Above threshold s-wave resonances illustrated by the $1/2^+$ states in ^{9}Be and ^{9}B

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We solve the persistent problem of the structure of the lowest $1/2^+$ resonance in ^{9}Be which is important to bridge the $A = 8$ gap in nucleosynthesis in stars. We show that the state is a genuine three-body resonance even though it decays entirely into neutron-^{8}Be relative s-waves. The necessary barrier is created by "dynamical" evolution of the wave function as the short-distance α-^{5}He structure is changed into the large-distance n-^{8}Be structure. This decay mechanism leads to a width about two times smaller than table values. The previous interpretations as a virtual state or a two-body resonance are incorrect. The isobaric analog $1/2^+$ state in ^{9}B is found to have energy and width in the vicinity of 2.0 MeV and 1.5 MeV, respectively. We also predict another $1/2^+$ resonance in ^{9}B with similar energy and width.

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Introduction Bound states, resonances and other continuum states are well understood and described for two particles interacting through a potential. By weakening the attraction of the potential bound states are pushed upwards into the continuum as resonances or virtual states when a barrier is present or absent, respectively [1]. For neutral particles virtual states arise for s-waves whereas resonances emerge for higher partial waves. Decreasing the attraction further until the resonance energy is above the potential barrier leads to an increase of the resonance width. Correspondingly the related S-matrix pole moves in the complex energy plane as a resonance with non-vanishing imaginary part.

For three particles interacting via two- and three-body potentials the continuum structures can be much more complicated due to combinations of the different structures for the three two-body subsystems [2, 3]. One intriguing possibility arises when one of the two-body subsystems has a low-lying s-wave resonance produced by a confining Coulomb barrier, and the third neutral particle has dominating s-wave attractions from the first two particles. Even when all higher partial waves are vanishingly small, the structure of the three-body continuum state is a priori not easily determined or described.

Let us assume that the two-body resonance is very narrow (long-lived) and the three-body energy is above zero but less than the two-body resonance energy. Then the three-body continuum state resembles a two-body bound state of the third particle and the composite resonance of the two first particles. The lifetime would be determined by the lifetime of the two-body resonance. When the three-body energy is pushed upwards above the two-body threshold by decreasing the attraction, the corresponding structure can be described as a two or three-body virtual state or resonance [1, 2].

The purpose of the present letter is first to determine in general which structure arises, and second specifically to solve the long-standing controversy of the ^{9}Be$(1/2^+)$ continuum state. This state is important in the nuclear synthesis of light nuclei in stars [4–6], and has therefore received lots of attention both theoretically [6–9] and experimentally [10–15]. In a measurement of photo disintegration the cross section is interpreted and parametrized via R-matrix analysis as one neutron and the ^{8}Be ground state in a two-body s-wave resonance [11]. This seems to be against the two-body quantum mechanical description as such a state cannot survive as a resonance. In another interpretation the same neutron-^{8}Be system is described as a virtual state [9] but the resulting cross section does not reproduce the measurement [11].

The ^{9}Be$(1/2^+)$ structure is most often assumed to be one neutron and the ^{8}Be ground state [10] but sometimes also the $\alpha + \alpha + n$ recombination reaction is assumed to proceed by α-capture on the ^{5}He ground state [6]. It is apparently very difficult to avoid assumptions of two-body sequential structures and processes via subsystems of either ^{8}Be or ^{5}He. Interestingly a two-center Born-Oppenheimer model based on symmetries alone may combine these structures as in [7] where the $1/2^+$ is lowest at large distance whereas a $3/2^-$ state is lowest at small distance. We shall allow an entirely general three-body structure without a priori assumptions of substructures or decay mechanisms.

Formulation Let us consider three composite structures as point-like particles denoted n, α_1 and α_2. The two mass scaled Jacobi vector coordinates, $(\boldsymbol{x}, \boldsymbol{y})$, can be substituted by hyperspherical coordinates $\{\rho, \alpha, \Omega_x, \Omega_y\}$, where (Ω_x, Ω_y) describe the directions of $(\boldsymbol{x}, \boldsymbol{y})$, $\rho = \sqrt{x^2 + y^2}$ and $\alpha = \arctan(x/y)$, see [3]. We solve this three-body problem by use of adiabatic hyperspherical expansion of the Faddeev equations, i.e. the angular equations are solved for each ρ, providing a set of an-