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Schematic Model for Continuum Resonances in Heavy-Ion Reactions

B. J. Cole and C. Toepffer
Department of Physics and Nuclear Physics Research Unit, University of the Witwatersrand, Johannesburg, South Africa
and
K. Dietrich
Physik-Department, Technische Universität München, D-8046 Garching, Germany

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The small widths of high-lying resonances can be explained by a fragmentation of a quasimolecular shape resonance through coupling to at least two exit doorway states.

During the last years a sharp continuum structure has been observed in a number of heavy-ion (HI) reactions involving the compound systems ^{28,29}Si and ^{24}Mg. In particular, correlated resonances have been found in the excitation functions for elastic and inelastic scattering and the p-, n-, d-, and α-decay channels of the systems ^{12}C-^{16}O and ^{12}C-^{12}C. From the (often still tentative) spin assignments, it appears that the resonance energies exhibit a $J(J+1)$ dependence. It has therefore been conjectured that they form high-lying rotational bands. The individual experiments have been discussed in recent review papers.[1-3] The resonances in the various channels are strongly correlated in energy. In some reaction channels peak-to-background fluctuation ratios of more than 10 have been observed[4] which point to a nonstatistical origin. One might surmise that these resonances are related to the gross structure oscillations observed in the elastic excitation functions for various HI systems which have been interpreted in terms of shape resonances or quasimolecular (QM) states[5] forming rotational bands with a $J(J+1)$ law.[6] However, the resonances observed in the reaction channels have a typical width of a few hundred keV while the shape resonances are a few MeV wide. Remembering that the Breit-Wigner formula implies the *same* width—namely the total width—for a given resonance in all the decay channels, it seems difficult to explain the narrow resonances discussed here as a signature of QM states. We want to show in this paper that the sharp continuum resonances can indeed be understood as an intermediate structure caused by the coupling of the shape resonance as entrance doorway state to a few exit doorway states which in turn couple to the reaction continua.

In order to discuss the likely structure of these exit doorway states we consider as an example the resonance observed in ^{12}C(^{12}C, p)^{23}Na at $E_{\mathrm{c.m.}} = 19.3$ MeV corresponding to an excitation energy $E_x = 33.2$ MeV in ^{24}Mg. After the emission of protons with $l_p = 4$ the residual ^{23}Na nucleus is left in excited states at $E_x = 9.04$ MeV and $E_x = 9.81$ MeV which subsequently decay by γ emission. p-γ angular correlation measurements show that both states have a spin $j = \frac{15}{2}^+$.[7] The nuclear structure of these states has recently been investigated in a shell-model calculation which reproduces the ^{23}Na level scheme and also the γ branching ratios rather well. It turns out that each of the $\frac{15}{2}^+$ states carries about 50% of the ground-state rotational band strength.[8] From conservation of angular momentum ($\vec{J}=\vec{I}_p+\vec{s}+\vec{j}$, $s=\frac{1}{2}$) and parity, the angular momentum J of the doorway is confined to the range $4 \leq J \leq 12$. Since the angular momentum of the shape resonance at the excitation energy of $E_x = 33.2$ MeV is estimated to be about 12 (see Fig. 7.15 in Ref. 3), one is led to assume that the exit doorway for the p decay of the parent resonance in ^{24}Mg is a particle-hole (p-h) state in the continuum coupled to a collective rotational state so as to yield a total spin $J=12^+$. It should be noted that ^{24}Mg is strongly deformed[9] ($\beta_2 = 0.542$) so that there are $l=4$ components in the intrinsic wave functions for p-h excitations in the s-d shell region. We assume that there are exit doorway states of a similarly simple structure in the other resonating channels, in particular in the α-^{20}Ne channel, and that these reaction doorway states are coupled to the QM shape resonances in the elastic channel as entrance doorways. In fact, a comparison of the Nilsson model and the two-center shell model[10] shows that both single-particle level schemes are still quite similar at center-to-center distances around $R=4$ fm. Also the reciprocal moments of inertia $\frac{1}{2}h^2/\theta$ for the resonance band in ^{24}Mg and the $\frac{15}{2}^+$ states in ^{23}Na are about 110 and 150 keV corresponding to distances $R=4.3$ and $R=3.1$ fm, respectively, between the ^{12}C fragments in a rigid dumbbell.

We now study the following schematic model which is symbolically represented in Fig. 1: One entrance (1) and two exit (2, 3) doorway states are each coupled to one continuum (the elastic channel and two different reaction channels) which implies that each doorway state acquires an "unperturbed" width $\tilde{\Gamma}_c$ ($c=1, 2, 3$). The three doorway states are coupled to each other by matrix elements V_{ij}. The interaction between the continua is neglected. This model is a special case of a system of M bound states φ_j coupled to Λ continua which is treated in Chaps. 4.2b and 4.2d of Mahaux and Weidenmüller.[11] All the relevant formulas can be found there.

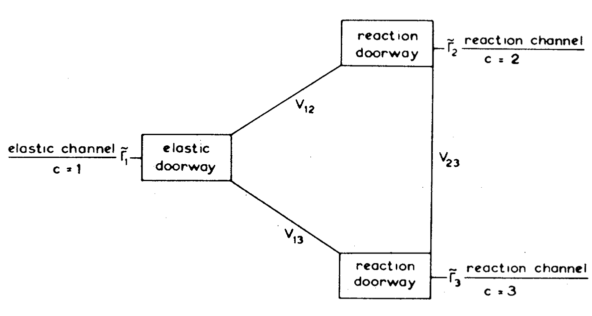

FIG. 1. The schematic model used in our calculations consists of an elastic shape resonance as entrance doorway and two reaction doorways which are coupled among one another with the strengths v_{ij} while the coupling to their respective continua is described by the unperturbed width $\tilde{\Gamma}_i$.

The input parameters are thus the unperturbed energies $\tilde{E}_i$, which are supposed to incorporate already the coupling of the doorway states into itself as well as the real part of its coupling to the corresponding channel c, the unperturbed widths $\tilde{\Gamma}_i$, and the coupling matrix elements F_{ij}. The interaction between the doorway states leads to shifts $\tilde{E}_i - \frac{1}{2}i\tilde{\Gamma}_i \rightarrow E_i - \frac{1}{2}\Gamma_i$ in the complex resonance energies at which the poles of the T matrix occur.[11,12] The sum of the total widths remains thereby unchanged:

$$\sum_{m=1}^{M} \Gamma_m \equiv \sum_{c=1}^{\Lambda} \sum_{m=1}^{M} \Gamma_{mc} = \sum_{m=1}^{M} \tilde{\Gamma}_m. \tag{1}$$

The strength of the mth resonance is determined by the residue ot the T-matrix pole at $(E_i - \frac{1}{2}i\Gamma_i)$, i.e., proportional to $\Gamma_{mc}^{1/2}\Gamma_{mc'}^{1/2}$, where Γ_{mc} is the partial width for decay of the interacting doorway state into channel c.

Under the assumption that each doorway state couples only to one continuum and that all continua are different from each other, one finds the sum rule

$$\sum_{m=1}^{M} \Gamma_{mc}^{1/2}\Gamma_{mc'}^{1/2} = 0 \text{ for } c \neq c'. \tag{2}$$

It follows from (2) that for a system of two doorway states coupled to two different continua (c, c') it is impossible to have fragmentation of only one of the unperturbed resonances; i.e., $|\Gamma_{1c}| \approx |\Gamma_{2c}| \neq 0$, $\Gamma_{1c'} = 0$, $\Gamma_{2c'} \neq 0$ contradicts (2). For $M \geq 3$, however, it may happen that at least one of the residues is small in a given reaction channel so that the effective width is smaller than in the case where all the residues are of comparable magnitude. A typical result is shown in Fig. 2: The shape resonance in the elastic channel ($c=1$) is fragmented into three peaks; i.e., it acquires an intermediate structure. At sufficiently low energy resolution these peaks coalesce into one gross structure resonance of about 3 MeV width. In each of the reaction channels one of the unperturbed resonances is completely suppressed. In channel $c'=2$, the two remaining resonances overlap thus forming a single asymmetric peak of width 700 keV. Similar features are obtained as long as the coupling matrix elements V_{ij} are smaller than about 1 MeV and the unperturbed

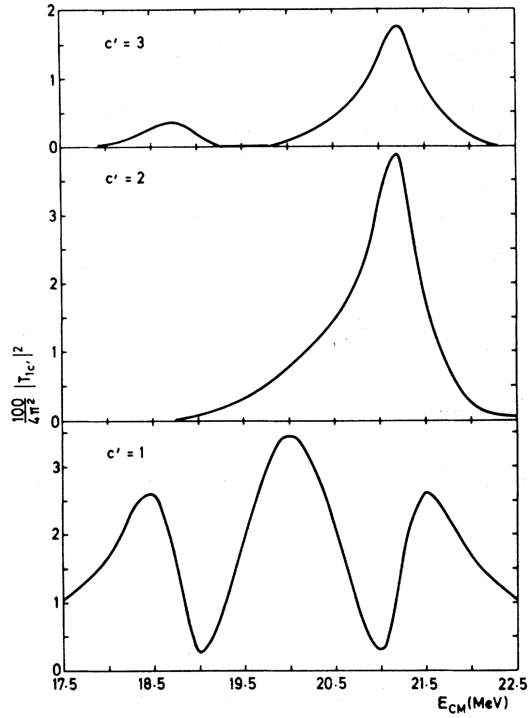

FIG. 2. The T-matrix elements for elastic scattering (lower part), and for the two reaction channels (center and upper part), as a function of the energy in the region of a shape resonance. The parameters employed in MeV, are $\tilde{E}_1 = 20.0$, $\tilde{E}_2 = 20.42$, $\tilde{E}_3 = 19.58$, $\tilde{\Gamma}_1 = 2.5$, $\tilde{\Gamma}_2 = \tilde{\Gamma}_3 = 0.25$, $v_{12} = 0.64$, $v_{13} = 0.67$, and $v_{23} = 0.92$.

widths $\tilde{\Gamma}_2$ and $\tilde{\Gamma}_3$ are small compared to the unperturbed elastic width $\tilde{\Gamma}_1$. Optical-model calculations for p-^{23}Na and α-^{20}Ne scattering show that the unperturbed widths we used (see caption of Fig. 2) are quite realistic for the energies and angular momenta carried away by the emitted[4] particles.

The three-doorway-state, three-continua model is the simplest system which is capable of exhibiting at the same time narrow resonances in the reaction channels and a fragmented gross resonance in the elastic channel. The actual situation is in general more complicated; i.e., more than three doorway states are to be coupled together. As long as the interaction between the channels can be neglected and the number of bound states embedded in the continuum is not too large, we expect the above-mentioned features to remain the same. More detailed investigations where the majority of the input parameters are calculated from microscopic theory are in progress.

We conclude with a few comments.

(i) In Scheid, Greiner, and Lemmer[13] the nonstatistical component in the *elastic* excitation function has also been interpreted in terms of a coupling of the entrance doorway to low-lying collective states which, in contrast to our model, have a vanishing width $\tilde{\Gamma}_{c\neq 1} \approx 0$. It cannot be excluded that both these origins of intermediate structure are of importance.

(ii) The omission of channel-channel coupling (i.e., direct reactions) represents a drastic assumption which is expected to hold only for special reactions like the ones considered. The effect of channel-channel coupling will be to broaden and finally wash out the peaks of the intermediate structure.

(iii) As the number of interacting doorway states becomes larger and their complexity increases, one approaches the conventional compound nucleus reaction. Therefore, a situation as described by our model is likely to exist in nuclei with good rotator properties where a large angular momentum, which at the same time reduces the number of available doorway states is taken up in the simple form of a collective rotation.

(iv) The assumption of a coupling of comparable strength between a number of doorway states is not what one would expect in view of the result of Deubler and Fliessbach,[14] where it was found that the QM resonances in the ^{16}O-^{16}O channel essentially couple to only *one* configuration of the intermediate ^{32}S. This result was reached as a consequence of symmetry considerations. One might conjecture that symmetry breaking which is also found to be of primary importance in Hartree-Fock and time-dependent Hartree-Fock calculations would alter the results of Ref. 14 so as to increase the number of effective doorway states.

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Dynamic Polarization Potential for Coulomb Excitation Effects on Heavy-Ion Scattering

W. G. Love[(a)]
University of Georgia,[(b)] Athens, Georgia 30602, and Oak Ridge National Laboratory,[(c)] Oak Ridge, Tennessee 37380

and

T. Terasawa[(d)]
Institute of Physics, College of General Education, University of Tokyo, 3-8-1 Tokyo, Japan

and

G. R. Satchler
Oak Ridge National Laboratory,[(c)] Oak Ridge, Tennessee 37830
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The very large deviations from Fresnel diffraction due to Coulomb excitation seen in heavy-ion scattering can be reproduced by a polarization potential which is derived without making the adiabatic approximation. This potential is predominantly imaginary.

Recent measurements[1-3] have confirmed that Coulomb excitation occurring during the scattering of two heavy ions can have dramatic effects upon the elastic cross sections when there is strong coupling to low-lying 2^+ states. The cross section deviates from the typical Fresnel shape by falling below the Rutherford cross section at small scattering angles which correspond to impact parameters much larger than those for grazing collisions. This is due to the long range of the Coulomb excitation interaction.

This effect can be reproduced by coupled-channel calculations which include Coulomb excitation.[1-3] However, these are time consuming and expensive, so there is considerable interest in having an effective potential to add to the usual optical-model potential which will reproduce this effect. We present here such a potential together with some applications.

The existence of such a polarization potential was suggested long ago.[4] However, previous attempts to construct it have relied upon an adiabatic approximation which results in a real potential; our approach shows that the polarization potential is predominantly imaginary.

We construct the potential to second order in the interaction V coupling the two ions. We will describe the derivation in detail elsewhere, but the essential approximation is to use plane waves in the intermediate states and to consider the effect of the potential acting on a plane wave. To lowest order, this is the approach used by Mott and Massey[5] for atomic collisions and it results in a local potential. We next make a sudden approximation in which it is assumed that the excitation energy of any important intermediate state is small compared to the bombarding energy. This yields a polarization potential for a 2^λ-pole excitation which has the form

$$U_{p,\lambda}(R) = -\frac{2\lambda+1}{16\pi}\frac{V_\lambda(R)}{E_{\mathrm{c.m.}}}\left[V_\lambda(R) + i2kF_\lambda(R)\right], \quad (1)$$