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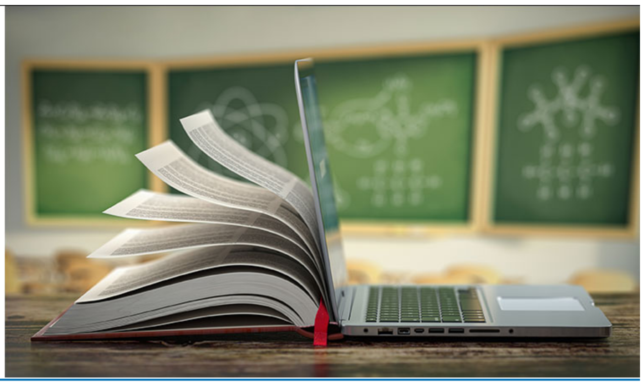

Are sequential and direct decays distinguishable?

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Abstract. We compute the momentum distributions of the particles emerging in three-body decay of a nuclear resonance. We discuss if it is possible to distinguish between sequential decay proceeding through non-observable intermediate configurations and direct decay into the three-body continuum. Detailed investigation of the decay of the ^{9}Be($5/2^-$) resonance is used as a theoretical prototype for explaning the general principles.

Introduction. The measurement of the fragment momenta after three-body decay of a resonance is the information from which the combination of initial state structure and decay mechanism must be extracted if possible at all [1, 2, 3, 4]. This connection from initial via intermediate to final state can only be investigated in models which can account for the most important intermediate paths [5, 6]. Data analyses use the R-matrix formalism where sequential decays via intermediate two-body configurations are preselected. The most reliable experimental results are obtained by complete kinematics measurements of fragment momenta [7, 8, 9, 10]. Most of the microscopic theoretical investigations are concerned with resonance structures, energies and decay widths [11] while the direct comparison between observable momentum distributions are rather scarce [4, 5, 6]. In the present work we study the decay mechanism by comparing computed and measured [10] distributions for the ^{9}Be($5/2^-$) resonance. We try to extract the general lessons from the specific results.

Ingredients. The large-distance observable structure is a three-body continuum state and we therefore compute the resonance structure in a three-body cluster model. We use the hyperspherical Faddeev expansion method with complex scaling of the coordinates [12, 13]. For sufficiently large rotation the resonances are then solutions with complex energies and exponentially decreasing large-distance behavior. The difficulties are that different asymptotic large-distance structures simultaneously must be accurately described within the same framework, e.g. different two-body resonances, three-body continuum states, and possibly coherent combinations. Both Coulomb and nuclear short-range interactions are important.

The short-distance boundary condition is selected by a three-body potential adjusted to reproduce the desired three-body resonance energy. This avoids dealing with the many-body degrees of freedom which at larger distances eventually have to reduce to that of three particles. The successful analog is the α-particle emission from inside a confining potential where the preformation factor also allows reduction to the α-daughter relative degree of freedom.

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The assumptions are then that a nuclear resonance is populated by beta-decay or in a reaction, the decay is independent of the previous history, the resonance wave function obtained after complex scaling contains information about the decay mechanism, and the large-distance properties reflect directly the measurable fragment momentum distributions.

Procedure. The relative coordinates, $\boldsymbol{r_{ik}} = \boldsymbol{r_k} - \boldsymbol{r_i}$, are given in terms of the particle positions $\boldsymbol{r_i}$. The hyperradius ρ is defined by $m\rho^2 = \sum_{i<j} m_i m_j r_{ij}^2/M$, where $M = m_i + m_k + m_j$ is the total mass of the three particles and m is a normalization mass. The complex scaling means $\rho \to \rho\exp(i\theta)$ in all equations. We choose the two-body interactions to reproduce low-energy scattering properties [14, 15]. A three-body potential is added and the angular Faddeev equations solved in coordinate space for each ρ by expansion of each component in hyperspherical harmonics in the corresponding set of Jacobi coordinates. This defines the adiababtic potentials in terms of the angular eigenvalues λ_n where each is associated with an eigenfunction. Finally the coupled set of radial equations are solved and the total resonance wave function Ψ is obtained. The Fourier transform of Ψ has the same angular dependence as Ψ itself.

Sequential decay. We can define sequential decays by intuitive physics considerations where two particles interact after the third particle is emitted. Eventually also this intermediate configuration decays into the continuum but the momentum distributions carry information about this history. The first trace is the uniquely defined angular momentum of the intermediate state which must couple to that of the third particle to give the total angular momentum of the three-body state. However, in coordinate space also the distance between the two particles should remain small for a while compared to the distance to the third particle. In momentum space the two-body energy should be transformed into an outgoing plane wave corresponding to two particles moving apart with that energy. For narrow and energetically allowed two-body resonances this definition is consistent and complete. However, the intermediate configuration gradually becomes less and less defined when the width increases or the energy moves into the classically forbidden region.

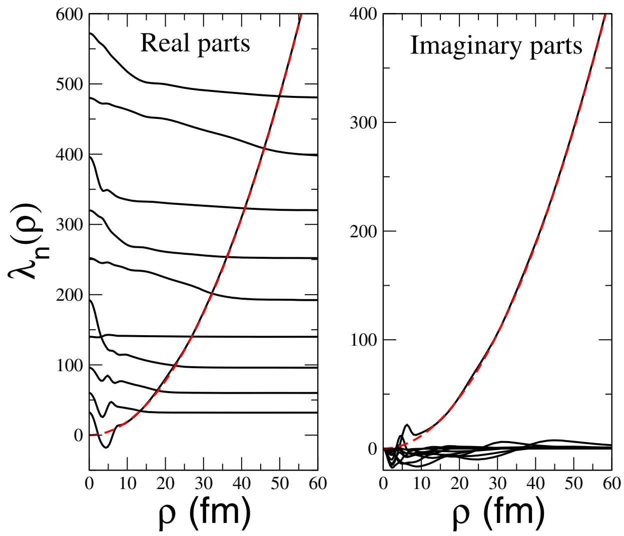

Figure 1. The 10 real and imaginary angular eigenvalues as function of ρ for 0^+ for three bosons interacting by d-waves. The two-body systems have a d-resonance at 4.53 MeV with a width of 2.36 MeV ($\theta_R = 0.127$). The red curves are the real and imaginary parts of the parabola $2m|E|\rho^2\exp(2i(\theta-\theta_R))/\hbar^2$. The complex scaling angle $\theta = 0.4$.

Exploiting the complex scaling formalism we can also make a mathematical distinction. Assume that the rotation angle θ is larger than the angle corresponding to the resonance, i.e. $\theta_R = \arctan(-E_I/E_R)$ where E_R and E_I are real and imaginary part of the resonance energy. Among the angular eigenvalues would then be one increasing parabolically with ρ proportional to the resonance energy in perfect analogy to a parabolic decrease corresponding to a bound two-body state. This is seen in fig. 1 where all the other eigenvalues describe different three-body continuum states.

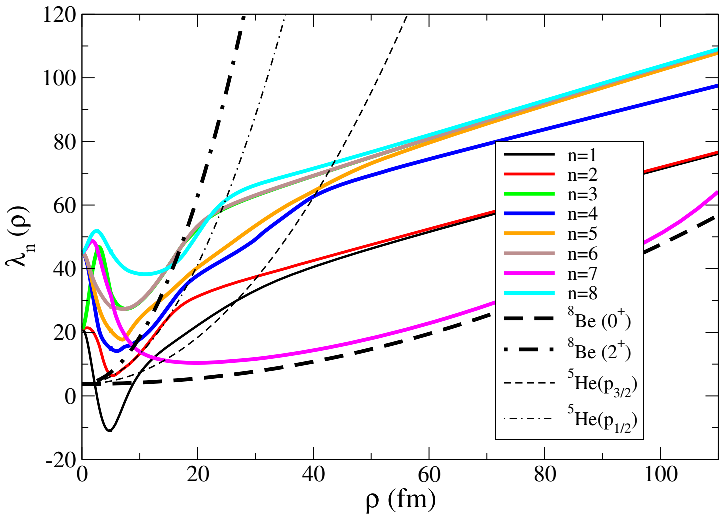

Figure 2. The real part of the lowest angular eigenvalues for the ^{9}Be$(5/2^-)$-resonance. The thick and thin dashed parabolic curves are the asymptotics corresponding to the lowest $(0^+,2^+)$ and $(p_{3/2},p_{1/2})$ resonances for ^{8}Be and ^{5}He, respectively.

The adiabatic potential related to the upgoing eigenvalue converges towards the two-body energy. The fraction of sequential decay via one of these structures can then be defined as the probability of finding that adiabatic component populated for large values of ρ. If the state is asymptotically forbidden by energy conservation this adiabatic component may still be populated for ρ-values where the distance between the two particles is comparable to the range of the attractive potential but much smaller than the distance to the third particle. This is called virtual sequential decay [16] because the intermediate configuration maintains the signature of all conserved two-body quantum numbers except for the energy.

Wave Functions. Unfortunately an unlimited increase of rotation angle beyond all θ_R of interest is not possible and we have to make the best out of the achievable. Fortunately the momentum distributions can be obtained even without rotation but much easier with a rotation angle larger than that of the three-body resonance. The location of the two-body resonances used as vehicles for the sequential decay can in principle be anywhere in the complex plane. We illustrate by the eigenvalues in fig. 2 for the practical example of decay of the ^{9}Be$(5/2^-)$-resonance.

The lowest eigenvalue at large distance corresponds to the ^{8}Be(0^+) structure. The second is smoothly connected to the only attractive potential at small distances where it therefore has to be responsible for the structure of the three-body resonance. These two eigenvalues cross each other around $\rho \approx 12$ fm. We find that the two lowest levels are responsible for 94% of the decay. All levels, except the lowest, increase linearly with ρ reflecting the Coulomb repulsion. At the crossing the compromise between maintaining the structure or minimizing the energy is decided

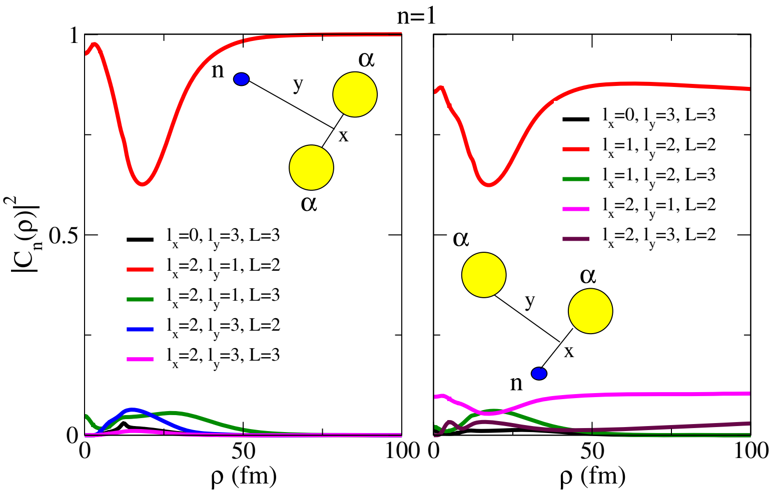

Figure 3. The partial wave decomposition in the two Jacobi coordinates of the dominating adiabatic potential for the ^{9}Be($5/2^-$)-resonance.

by the coupling between the levels. The result is a fraction of sequential decay via ^{8}Be(0^+) calculated to be around 2%.

The remaining part is then distributed over other sequential or direct decay modes. The structure of the dominating wave function is seen in the partial wave decomposition shown in fig. 3. Expressed in the Jacobi coordinates natural for the ^{8}Be structure we find asymptotically 100% of the 2^+ relative $\alpha - \alpha$ structure combined with an orbital angular momentum of $1\hbar$ of the neutron. Transforming this wave function into the other Jacobi coordinates we find α-neutron structures of about 86% in $p_{3/2}$ and about 11% in $p_{1/2}$ relative states. Thus the angular momentum structures corresponding to ^{8}Be(2^+) is essentially equivalent to ^{5}He in this combination of $p_{3/2}$ and $p_{1/2}$. Other than angular momentum signatures are necessary to distinguish between sequential decay through these intermediate states.

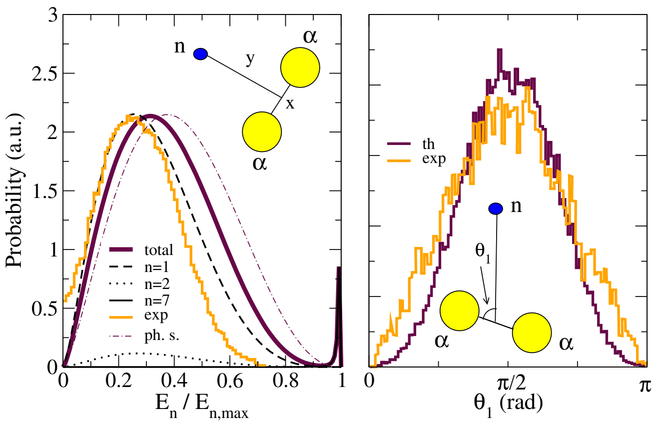

Figure 4. The measured [10] and computed distributions of the neutron energy (left) in units of the maximum, and the angle θ_1 (right) between the relative momenta of the α-particles and the neutron momentum. Phase space is abbreviated ph.s. Contributions from different adiabatic components are shown.

Energy distributions. Results from the recent measurement of both neutrons and α-particles is available [10]. First the unmistakable signal from sequential decay via ^{8}Be(0^+) is detected and the contribution of about 10% is removed from the measurement. The remaining distributions, shown in fig. 4, are relatively broad and rather smooth. The computed neutron energy distribution is shifted a little towards higher energies but resemble otherwise the experimental result. The extremely simple phase-space distribution is shifted a little more but resembles as well. The angular distribution also compares very well with the measured distribution. Now the computed distribution is a little more narrow but the peak is located at the same angle.

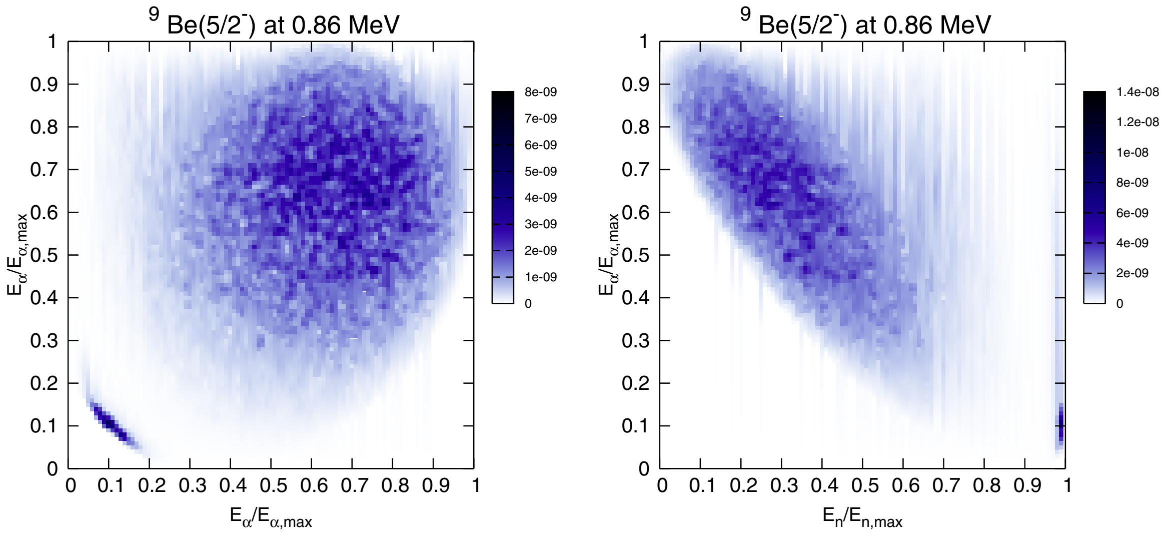

Figure 5. The computed probability distribution for finding one α-particle energy when another α-particle (left) or a neutron (right) already has a given value.

Dalitz plots. More detailed information is obtained through the energy correlations exhibited by Dalitz plots [1]where two-dimensional probabilities are shown as functions of two independent fragment energies. For the three-body decay of ^{9}Be we have only neutrons and α-particles as shown in fig. 5. We first notice the small dense region of two simultaneously small α-particle energies and correspondingly a region of large neutron energy and small α-particle energy. These structures reflect the small contribution from sequential decay via the ^{8}Be ground state.

The symmetry in the left plot between α-particle energies is necessary since the α's are identical particles. The density increases towards higher energies because the Coulomb repulsion enlarges the charged particle energies and correspondingly reduces that of the neutron. The opposite correlation is seen between neutrons and α-particles in the right part where a large α-energy corresponds to a small neutron energy. The dense regions correspond to the peaks in fig. 4.

Summary and Conclusions. We investigated the three-body decay of the ^{9}Be($5/2^-$) resonance into two α-particles and one neutron. The resonance wave function in complex scaled hyperspherical coordinates is computed and the large-distance properties extracted as accurately as possible. The basis size required increases tremendously with the spatial extension of the system. It suffices to achieve convergence at an intermediate distance outside which the observables do not change provided the basis is correspondingly increased. The computed momentum distributions for the ^{9}Be($5/2^-$) decay show a few per cent decaying via the ^{8}Be ground state. Also the remaining part compares rather well with the measured results, and resemble furthermore the simplest possible phase-space distributions consistent with the computed relative partial waves.

The $\alpha - \alpha$ relative angular momentum is $2\hbar$ which to within a few per cent coincides with the α-neutron relative orbital angular momentum of $1\hbar$. Thus, from an angular momentum point of view both ^{8}Be(2^+) and ^{5}He(p) are equally correct in a sequential description. However, the spatial distributions at large distances do not favor intermediate configurations where two particles are close while the third particle is far away. The resulting momentum distributions are much more consistent with direct decay.

This does not exclude a successful description in terms of a complete set of basis states expressed as tails of two-body resonances, and therefore subsequently interpreted as sequential decay through these states. The only problem is that these intermediate states very easily are non-orthogonal as the ^{8}Be(2^+) and ^{5}He(p) configurations which furthermore overlap with the three-body continuum states used in description of direct decay. The conclusion in the present case is then that one sequential decay mode is found while two other sequential decay modes cannot be distinguished from each other and from direct decay. Regardless, except for pronounced cases, a distinction requires a definition which probably would be model dependent.

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