Physics Letters B 684 (2010) 132–136

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

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ARTICLE INFO

Article history:
Received 10 November 2009
Received in revised form 18 December 2009
Accepted 23 December 2009
Available online 8 January 2010
Editor: J.-P. Blaizot

ABSTRACT

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.

1. 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 [2,1].

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 [6,4,5], and has therefore received lots of attention both theoretically [6,7,9,8] and experimentally [10–12,14,15,13]. 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.

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0370-2693
doi:10.1016/j.physletb.2009.12.065

2. 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 angular eigenfunctions ϕ_n and their corresponding eigenvalues λ_n. The three-body wave function is then written as $\psi = \frac{1}{\rho^{5/2}} \sum_n f_n(\rho)\phi_n(\boldsymbol{x}, \boldsymbol{y})$, where n labels each of the adiabatic terms. The radial functions $f_n(\rho)$ are obtained after solving a coupled set of radial equations where the λ_n angular eigenvalues enter as effective adiabatic potentials. The coupling between the different adiabatic terms appears through the functions $P_{nn'}(\rho)$ and $Q_{nn'}(\rho)$ defined for instance in [3].

Each adiabatic potential describes a specific relative structure of the three particles for a given root mean square radius, ρ, with wave function ϕ and eigenvalue λ. When only one adiabatic potential is considered, the coupled set of radial equations reduces to

$$\left[-\frac{d^2}{d\rho^2} + \frac{\lambda(\rho) + 15/4}{\rho^2} - Q(\rho) - \frac{2m(E - V_{3b}(\rho))}{\hbar^2}\right] f(\rho) = 0, \tag{1}$$

where Q is the diagonal coupling term Q_{nn}, which is in general not zero (contrary to what happens with $P_{nn'}$, whose diagonal terms are zero). $V_{3b}(\rho)$ is the three-body potential usually used in three-body calculations to take into account all those effects that go beyond the two-body interactions. The total wave function, ψ, and Q are given by

$$\psi = \frac{1}{\rho^{5/2}} f(\rho)\phi(\boldsymbol{x}, \boldsymbol{y}), \qquad Q(\rho) = \left\langle \phi \left| \frac{\partial^2}{\partial \rho^2} \right| \phi \right\rangle_\Omega . \tag{2}$$

The expectation value is over angular coordinates, Ω, excluding only ρ. When only s-waves contribute for both $\boldsymbol{x}$ and $\boldsymbol{y}$ the angular wave function ϕ only depends on ρ and α. For short-range attractive two-body interactions the angular eigenvalue $\lambda(\rho)$ would be monotonously increasing towards a constant asymptotic value.

3. Narrow two-body resonance

When the $\alpha_1 - \alpha_2$ two-body s-wave interaction supports a bound state, the adiabatic potential approaches the bound state energy at large distance. This reflects a two-body structure corresponding to particle n far away from the $\alpha_1 - \alpha_2$ bound state. For less $\alpha_1 - \alpha_2$ attraction this state moves into the continuum. With a confining Coulomb barrier from repelling charges on the particles, the state would appear as a resonance at low energy E_2. The adiabatic potential would then approach the positive value equal to E_2 corresponding to the large-distance two-body structure of n far away from the resonance $\alpha_1 - \alpha_2$. We illustrate in Fig. 1 by the specific examples, ^{9}Be$(\alpha + \alpha + n)$ and ^{9}B$(\alpha + \alpha + p)$.

This description is only correct when the two-body resonance width Γ_2 is very small and the coupling to the three-body continuum states can be ignored. In general the first adiabatic potential is crossed by numerous others while ρ increases. However, the couplings are negligibly small for three-body energies E until distances $\rho \simeq 9\sqrt{E - E_2}/\Gamma_2$ where the energies are in MeV and ρ in fm. Thus for small Γ_2, say eV or keV, the couplings for moderate energies below 1 MeV can be neglected far outside the distance where the short-range $n - (\alpha_1 - \alpha_2)$ interaction has vanished. Then the system can effectively be described as a two-body system until the two-body resonance eventually decays.

Let us now consider the three-body system with interactions leading to a three-body state of positive energy E_r but below E_2. Effectively this is a bound $n - (\alpha_1 - \alpha_2)$ two-body state, or rather a resonance decaying precisely with the width $\Gamma_r = \Gamma_2$ of the $\alpha_1 - \alpha_2$ resonance. For less $n - (\alpha_1 - \alpha_2)$ s-wave attraction this two-body bound state moves into the continuum above E_2. The expectation is that the proper description is as a virtual state with no width in contrast to a resonance [9]. However, this is not necessarily true.

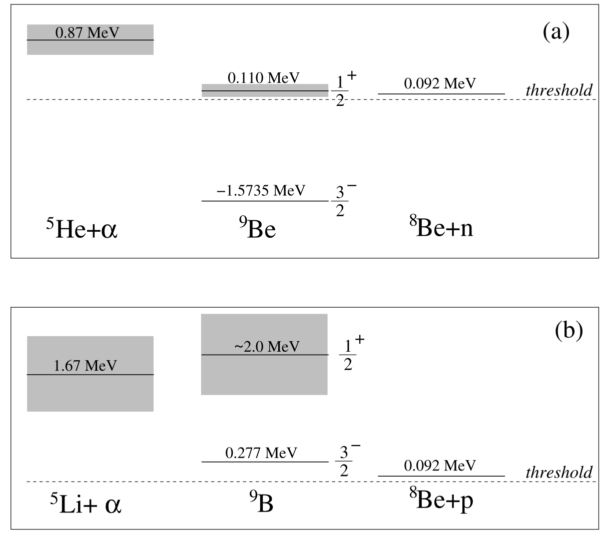

Fig. 1. The two lowest energy levels for ^{9}Be (a), and ^{9}B (b), and the resonance energies of the corresponding two-body subsystems [17]. For ^{9}B the quoted $1/2^+$ state corresponds to the estimation obtained in this work. The widths of the resonances are represented by the shadowed regions.

4. The ^{9}Be$(1/2^+)$ example

The low-lying states of ^{9}Be are expected to be well described as cluster states consisting of one neutron and two α-particles [16]. The $\alpha - \alpha$ interaction, including short range attraction and Coulomb repulsion, produces a low-lying s-wave two-body resonance at 0.0918 MeV with a width around 9 eV. Adding one neutron in s-waves leads to angular momentum and parity $1/2^+$ of the resulting three-body system. Such a state is listed in the tables of energies [17] at an excitation energy of 1.684 MeV, or 0.110 MeV above threshold, with a width of 0.217 MeV (see the upper part of Fig. 1(a)). Thus the state is above the two-body resonance energy by 0.018 MeV and s-waves are most likely the dominating composition.

The listed width is much larger than the distance to the two-body resonance threshold and even about two times larger than the three-body energy itself. It is a peculiar resonance structure which apparently extends into the bound state region below the threshold. These values are consistent with photodissociation cross section measurements and the entangled R-matrix analysis of an a priory assumed resonance [11]. The fitting parameters are position- and energy-dependent width of a two-body neutron–^{8}Be resonance of s-wave character. Several years prior to this analysis it was suggested that the state should be understood as a virtual state and the photodissociation cross section correspondingly analyzed [9]. However, this does not reproduce the measurements in [11].

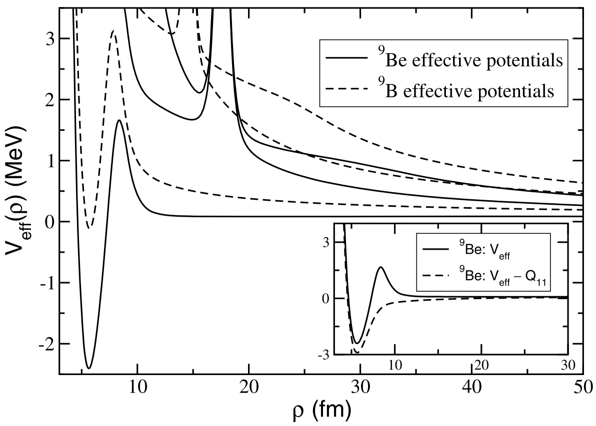

Fig. 2. Lowest adiabatic potentials for ^{9}Be and ^{9}B as a function of the hyperradius. The inset shows the ^{9}Be lowest potential with and without the rearrangement coupling term Q.

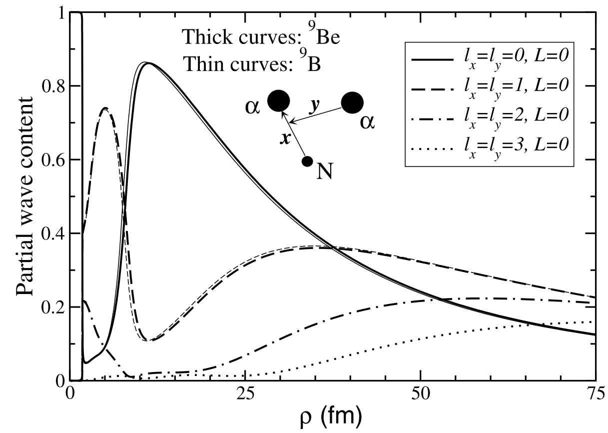

Fig. 3. The partial wave decomposition of the lowest adiabatic angular wave function for ^{9}Be (thick) and ^{9}B (thin) as function of hyperradius ρ. The partial angular momenta l_x and l_y correspond to the coordinates indicated in the figure. For $l_x = l_y = 2$ and $l_x = l_y = 3$ the curves for ^{9}Be and ^{9}B cannot be distinguished.

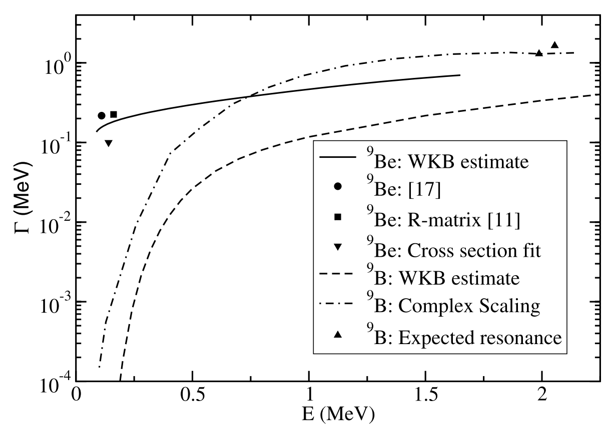

Fig. 4. Width of the resonances for ^{9}Be and ^{9}B as function of the energy which is varied through the strength V_0 of the three-body potential. The solid and dashed curves are the WKB results with a knocking rate corresponding to $\Gamma_0 = 0.6$ MeV ($\Gamma = \Gamma_0 e^{-2S}$) for both nuclei [21]. The dot-dashed curve results from complex scaling for ^{9}B. The square and the circle are from the R-matrix analysis in [11] and the table in [17], respectively. The down triangle is obtained by direct fit of the cross section in [11]. The triangles at about 2 MeV are the first and second resonances of ^{9}B.

5. Three-body results for ^{9}Be($1/2^+$)

The shortcomings of many previous methods are the initial assumption of two-body character of this structure. Since the final decay products are three particles we proceed to treat the system as a three-body system. We use the well established nucleon–nucleon and α–nucleon interactions from [18,19].

The adiabatic potentials produced through the adiabatic hyperspherical expansion method for these quantum numbers are shown in Fig. 2. The higher ones show pronounced peaks at about 15–18 fm. The origin of the peaks is in the crossing between different angular eigenvalues. In particular, the Q-functions in the effective potentials, (see Eqs. (1) and (2)), are responsible for the behavior shown in the figure in the vicinity of the crossings. These couplings involve second derivatives of the adiabatic eigenfunctions, and they therefore reflect restructuring of these functions. The lowest potential has a dominating attractive pocket at small distance. After hyperradii ρ larger than 12–14 fm the potential stabilizes at the resonance energy of 0.091 keV for the ^{8}Be ground state. This stable region continues until interrupted by the crossings with the (infinitely many) higher potentials. The first of these crossings occurs at about $\rho = 130$ fm.

An attractive pocket and a constant large distance potential without any barrier in the transition region is not able to support a resonance of finite width at energies above the large distance asymptotic value. However, inclusion of the coupling term Q (see Eq. (1)), provides an otherwise totally absent barrier as seen in the inset of Fig. 2. This all decisive barrier then arises from a strong ρ dependence of the intrinsic (angular) wave function ϕ, as seen from the definition in Eq. (2).

The three-body restructuring can be seen from Fig. 3 where the small distance structure of ρ less than 9 fm is p-waves between neutron and α-particles. This is due to the $p_{3/2}$-resonance which provides the main part of the attraction. As ρ increases above 10 fm this partial wave is rapidly substituted by s-waves which are energetically more advantageous at larger distance where the attraction vanishes and the centrifugal barrier dominates. At much larger distances an increasing number of partial waves contribute corresponding to the neutron far away from the two-body system of two α-particles in the spatially much smaller s-wave resonance, i.e. ^{8}Be in the ground state.

The combined result of the lowest adiabatic potential and the diagonal coupling is able to support a resonance. We compute the energy and width numerically as the S-matrix pole found by complex scaling [20]. By adding a structureless short-range potential ($V_{3b} = V_0 \exp(-\rho^2/\rho_0^2)$, with $\rho_0 = 5$ fm), which contributes only in the pocket region, we can move the resonance energy by modifying the V_0 strength but without disturbing the resonance structure. This is useful both because the three-body computation cannot place the resonance at precisely the correct measured energy, and because the width is strongly dependent on the height and thickness of the barrier at the correct energy.

In Fig. 4 we show the width as a function of the resonance energy. The solid line shows the WKB estimate for ^{9}Be. For an energy just above the threshold energy of the ^{8}Be ground state (0.0918 MeV) the width is about 0.1 MeV. This agrees with the result obtained by fitting the measured peak in the photodissociation cross section [11] (triangle down). The width increases slowly up to about 0.7 MeV at the top of the barrier. At smaller energies the width is vanishingly small due to the thick barrier provided by the ^{8}Be structure.

The complex scaling computations for ^{9}Be present numerical difficulties due to the fast increase of the width for energies above 0.0918 MeV. To get an estimate we have instead attached a unit charge to the neutron, which immediately leads to the results shown in Fig. 4 for the $1/2^+$ analog state in ^{9}B. A continuous decrease of the charge leads us back to ^{9}Be which is approached and finally reached by extrapolation. Unfortunately the accuracy only allows the conclusion that the width at an energy of 0.11 MeV is larger than 0.06 MeV and most likely around 0.1 MeV but 0.2 MeV is not numerically excluded. The inaccuracy is due to the very large width compared to the distance to the threshold. Then the poles computed by the complex scaling method are very difficult to distinguish from the continuum background. This becomes increasingly worse as the charge of the neutron is decreased from unity to zero where our present techniques prohibits a clean result.

Comparison to widths obtained in previous works requires precision in the definitions of a resonance. The ambiguities arise when the resonance is broad and then necessarily asymmetric. To account for the energy dependence of the decay probability the R-matrix theory employs an energy dependent width. This immediately implies that any number claimed to describe the width must be an average of some kind. The "observed" width in R-matrix theory is in [22] most directly related to the full width at half maximum, or the S-matrix pole, and then adopted as the width in tables of resonance properties [17]. The results quoted in [11] and [22] are shown in Fig. 4 by the square and the circle, respectively.

Our computed three-body resonance width is from the WKB tunneling and crude extrapolations from the imaginary value of the pole of the S-matrix. Our estimate is very inaccurate but we expect a value of about 0.1 MeV which is only about half the "observed" table value from R-matrix theory. This rather large discrepancy can be due to inaccuracies in the complex scaling extrapolation to zero charge of the neutron, or the WKB approximation of only one adiabatic potential combined with the uncertainty in the knocking rate estimate. However, we believe that the main reason is that our three-body barrier, which entirely is responsible for the width, arises from three-body restructuring effects inherently impossible to include in the R-matrix analysis. An unambiguous settlement of this accuracy issue would require the use of another method dedicated to precise width computations near threshold.

Attempts to settle the issue experimentally face the problems inherent to relatively very broad resonances. Population in a reaction or beta-decay provide information about lifetime, which necessarily is an average, or details about decay probability as function of energy, which requires a model for analyzing the data. The direct measurements in photo dissociation [11] reveal an asymmetric peak with a width of about 0.1 MeV. This is consistent with corresponding computations in the present model with a method to compute strength functions by discretization of the three-body continuum [23].

6. Three-body results for ^{9}B($1/2^{+}$)

The isobaric analog state should exist in ^{9}B but so far it has never been found. The influence of the additional Coulomb interaction in the present fragile case could be substantial and perhaps even destructive. The corresponding low energy three-body and two-body levels are shown in Fig. 1(b). To discuss this problem we also show in Fig. 2 the corresponding lowest adiabatic potential for ^{9}B. The additional Coulomb repulsion due to the proton in ^{9}B has a relatively small effect. At small distances the pocket is as pronounced but almost entirely above zero energy. The barrier is higher and thicker at small energy where the adiabatic potential itself already exhibits a small barrier. The same constant energy is approached at larger energies again corresponding to ^{8}Be in addition to the Coulomb tail from the proton. The partial wave decomposition in Fig. 3 resembles the ^{9}Be results with a tendency towards an increase of higher partial waves due to the additional Coulomb potential.

In Fig. 4 we show the WKB estimate (dashed line) and the resonance width obtained after a complex scaling calculation (dot-dashed line). In both cases the width is small even above the ^{8}Be ground state energy due to the additional adiabatic barrier and the extended Coulomb tail. However, the precise value of the energy depends on the three-body potential used in Eq. (1). A minimum value for the attractive strength of the three-body force can be obtained by placing the ^{9}Be resonance at the ^{8}Be resonance energy threshold. Using this three-body force we can then estimate a lower limit for the $1/2^{+}$ resonance in ^{9}B, which is found to be slightly below 2 MeV with a width of 1.3 MeV (left triangle up in the figure).

This resonance is accompanied by a second state at 2.05 MeV with a width of 1.6 MeV (right triangle up in the figure). This second resonance is very stable, basically independent of the structureless three-body force. Therefore, further decrease of the three-body attraction in V_{3b} would eventually make this second resonance at 2.05 MeV the first $1/2^{+}$ excited state. The two resonances are dominated by s- and p-waves between proton and α-particle, respectively. Crudely speaking these two structures correspond to ^{8}Be + proton and ^{5}Li + α. Since the large-distance p-wave properties essentially are unaffected by the three-body potential the second resonance remains close to the same energy. Thus the unobserved resonance in ^{9}B may in fact be either two or a combination of two resonances. In any case we expect genuine three-body structures with an energy around 2 MeV and a width in the vicinity of 1.5 MeV.

7. Discussion and conclusions

The $1/2^{+}$ continuum structures of ^{9}Be and ^{9}B are computed as genuine three-body resonances. The energies are above the threshold for forming the ground state ^{8}Be-resonance and the partial wave decompositions are dominated by s-waves in the Jacobi coordinates connecting the two α-particles and their center-of-mass and the nucleon. Nevertheless the Faddeev component corresponding to the other Jacobi coordinate presents a very different partial wave decomposition where the α-nucleon $p_{3/2}$ attraction maintain p-waves at hyperradii smaller than 9 fm rapidly changing into s-waves at 10 fm. This "dynamic evolution" from α-^{5}He at small distance to neutron–^{8}Be at intermediate and large distance reconciles the two limits for the resonance structure. The restructuring of the wave function results in a potential barrier similar to an above barrier reflection at a discontinuity.

The structures are then genuine three-body resonances mixing s- and p-waves at small distances while at large distances turning into a two-body system entirely of s-waves for a nucleon and ^{8}Be in the unbound ground state. The deceiving appearance as a two-body virtual state is incorrect. The interpretation as a two-body nucleon–^{8}Be resonance is also incorrect since the small-distance structure is of genuine three-body character and this is the very reason for the existence of a barrier allowing the appearance of resonance features. Furthermore the parameters from R-matrix analysis of the experimental data is misleading because of the incorrect but crucial assumption of the existence of a two-body nucleon–^{8}Be resonance.

The astrophysical $n\alpha\alpha$ recombination rate is probably unaffected provided the corresponding cross section is obtained by precisely the same parametrization for the measured inverse process of photodisintegration. The problem only seems to arise when a different procedure is applied in these mutually inverse processes. However, all resonance decays do not necessarily proceed through two-body channels.

The implication is that the decay mechanism is entirely through the ^{8}Be ground state as assumed in most previous publications. However, the present tabulated value of the resonance width emerges through an averaging procedure of data analysis and parametrization of a decaying two-body structure. The energy dependent width arising from the R-matrix interpretation as a two-body structure is suspicious since the three-body effects responsible for the barrier and the width are not included in the analysis. The true resonance lifetime should be related to the tunneling probability through the barrier arising from restructuring the three-body wave function. The width is more likely directly found from the peak in the measured cross section. We conclude that the controversy over the $1/2^+$ continuum structures of ^{9}Be and ^{9}B is resolved in a full three-body model.

Acknowledgements

We are grateful for many clarifying discussions with H.O.U. Fynbo and K. Riisager. This work was partly supported by DGI of MEC (Spain), contract No. FIS2008-01301.

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