf{r}-\mathbf{R}(t))$ moves past on a constant velocity path with velocity v in the z-direction with an impact parameter b_c in the x-direction in the plane $y = 0$. The first-order time-dependent perturbation amplitude can be put in a simple form by changing variables as $z' = z - vt$. Also $q = (\varepsilon_f - \varepsilon_i)/\hbar v$, and $V_2(x-b_c, y, q) = \int_{-\infty}^{\infty} \mathrm{d}z V_2(x-b_c, y, z)e^{iqz}$. In order to obtain a simple analytical formula we consider the special case in which $V_2(r)$ is a delta function potential $V_2(r) = v_2\delta(x)\delta(y)\delta(z)$, with $v_2 \equiv$ [MeV fm^3]. Then the integrals over x and y can be calculated and

$$A_{fi} = \frac{v_2}{i\hbar v}\int_{-\infty}^{\infty} \mathrm{d}z\ \psi_f^*(b_c,0,z)\psi_i(b_c,0,z)e^{iqz}. \qquad (2)$$

[a] In collaboration with G. Blanchon, D.M. Brink, N. Vinh Mau; e-mail: bonac@df.unipi.it

The initial state is the numerical solution of the Schrödinger equation which fits the experimental neutron separation energy and the final continuum state is given by

$$\psi_f(b_c, 0, z) = C_f k \frac{i}{2}\left(h_{l_f}^{(+)}(kr) - S_{l_f} h_{l_f}^{(-)}(kr)\right) P_{l_f}\left(\frac{z}{r}\right). \tag{3}$$

$k = \sqrt{2m\varepsilon_f}/\hbar$ is the neutron momentum in the final states and C_f is the asymptotic normalization constant. S_{l_f} is the S-matrix representing the final-state interaction of the neutron with the projectile core. The probability to excite a final continuum state of energy ε_f is an average over the initial state and a sum over the final states. Introducing the quantization condition and the density of final states [5] the probability spectrum reads

$$\frac{\mathrm{d}P_{in}}{\mathrm{d}\varepsilon_f} = \frac{2}{\pi}\frac{v_2^2}{\hbar^2 v^2} C_i^2 \frac{m}{\hbar^2 k} \Sigma_{l_f}(2l_f+1)|1-\bar{S}_{l_f}|^2 |I_{l_f}|^2 , \tag{4}$$

where $|I|$ and α are the modulus and phase, respectively, of the integral in eq. (2). Here $\bar{S} = e^{i2(\delta+\alpha)}$ does not represent the free neutron-core scattering, since there is an additional contribution α to the free neutron phase δ. An absorption term $1 - |\bar{S}_{l_f}|^2$ should be included if the neutron energy is higher than the core inelastic excitation energy threshold.

2 Application to ^{13}Be

One of the aims of this paper is to simulate the neutron-^{12}Be relative energy spectra obtained from fragmentation of ^{14}Be or ^{14}B on a ^{12}C target at 70 A. MeV and to see whether they would show differences predictable in a theoretical model. In the case of ^{14}B the neutron is in a state combination of s and d components [2], and we assume the binding energy $|\varepsilon_i| = 0.97\,\mathrm{MeV}$. In ^{14}Be a combination of s, p and d components can be supposed and we take the binding energy $|\varepsilon_i| = 1.85\,\mathrm{MeV}$. Figure 1 shows results obtained including the s and d states according to eq. (4). The p-state is included only in the ^{14}Be case. In ^{12}Be the ground state wave function is a combination of such states with almost equal weight and none of them is fully occupied, then we assume that each of them has also components in the continuum. For each initial state a unit spectroscopic factor is taken. The result includes the transition bound to unbound from an s initial state to an s and d unbound states and from a bound d-state to unbound s and d states and from a bound p-state to an unbound p-state. In our model transitions with change of parity give no contribution. Keeping fixed binding energies and the resonance energies of the p and d states, we have varied the scattering length of the final s-state (given in the figure). The s-peak is dominant because of the well-known threshold effect. It does not have a Lorentzian shape because it receives contribution from both the s and d bound

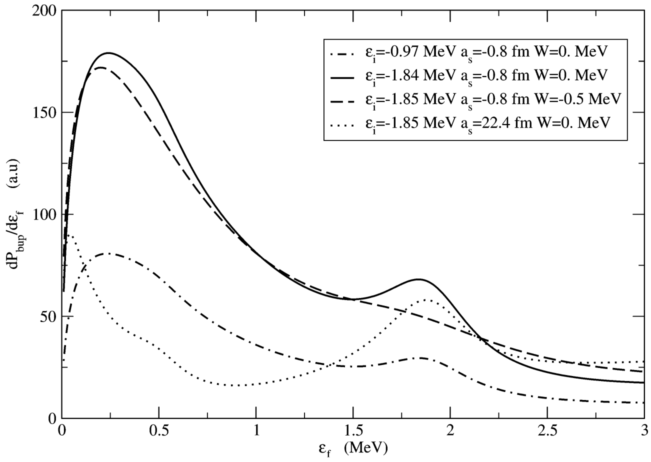

Fig. 1. n-^{12}Be relative energy spectrum. Initial binding energy and final s-state scattering lengths are given in the figure.

components. In the case of a final bound s-state there is a very narrow peak close to threshold, while for $a_s > 20$ fm there is no peak at all. In this case the p-state contribution appears as a little bump at 0.5 MeV but the peak takes less strength than that of the d-state around 2 MeV. This is due to the concentration at threshold of the s-state, which has a less diffuse tail. When the s-state is unbound, the p-resonance peak disappears in the tail of the s-state, while the d-resonance peak can be clearly seen around 2 MeV because of the enhancement due to the $2l_f + 1$ factor in eq. (4).

Finally we wanted to address the issue of possible core excitation effects in ^{14}Be. They can be modeled in the present approach by considering a small imaginary part in the neutron-core optical potential. A potential of Woods-Saxon derivative form has been taken with a -0.5 MeV strength. The result is shown in fig. 1 by the dashed line. The effect of the imaginary potential is to shift the s-state peak towards threshold and to wash out the d-resonance peak. It seems then that the spectrum of unbound nuclei would reflect the structure of the bound parent nucleus and that reaction mechanism models used to extract structure information should carefully include the effects discussed above. The model presented here seems to be promising in this respect. Details of potentials and physical parameters used will be given in a forthcoming publication [3].

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