RESONANCES IN s-d SHELL NUCLEI

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Introduction

I would like to start out this talk with a mild critique of the field of heavy-ion resonance studies. We have been perhaps so bedazzled by the qualitative richness of phenomena, that we have forgotten some of the basic quantitative criteria that allow us to distinguish experimentally verifiable theories, from more nebulous points of view. I would like to comment on four points.

We are suffering from considerable semantic confusion in this field. There is a tendency to treat terms, such as "molecular resonances", "shape resonances", "rotational bands", "Regge trajectories", "barrier top resonances", "intermediate structures" as if they represented a set of well-defined orthogonal theories. In fact, they represent very similar, closely-linked models and people use the same terms to describe somewhat different concepts, or different terms to describe the same concept. We would all benefit if this nomenclature could be defined a little more clearly, so we may have assurance that when we hear a term we know which concept is meant, and not have to guess at it from the general context of the discussion.

Second, the criteria for identifying a resonance and assigning angular momenta, are not very strict. Often a Legendre polynomial is slapped on top of a few oscillations in an angular distribution and if the maxima line up, an unqualified spin assignment is quoted. I really believe one has to do more than that for the angular distribution and, whenever possible, one should try to follow the phase shift through a resonance. At the very least one should indicate the tentativeness of angular momentum assignments if the data are incomplete. Some examples of such problems are shown in Fig. 1.

Thirdly, the question of what is meant by a reduced width seems to be almost forgotten. Yet this is the only parameter, other than the energy and spin-parity of a resonance, that permits testing against models. The fraction of the single-particle width that is contained in a partial width depends sensitively on energy and angular momentum. In R-matrix theory¹ we have

$$\Gamma_{\lambda c} = \underbrace{\text{outside}}_{2kR^2} \times \underbrace{\text{inside}}_{\gamma_{\lambda c}^2}$$

where the outside term is readily calculable, requiring only the definition of a radius, and all the "inside" structure information is contained in γ^2 . This reduced width γ^2 then must be divided by the "Wigner-Teichman Limit"

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Fig. 1. Hypothetical angular distribution corresponding to a pure $L = 22$ resonance, alongside an equal coherent mixture of $L = 21$ and 23 amplitudes. Note that the two are indistinguishable over a limited range of angles, but become more easy to separate if data over an angular interval $\Delta \theta/2$ become available.

$$\theta_{\lambda}^2 \equiv \gamma_{\lambda}^2 / [3/2 (\kappa^2/MR^2)]$$

to give the single-particle fraction. The penetrability factors may be slightly in error because of uncertainties in radii and correction for diffuseness and there are refinements for large reduced widths arising from energy-derivatives of the shift functions—but it is better to have a uniform procedure that may be in error in some systematic way, than to have to rely entirely on qualitative statements.

And finally as my fourth pedantic complaint, I would like to mention the confusion regarding concepts of the mixing width (sometimes called Γ_{+}) and its connection to the imaginary potential. In the simple optical model,² the imaginary potential is introduced to provide the mixing between the simple model degree of freedom (the single particle state in the optical model) and the more complicated states of the nucleus. It simply provides a damping of the model wavefunction on the time scale corresponding to the width of the giant resonance. The quantities of interest are no longer the reduced widths of the individual fine-structure resonances, but the average reduced width or strength function. The reduced width of a whole bump may be extracted without reference to the details of the fine structure underneath. The extent of this mixing on the average is contained in the imaginary potential. But its magnitude does not depend on the fine structure level density as is sometimes assumed in the literature. As was shown many years ago in the estimate of radiative widths by Blatt and Weisskopf,³ the mixing matrix element per state is proportional to the "complexity" of these states, which in turn is inversely proportional to the density of states. If there is a more complex regime with a higher density of states, more states will be mixed with smaller matrix elements, but the energy spreading width will be unchanged. That is why we have

giant resonances with almost the same widths in heavy nuclei as light ones, even though the fine-structure level densities differ by many orders of magnitude. All this, of course, applies to all "simple" states mixing into more complicated ones. It does not matter whether it is a single-neutron state, a multipole giant resonance, or some other model configuration. The behavior of the strength function is a method of model testing that is schematically outlined in Fig. 2.

Fig. 2. Schematic representation of model testing by looking for giant resonances in a strength function. The top (a) represents a "perfect model" which puts all the strength into one state (e.g. the shell model for ^{209}Bi g.s.). The next (b) represents a rather good model, such as isobaric analog resonances; (c) is a typical giant resonance, such as the giant dipole resonance or neutron shape resonance; while (d) stands for a model description which may be technically correct, but not useful.

Optical Potential Surface Transparency

For one to see high angular momentum giant resonances in heavy-ion reactions it is a necessary (but not sufficient) condition that the imaginary potential be small in the relevant region. For high angular momentum states this is the surface region of the nucleus-nucleus potential. In Fig. 3(a) we show two such potentials differing only in the surface imaginary part, and Fig. 3(b) shows the dramatic result in the back-angle scattering. Such effects have been known for many years in back-angle alpha-particle scattering⁴—where these back-angle structures suddenly disappear as valence nucleons are added in a new oscillator shell. It seems qualitatively plausible that valence nucleons in a new (and larger) shell should suddenly increase the surface absorption, though we have no microscopic theory for imaginary potentials, comparable to the folding model for the real

Fig. 3. Elastic scattering for $^{16}\text{O} + ^{24}\text{Mg}$ calculated for two potentials in which the surface absorption has been modified, as shown in Fig. 3a, in the region critical for the $L = 20$ partial wave. Potential 1 has small surface absorption, while in potential 2 absorption is increased. The resulting scattering is modified somewhat at forward angles, and is drastically different at back angles.

potential. In heavy-ion reactions similar effects have been found, not only at closed oscillator shells, but in the middle of the s-d shell, where there are dramatic differences between the back-angle scattering of ^{16}O from ^{28}Si and ^{30}Si .⁵ Here the $s_{1/2}$ neutron shell is filling, which has a larger surface component and may thus have a strong influence on the surface damping.

But here, as may be seen in Fig. 4, there is also a strong resonance-like behavior in the back-angle scattering. Unfortunately the elastic scattering involves many partial waves and it does not seem very easy to make unique angular momentum assignments to these structures.

Fig. 4. Excitation functions at 180° for elastic ^{16}O scattering from $^{28,29,30}\text{Si}$ from Ref. 5. The average level of back angle yields is shown on the right.

Transfer Reactions

The difficulty with studying resonance effects in elastic and inelastic scattering is the fact, illustrated in Fig. 5 schematically, that there are relatively many partial waves contributing to the process—and the anomalous resonant behavior of one partial wave will not have a unique signature unless one has a very accurate model of the non-resonant processes. There are similar problems in inelastic scattering. The situation is, however, somewhat more favorable for a well-matched transfer reaction.

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Fig. 5. Schematic illustration of the number of partial waves contributing to elastic or inelastic scattering and a well-matched transfer reaction. The influence of one anomalous (resonant partial wave is shown as a dashed line.

Such is the case for $^{24}\text{Mg}(^{16}\text{O}, ^{12}\text{C})^{28}\text{Si}$, where, as we may see in Fig. 6, there are dramatic effects at 0° , 90° and 180° .⁶ The yield at forward angles is well correlated between the ground state of ^{28}Si and the

Fig. 6. Excitation functions for the $^{24}\text{Mg}(^{16}\text{O}, ^{12}\text{C})^{28}\text{Si}$ reaction at $\theta_{\text{cm}} = 0^\circ$, 90° , and 180° from Ref. 6.

1.78-MeV 2^+ state, as well as the 6.9-MeV 3^- and 9.7-MeV 5^- states. In fact, all the states strong in inelastic scattering on ^{28}Si seem to show the correlation over the resonances.⁷ Detailed angular distributions for the ground-state transition have allowed us to follow the phases through Breit-Wigner circles and assign angular momenta of 20^+ , 23^- , and (26^+) to the structures at 27.6, 30.8, and 36 MeV.⁶ Please note the critical role played by the excitation functions at 0° , 90° and 180° in these assignments (odd L states cannot appear at 90° and the lack of correlation between 0° and 180° must mean contribution from both odd and even parity states). The reduced widths we can only obtain as a product between the entrance and exit channel widths, since it has not been possible to locate the same resonances uniquely in the elastic channels, the values for $\sqrt{\theta_{\text{in}}^2 \theta_{\text{out}}^2} \approx 1\text{-}2\%$. The partial widths for the higher excited states of ^{28}Si can only be estimated roughly because angular distributions have not been measured. It appears that the reduced widths summed over the observed ^{28}Si states and the ^{24}Mg ground state are somewhere between 10 and 40% of the Wigner limit.

Our information on these resonances is still rather limited. We observe a spin sequence that does not fit any simple model. We know as yet nothing of the partial widths for these resonances to excited states of ^{24}Mg or some of the equally well-matched channels in $^{20}\text{Ne} + ^{20}\text{Ne}$. Perhaps they are structurally related to the ground states and strongly-coupled excited states of these nuclei.

The resonances continue up to higher excitation energy as may be seen in the 0° excitation function in Fig. 7. The corresponding excitation function at 180°

Fig. 7. Excitation function of the $^{24}\text{Mg}(^{16}\text{O}, ^{12}\text{C})^{28}\text{Si}$ reaction at 0° , using the superconducting linac booster at Argonne.

has also been measured and no simple pattern emerges—though some statements about the parities of underlying resonances may be made, as is summarized in Table I.

Table I

E_{cm}	J	π
27.6	20	+
30.8	23	-
36	(26)	+
38.5		-
41.5		(-)
43.5		(+)
46		(-)
50.5		(-)

The general decrease in cross sections is mirrored in the predicted decrease of the direct reaction calculation—but the forward-backward asymmetry seems to remain at roughly 10:1.

Other systems have been investigated in searching for such resonances. These seem much weaker in $^{26}\text{Mg}(^{16}\text{O}, ^{12}\text{C})$ and in $^{28}\text{Si}(^{16}\text{O}, ^{12}\text{C})^{32}\text{S}$.

Conclusion

It appears that the system we have studied here, representing ^{40}Ca as the composite nucleus, is perhaps the heaviest one that exhibits strong enough resonances that quantitative measurements may be contemplated. But we have uncovered only a small corner of what is there and even within this system a huge amount of work remains. The work so far represents perhaps 3 man years of research effort. There is easily an order of magnitude more work remaining, unless there is a substantial improvement in detection techniques.

The nature of these resonances is not yet clear. The sequence may perhaps have an explanation that is schematically outlined in Fig. 8, namely that there are several families of quasistationary states in ^{40}Ca , but that the slopes of these families do not necessarily coincide with the slope of the grazing partial waves that provide us with a narrow transparent strip of a window on the underlying structure of the nucleus. We must concentrate a lot of effort and ingenuity in order to maximize the information we gather through this window and only then may we hope to sensibly attempt forming hypotheses about the underlying simple pattern.

That the structures we see are "simple" is clear from the fact that we are in the region of ^{40}Ca where the density of states is higher (by 3-6 orders of magnitude) than the spacing of the observed structures. It is not clear whether the fact that the structures appear primarily in alpha-particle nuclei may have some

Fig. 8. Schematic representation of a possible interaction between the transparency of the "grazing window" and some underlying ordered structure in heavy-ion scattering or reactions.

special structural significance—or whether it may be a feature of the transparency in the reaction mechanism. A lot of hard work remains but the evidence that there is some relatively simple underlying order appears to be overwhelming.

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