Three-particle decays of light-nuclei resonances

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Abstract
We have studied the three-particle decay of $^{12}$C, $^{9}$Be and $^{6}$Be resonances. These nuclei have been described as three-body systems by means of the complex scaled hyperspherical adiabatic expansion method. The short-distance part of the wave function is responsible for the energies, whereas the information related to the observable decay properties is contained at large distances, which must be computed accurately. As an illustration we show the results for the angular distribution of $^{9}$Be and $^{6}$Be resonances.
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1. Introduction
In quantum mechanics, the decay of two fragments is well determined by energy and momentum conservation laws. But the decay of three particles is a much more complicated issue. The energies of the decaying fragments are not fixed. The energy distribution of the three-body final state after the decay is an observable, and can be used to understand the structure of the initial state and the decay mechanism itself. On the other hand, the intermediate path connecting the initial and final states is not an observable. The only way of extracting information about the decay mechanism is by trying to understand the measurable final state by means of theoretical models. The decay is usually interpreted as either sequential via an intermediate configuration or direct to the continuum. The interpretations are often used to derive reaction rates for the inverse process in astrophysical environments. It is therefore important to have a reliable interpretation of the data.

We have focused our attention on three-body decaying nuclei involved in stellar nucleosynthesis reactions. $^{12}$C, $^{9}$Be and $^{6}$Be. For all three there are experimental data available that help us to test the validity of our theoretical model.

2. Theoretical framework
The three-body decaying nuclei are described as three-body systems within the complex-scaled hyperspherical adiabatic expansion method [1]. According to this method, the angular part of the Hamiltonian is first solved keeping fixed the value of the hyperradius $\rho$. Its eigenvalues serve as effective potentials while the eigenfunctions $\Phi_{nJM}$ are used as a basis to expand the total wave function $\Psi_{JM} = \frac{1}{\rho} \sum_n f_n(\rho) \Phi_{nJM}(\rho, \Omega)$. The $\rho$-dependent expansion coefficients, $f_n(\rho)$, are the hyperradial wave functions obtained from the coupled set of hyperradial equations.

$^{12}$C is described as three $\alpha$-particles, $^{9}$Be as two $\alpha$-particles and one neutron, and $^{6}$Be as one $\alpha$-particle and two protons. Our Hamiltonian contains short-range and Coulomb potential (between charged particles). We have considered $\alpha-\alpha$ potential from [2], $\alpha$–nucleon from [3] and nucleon–nucleon from [4]. These potentials have been built in order to reproduce the two-body scattering data. On top of these interactions we include a structureless three-body potential of the form $V_{3b} = \frac{S}{\rho^2} \exp(-\rho^2/b^2)$, fitted to reproduce the resonance energies. This potential is included because at short distances the structure of these nuclei is not necessarily of three-body character. The complex scaling method helps us to treat the resonances as if they were bound states.

The many-body initial state resonance evolves into three clusters at large distances. Total angular momentum and parity $J^\pi$ are conserved in the process. This symmetry imposes constraints on the resulting momentum distributions. The energy distribution is the probability of finding a given particle
at a given energy. It can be measured experimentally and is the only information that allows us to study the decay path, which can be either sequential or direct or a mixture. The information about the energy distributions of the fragments after the decay is contained in the large-distance part of the wave function, which must be accurately computed. The single-particle probability distributions are obtained after Monte Carlo integration of the absolute square of the large-distance wave function.

3. Results

3.1. $^{12}$C

Within this theoretical framework, we have extensively studied the decay of the low-lying $^{12}$C resonances [5]. Our results have been compared to recent experimental data [6] with a high level of agreement. Moreover, our suggestion to change the previously assigned spin and parity of the 13.35 MeV state [7] from $2^-$ to $4^-$ has been supported by the experimental community [6, 8].

3.2. $^{9}$Be

We have studied the five lowest resonances of $^{9}$Be [9] and compared them to the experimental data from [10]. Figure 1 shows the angular distributions of these resonances, i.e. the probability of finding one of the decaying particles in a certain direction with respect to the direction formed by the other two. In all the cases, we have removed the sequential decay via $^{8}$Be($0^+$). This kind of plot contains information about the angular momentum of the first particle relative to the centre-of-mass of the other two. We observe that the angular distribution patterns are different for different $J^\pi$ states. These features are clearly distinguishable, demonstrating that these observables can be used to determine the large-distance structure of these resonances. The initial state can still be determined only through the theoretical information about the dynamical evolution of the resonances.

3.3. $^{6}$Be

The $^{6}$Be is an unbound nucleus that has only two low-lying resonances, $0^+$ and $2^+$. Its decay has recently been measured [11] and compared to theoretical predictions given by our formalism. We have not found any signature of sequential decay of these resonances via intermediate two-body states. We show in figure 2 the angular distributions for the two resonances of $^{6}$Be. The upper panels can be compared directly to the experimental data from [11]. They show that the $\alpha$-particle prefers to come out perpendicular to the direction formed by the two protons.

4. Summary and conclusions

We have applied a general method for computing the momentum distributions of three-body decaying light-nuclei resonances. We have conjectured that the energy distributions of the decay fragments are insensitive to the initial many-body...
structure. The energy distributions are then determined by the energy and three-body resonance structure as obtained in a three-body cluster model. These momentum distributions are determined by the coordinate space wave functions at large distances, which must be computed with a high accuracy.

The method has been applied previously to the study of the decay of $^{12}$C resonances with great success. In this paper, we have shown the angular distribution of the low-lying $^9$Be and $^6$Be resonances decaying into $\alpha + \alpha + n$ and $\alpha + p + p$, respectively. Our distributions are open to experimental tests.

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References

[1] Nielsen E, Fedorov D V, Jensen A S and Garrido E 2001 Phys. Rep. 347 373
[2] Ali S and Bodmer A R 1966 Nucl. Phys. 80 99
[3] Cobis A, Fedorov D V and Jensen A S 1997 Phys. Rev. Lett. 79 2411
[4] Garrido E, Fedorov D V and Jensen A S 1997 Nucl. Phys. A 617 153
[5] Álvarez-Rodríguez R, Jensen A S, Garrido E, Fedorov D V and Fynbo H O U 2008 Phys. Rev. C 77 064305
[6] Kirsebom O S et al 2010 Phys. Rev. C 81 064313
[7] Álvarez-Rodríguez R, Garrido E, Jensen A S, Fedorov D V and Fynbo H O U 2007 Eur. Phys. J. A 31 303
[8] Freer M et al 2007 Phys. Rev. C 76 034320
[9] Álvarez-Rodríguez R, Jensen A S, Garrido E and Fedorov D V 2010 Phys. Rev. C 82 034001
[10] Fulton B R et al 2004 Phys. Rev. C 70 047602
[11] Papka P et al 2010 Phys. Rev. C 81 054308