THE ROLE OF GIANT RESONANCES IN HEAVY-ION RADIATIVE CAPTURE

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INTRODUCTION

The capture reactions discussed at this conference have dealt almost exclusively with the radiative capture of light particles (n, p, He). These reactions have been used in a variety of ways for many years as spectroscopic tools. In contrast, much less is known about the radiative capture of heavier ions. This, and the following review by Snover, attempt to summarize the main features and physics of heavy-ion capture.

Very generally, the deexcitation process in such a reaction can follow one of the routes shown schematically in Figure 1. In case (a) the compound nucleus loses energy by the emission of a high-energy gamma ray to states below particle-emission threshold (t_p). Subsequent gamma decay then leads to the fused nucleus in its ground state. It is the experimental information on this process that is discussed here. Type (b) radiative transitions, involving high-energy gamma decay to specific states above t_p , become increasingly difficult to separate from the background as the gamma-ray energy decreases. In fact this process (b) has only been observed when decays to many different final states coincide in transition energy. Such is the case for the decay of large numbers of giant resonances, one built on each excited level that is statistically populated in a heavy-ion reaction. This latter process is reviewed by Snover.

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Fig. 1. Possible radiative decay routes following heavy-ion capture.

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GENERAL CONSIDERATIONS FOR DECAYS TO BOUND LEVELS

The most interesting characteristic of radiative decays to levels below t_p (Fig. 1) is the presence of resonances that exhibit nonstatistical heavy-ion partial widths. Most of these structures are not correlated with previously identified features in other heavy-ion reaction channels. However, there are three factors that strongly affect the likelihood of observing such resonances. First of all, the multipolarity of high-energy gamma-ray transitions is very unlikely to be greater than 2. ¹⁾ Since the spins of states below t_p are generally low ($J \leq 5$), these transitions can be observed only if the spins of the capturing states are relatively low. With heavy-ions, these states can be excited only in the vicinity of the Coulomb barrier, which is much more well-defined than it is in light-ion reactions. As the heavy-ion bombarding energy is increased above the barrier, the cross section for forming the compound nucleus peaks at increasingly higher spin, with the result that at energies above about twice the barrier high-energy gamma decay to bound levels is greatly diminished. A second consideration is that, the average capture yield is always indirectly dependent upon the location of giant electromagnetic resonances. The dependence arises simply because the capture cross section is proportional to Γ_γ , the radiative width, and sum rules restrict the total radiative width of a given multipolarity. If nearly all of the strength is contained in a giant resonance (GR) at an energy E_{GR} , then the magnitude of Γ_γ , and hence the capture cross section, cannot help but be greatly reduced at energies significantly different from E_{GR} . However, this is a dependence imposed by sum rules and need not necessarily reflect any structural similarity between the capturing states and giant resonances. Finally, the behavior of the Coulomb barrier, and the sum-rule restrictions on the total Γ_γ available, effectively limit heavy-ion capture measurements to s-d shell nuclei. For heavier projectiles and targets, the Coulomb barrier is significantly higher, while the giant resonances, which change in position with $A^{-1/3}$, are shifted to lower energies. The farther the barrier is from the GR, the more difficult radiative capture will be to observe. (This, of course, ignores the possibility of high-lying pockets of multipole strength, about which little experimental information is available.)

These general considerations are indeed born out by the available experimental data. But apart from these, it is difficult to isolate trends that persist through the various systems that have been studied. The decays to the ground state of the compound nucleus, or to the members of its rotational band, should be the easiest to understand, since the wavefunctions of these final states are fairly well understood and since the giant multipole strength built upon them has been measured. This information has been used to deduce interesting and unexpected characteristics of resonances in the decays to low-lying levels. However, these characteristics vary considerably among different heavy-ion systems. Most of the

capture data is in this general category. However, in at least one case, decays have been observed to higher-lying levels that are shape-isomers of the compound nucleus, and these results are particularly simple to interpret. Data from three reactions -

are discussed here as examples of heavy-ion capture. A more extensive review is given in reference 2. Large anticoincidence-shielded NaI spectrometers were used for these measurements, and these are described in reference 3. In addition to the obvious requirements of good energy resolution and efficient cosmic-ray rejection, the small cross sections encountered in these reactions necessitate using high beam currents and maintaining a stable gain at high counting rates for periods of typically 6 hours in duration. The experimental problems peculiar to heavy-ion capture are discussed in some detail in reference 2.

DECAYS TO THE GROUND STATE AND ITS ROTATIONAL BAND

One of the more extensively studied heavy-ion capture reaction is the fusion of two ^{12}C nuclei leading to low-lying levels in ^{24}Mg . A typical spectrum is shown in Fig. 2. The decays to the ground

state of ^{24}Mg , 1.37 MeV (2^+) first excited state, and 4.1-4.2 MeV ($4^+ - 2^+$) second and third excited states are clearly visible. The peaks are superimposed upon a smooth background due primarily to the pileup of many lower-energy events. Spectra taken at energies below the Coulomb barrier often show additional lines corresponding to decays to higher lying levels.

Fig. 2. A high-energy gamma-ray spectrum from the $^{12}\text{C}(^{12}\text{C}, \gamma)^{24}\text{Mg}$ reaction.

The $\theta_\gamma = 45^\circ$ excitation functions for these transitions are shown in Fig. 3. There are two striking features of these data. First, as we have already anticipated, the yield is localized in the vicinity of the Coulomb barrier (6.6 MeV c.m.), especially in the γ_0 channel where it extends from 19 MeV excitations up to about 24 MeV. Second, within this gross structure, there is considerable finer structure in the form of narrow ($\Gamma < 0.3$ MeV) resonances, several of which are correlated in all three γ -decay channels.

For identical bosons in the entrance channel, the J^π of the compound state is limited to 0^+ , 2^+ , 4^+ , The observation of a photon decaying to the 0^+ ground state rules out 0^+ assignments for structures appearing in this channel, and makes multipolarities greater than 2 extremely unlikely.¹⁾ Thus, all of the yield in the

$^{12}\text{C}(^{12}\text{C}, \gamma_0)$ reaction arises from 2^+ states in ^{24}Mg and exhibits a $\sin^2(2\theta\gamma)$ angular dependence. The dashed line through the γ_0 excitation function is the result of a fit to an incoherent sum of Breit-Wigner resonances.⁴⁾ The fit falls below the data near 20.3 and 21.3 MeV excitation, which may indicate contributions from additional less prominent structures. The dashed lines through the γ_1 and $\gamma_{2,3}$ excitation functions are merely to guide the eye.

Fig. 3. Excitation functions for $^{12}\text{C} + ^{12}\text{C}$ radiative capture to the low lying levels of ^{24}Mg .

A great deal of structure has been observed in $^{12}\text{C} + ^{12}\text{C}$ reactions ranging from below the Coulomb barrier up to more than six times the barrier. A large number of resonances have been reported in elastic, inelastic, and a variety of reaction channels, and most of these are viewed as resulting from the formation of some kind of nuclear molecule. In Fig. 4 the $^{12}\text{C}(^{12}\text{C}, \gamma_0)$ excitation function (Fig. 4b solid curve) is compared with the previously identified 2^+ $^{12}\text{C} + ^{12}\text{C}$ "quasimolecular" resonances above 5.0 MeV c.m. (Fig. 4c). The γ_0 peak at 5.6 MeV corresponds to a 2^+ quasimolecular resonance. However, the more prominent peaks at 6.0, 6.8, and 8.0 MeV c.m. do not correlate with any known $^{12}\text{C} + ^{12}\text{C}$ 2^+ structures. Furthermore, the average width of a 2^+ level between 19 and 23 MeV excitation in ^{24}Mg is about 20 KeV, while the total widths of the capture resonances of Fig. 4b are an order of magnitude larger. An Ericson fluctuation phenomenon⁵⁾ can thus be ruled out.

The best available data on the distribution of E2 strength built on the ^{24}Mg ground state have come from several high-energy $^{24}\text{Mg}(\alpha, \alpha')$ experiments. If this E2 strength would entirely fission into two ^{12}C nuclei, then the corresponding capture cross section would be given by the curve in Fig. 4a.⁴⁾ Upon comparing Figure 4a with Figure 4b, solid curve, we see that the small 5.6-MeV c.m. resonance seems to be correlated with a peak in the E2 strength function. However, the 6.0- and 6.8-MeV c.m. resonances line up with valleys in the E2 distribution, while the 8.0 MeV c.m. resonance appears near the middle of a much broader structure. On the whole, the pronounced features of the capture yields do not directly reflect

Fig. 4 (a) Predicted cross sections for capture through the giant quadrupole resonance in ^{24}Mg .

(b) The $^{12}\text{C}(^{12}\text{C}, \gamma_0)^{24}\text{Mg}$ excitation function (solid line) and various calculations - see text.

(c) The locations of 2^+ quasimolecular states. Total widths of resonances are indicated in MeV.

The statistical model can also be used to estimate statistical photon decay, that is the decay of a resonance excited in the $^{12}\text{C} + ^{12}\text{C}$ channel (i.e., a resonance in Γ_c) which then mixes into the underlying compound levels, and emits a photon by virtue of the E2 strength of these underlying levels. If each of the resonances observed in $^{12}\text{C}(^{12}\text{C}, \gamma_0)$ were due to resonances in Γ_c then, assuming reasonable values for the elastic width, statistical photon decay would produce the dotted curve in Fig. 4b. This curve peaks wherever the data does, but of course that is by construction. What is important here is the relative magnitude. The γ_0 decay of the 5.6-MeV c.m. resonance (the only one that has been observed in other channels) is completely consistent with the process of statistical mixing into the compound nucleus followed by E2 γ decay. The magnitude of the 6.0-MeV resonance predicted by this calculation is about a factor of 2 below the data. This process could account for the 6.0-MeV γ_0 peak if Γ_c/Γ were as large as 0.30. However, this would be grossly inconsistent with elastic-scattering measurements.

the structure in Γ_c . Before trying to interpret the unusual features of this capture reaction, it is useful to know the extent of the contributions to the cross section from the process of compound nucleus formation followed by competitive statistical decay.^{2,4} If the carbon widths were purely statistical, then a Hauser-Feshbach calculation would predict a capture cross section given by the dashed curve in Fig. 4b. Viewing the reaction backwards, this would correspond to the process in which a photon excites the ^{24}Mg nucleus into its giant quadrupole resonance, which then mixes into the compound levels and decays statistically into two ^{12}C nuclei. This calculation reflects the structure of Fig. 4a. However, over most of the excitation function, it falls far below the data. Nonetheless it does succeed in explaining the drop in cross section below 5.5 MeV c.m. as resulting from the Coulomb barrier.

The other peaks in the γ_0 yield are far above the dotted curve.

Since statistical photon decay causes the 5.6-MeV c.m. resonance to appear in the $^{12}\text{C}(^{12}\text{C}, \gamma_0)$ excitation function, the other 2^+ quasimolecular resonances of Fig. 4c would also be expected, at some level, and this is given by the circle-dashed curve in Fig. 4b. These contributions are always small compared with the dominant features of the γ_0 yield. The conclusion from this analysis is that the photon widths of the capture resonances are, for the most part, significantly enhanced over statistical widths.

We can draw two conclusions from these statistical calculations. First, at least one and possibly all of the previously identified quasimolecular resonances (Fig. 4c) are present in the radiative capture yields, but only at a very low level consistent with a statistical γ decay to ^{24}Mg . Second, the $^{12}\text{C} + ^{12}\text{C}$ and the γ_0 decay probabilities of the dominant resonances observed in radiative capture are significantly greater than statistical probabilities for decay from the compound nucleus. These capture resonances must then reflect states with large $^{12}\text{C} + ^{12}\text{C}$ parentage that also have a close link with the structure of the ground state of ^{24}Mg . The wave functions of the levels in the ground-state rotational band (GSB) of ^{24}Mg are very similar, and thus 2^+ levels that decay strongly to the ground state would also be expected to have significant decay branches to the 2^+ and 4^+ members of the GSB. This is exactly what is observed in Fig. 3. The dominant 2^+ peaks at 6.0, 6.8 and 8.0 MeV are present in the γ_1 and $\gamma_{2,3}$ excitation functions as well as in γ_0 . (In contrast, the 5.6-MeV quasimolecular resonance appears only in the γ_0 excitation function. However, the γ decay of this resonance arises from statistical photon emission from an overlapping peak in the distribution of ground-state E2 strength. The E2 strength built on excited states of ^{24}Mg may be very different, and thus γ decay to the ground state via statistical photon emission does not guarantee a comparable decay rate to other members of the GSB.) These capture resonances are undoubtedly present in elastic scattering at some level due to their nonstatistical ^{12}C widths, but they have evidently been hidden by the much more dominant quasimolecular structures.

From these considerations it would seem that the heavy-ion capture reaction is a sensitive way of picking out unusual states of a nucleus that like to fission after absorbing a photon. This is an exciting prospect, which seems to fall completely apart when one looks at other heavy-ion systems. Recent results from the $^{14}\text{C}(^{12}\text{C}, \gamma)^{26}\text{Mg}$ reaction are reported in a contribution to this conference.⁶⁾ The excitation functions for decay to the low-lying states of ^{26}Mg are shown in Fig. 5. Some of these yields do indeed exhibit peaks with cross sections and widths comparable to the resonances of $^{12}\text{C}(^{12}\text{C}, \gamma)$, but these do not appear at the same c.m. energy. In particular, the yields to the 0^+ ground state, and to the 2^+ and 4^+ members of its rotational band at 1.81 MeV and 4.32 MeV, respectively, show essentially no structural similarities.

Although forbidden by the symmetry of the $^{12}\text{C} + ^{12}\text{C}$ system, E1 dipole radiation is both symmetry and isospin allowed in the

Fig. 5. Excitation functions for $^{12}\text{C} + ^{14}\text{C}$ radiative capture to the low lying levels of ^{26}Mg .

those observed in the ground state GDR. This suggests either that the GDR's built on excited states of ^{26}Mg are very different, which seems unlikely,¹²⁾ or that the photon widths are nonstatistical. The nature of the intermediate structure that gives rise to the yields of Fig. 5 is evidently quite complicated.

As a final example of heavy-ion capture, leading to the ground state band of the fused system, the γ_0 and γ_1 excitation functions of the $^{12}\text{C}(^{16}\text{O}, \gamma)^{28}\text{Si}$ reaction are shown in Fig. 6.⁸⁾ Again, as anticipated, relatively narrow resonances are present, which appear with cross sections comparable to those of $^{12}\text{C}(^{12}\text{C}, \gamma)$, and these are localized in the vicinity of the Coulomb barrier (8.7 MeV c.m.). However, the resonances do not appear simultaneously in γ_0 and in γ_1 and the cross sections for γ_0 decay are, for the most part, surprisingly small.

Since the ground state of ^{28}Si is oblate while the incoming heavy-ion channel is inherently prolate, the small γ_0 yield may be viewed as resulting from the inability to connect these two intrinsic shapes with a simple electromagnetic operator. Unfortunately, the same argument can be made for the γ_1 yield since the wave functions of the ground- and first-excited states of ^{28}Si look very much alike.⁹⁾ Alternatively, the resonances could be of spin higher than 2^+ , 3^- or 4^+ , for example. Since the multipolarity of the γ transitions is effectively restricted to 1 or 2, decays to the 1.78 MeV 2^+ first excited state could be observed, while decays to the ground state would be precluded. Angular distributions were measured at the positions indicated by the arrows in Fig. 6.²⁾ For the γ_1 peaks, these are not strictly definitive because of the $J^\pi = 2^+$ final state. Nonetheless, several of the peaks in Fig. 6 are quite well isolated and a unique spin and γ -ray multipolarity might well dominate each.

$^{14}\text{C}(^{12}\text{C}, \gamma)$ reaction, and indeed the radiation patterns indicate strong dipole components. Since E1 transitions can have much larger radiative widths than E2 decays, the excitation functions of Fig. 5 might have significant contributions from statistical carbon decay of the giant dipole resonance (GDR.) This question has been investigated in Ref. 6. Elastic scattering is almost devoid of any structure in this energy range,⁷⁾ suggesting that the carbon widths are largely statistical. With this assumption the photon absorption cross sections inferred from the capture data are factors of 2 to 10 less than

Fig. 6. Excitation functions for $^{12}\text{C} + ^{16}\text{O}$ radiative capture to the low-lying levels of ^{28}Si .

capture cross sections still fall far below the resonances of Fig. 6. This largely due to the increased Q value and Coulomb barrier which pushes the structures to higher excitation energies far above the quadrupole resonance in ^{28}Si . However, the GDR still has appreciable strength at these energies, and for the ground state transitions, dipole radiation is allowed by symmetry, although still inhibited by isospin. The γ_0 cross sections of Fig. 6a may well be accounted for by assuming statistical heavy-ion widths and γ decay through a small isospin-split component of the GDR.²⁾ This still leaves the dominant peaks of the γ yield which may have very nonstatistical carbon widths, as we have inferred. However, since they do not appear in the γ_0 excitation function, they would not be expected in $^{12}\text{C} + ^{16}\text{O}$ elastic scattering, which indeed shows almost no structure in this energy range.¹⁰⁾

In summary, the $^{12}\text{C}(^{12}\text{C}, \gamma)$ data and analysis provided the tantalizing suggestion that heavy-ion capture was a very sensitive tool for picking out unusual highly-deformed states of a nucleus that are simply connected to the ground state, and to its rotational band. The sensitivity to unusual highly-deformed structures is undoubtedly there, but it would seem that the connection, the intermediate structure leading to large photon and heavy-ion partial widths, is far from simple. Except for $^{12}\text{C}(^{12}\text{C}, \gamma)$ which seems to be somewhat anomalous, these structures do not resonate in the yields to all of the members of the GSB. It is more generally the case that the excitation functions to different members of the GSB are very different.²⁾

The 9.8-MeV resonance is likely a $4^+ \rightarrow 2^+$ decay, and so its absence in the decay to the 0^+ ground state is not surprising. However, the distributions for the 7.3-MeV c.m. and 8.5-MeV c.m. resonances suggest $J^\pi = 2^+$ assignments. These could decay to the ^{28}Si ground state, but do not, for as yet, unknown reasons.

An analysis of statistical decay probabilities is a bit more difficult here, since the more pronounced resonances occur in the γ_1 excitation function and the multipole strength built on the first excited state of ^{28}Si is unknown. Nevertheless, under the assumption that, on the average, the distribution of $E2$ strength built on the 2_1^+ state is just shifted up by 1.78 MeV from that built on the ground state, the calculated

CAPTURE THROUGH GDR'S BUILT ON SHAPE-ISOMERIC STATES

One might have thought that if capture to the ground state was difficult to understand, capture to a highly-excited state would be hopeless. Delightfully, there are at least some transitions for which this is not the case. In the course of the $^{12}\text{C}(^{16}\text{O}, \gamma)$ measurements described above, unusually strong transitions were observed to the 0_3^+ at 6.69-MeV excitation in ^{28}Si , with cross sections at least five times larger than the decays to the low-lying levels.⁸⁾ Although the ground and low-lying states of ^{28}Si are oblate, this 0_3^+ has been identified as the bandhead of a $K = 0$ prolate shape-isomer.^{9,11)} Enhanced high-energy gamma-ray transitions are usually characteristic of giant electromagnetic resonances. Some examples of such structures built upon excited states have been discussed by Dowell,¹²⁾ although none of these states involve a shape change. Capture through the heavy-ion channel would normally be a rather improbable way of looking for such giant resonance strength. However, since the incoming heavy-ion channel has inherently a large prolate distortion, heavy-ion capture will be much more sensitive to prolate shape-isomers than light-ion reactions, most of which involve relatively minor deformations.

The possibility of comparing giant resonances built upon different intrinsic shapes within a single nucleus is quite exciting. However, measurements of transition rates to excited final states, where the gamma-ray energy is significantly less than the maximum (the γ_0 transition to the ground state), are extremely difficult because of large backgrounds. These come mainly from the pileup of the very large numbers of low-energy signals, and increase very rapidly with bombarding energy. Essentially all of these backgrounds can be removed by detecting the fused compound nucleus in coincidence with the high-energy photon. A crossed $\vec{E}$ and $\vec{B}$ field velocity selector has been used for just such measurements and, as described in ref. 13, this technique reduces pileup backgrounds by up to four orders of magnitude.

These coincidence measurements revealed strong transitions, not only to the 0_3^+ , but also to the 2_1^+ and 4_1^+ members of this prolate band at 7.41-MeV and 9.16-MeV in ^{28}Si , respectively. Their excitation functions are shown in Fig. 7. The decay to the 6.7-MeV 0_1^+ is substantially stronger than to the 7.4-MeV 2_1^+ . The 4_1^+ is very β near the 6_1 at 8.54-MeV which was strongly β populated at a few bombarding energies, and it was not always possible to clearly separate the two. For this reason, only the sum of their yields is plotted in Fig. 7c. All three excitation functions display prominent peaks which are uncorrelated with center-of-mass energy. (This, again, is in contrast to $^{16}\text{O} + ^{12}\text{C}$ elastic scattering which shows very little structure below 12-MeV c.m.¹⁰⁾ However, the three lowest energy peaks in the 0_1^+ and 2_1^+ yield curves occur at the same excitation energy above the final state (i.e. at the same gamma-ray energy). This is evident in Fig. 8 where the $\sigma(\gamma)$ deduced for these decays is plotted against E_γ (see below). The second narrow structure in the $6_1^- - 4_1^+$ yield of Fig. 7c also lines up with one of these

Fig. 7. Excitation functions for $^{12}\text{C} + ^{16}\text{O}$ radiative capture to the members of the excited prolate band in ^{28}Si .

Fig. 8. Total absorption cross sections deduced from Fig. 7 under the assumption of statistical heavy-ion widths, and (bottom) the GDR of the ^{28}Si ground state.

peaks at $E_\gamma = 19$ -MeV, although the ambiguity of the final state makes the comparison with the 0_p^+ and 2_p^+ yields difficult.

The capture yields as displayed in Fig. 8 are remarkably similar to the GDR built on the oblate ground state of ^{28}Si . The photoabsorption data, showing the latter, are reproduced at the bottom of Fig. 8.¹⁴⁾ The envelopes of these three excitation curves are very nearly the same. Much of the intermediate structure in the gamma-ray strengths built on the 0_p^+ and on the 2_p^+ is the same, and the peak at $E_\gamma = 19$ -MeV even persists in the ground-state photoabsorption data. The angular dependence of the transitions to the 6.7-MeV 0_p^+ state, measured at several beam energies, is always strongly peaked at 90° indicating a dominant dipole component. The capture data of Fig. 8 are strongly suggestive of GDR's built upon the members of the prolate band in ^{28}Si .

The transition strength to the 0_p^+ level shown in Fig. 7a exhausts $0.14 / \langle \Gamma_{16} / \Gamma \rangle$ percent of the energy-weighted classical dipole sum rule. A Hauser-Feshbach calculation, taking into account isospin mixing in ^{28}Si , has been used to estimate the branching ratio $\langle \Gamma_{16} / \Gamma \rangle$,¹³⁾ and it is these results that are plotted in Fig. 8. In the calculation of $\sigma(\gamma)$ for the 2_p^+ state, radiative capture through 3^- levels was assumed. The calculated branching fraction is a smoothly varying function of E_γ and the structure of Fig. 8 reflects that of the capture data. The resulting absorption cross sections of Fig. 8 account for 1.9 ± 0.3 and 0.3 ± 0.1 classical sum rules built on the 6.7-MeV 0_p^+ and 7.4-MeV 2_p^+ levels, respectively.

These data and calculations are consistent with giant dipole excitations of the prolate intrinsic shape of ^{28}Si . However, it is surprising that the prolate-GDR appears narrower than the oblate ground-state GDR, since the widths of GDR's built on excited states increases with energy.¹²⁾ A lack of significant broadening of the giant resonance might be reasonable if the 6.7-MeV 0_p^+ is viewed as the ground state of the prolate shape, and indeed the mixing between prolate and oblate states in ^{28}Si is very small.⁹⁾ Nonetheless, the quadrupole moment of the prolate states (+876mb) is twice as big as that of the oblate states (-480mb),¹¹⁾ and all models coupling deformation degrees of freedom to the GDR would predict a significantly broader prolate giant resonance.

Prolate shape isomers have been predicted in other s-d shell nuclei, notably ^{24}Mg , ^{32}S and ^{40}Ca ,^{15,16)} and it would be extremely interesting to study the giant resonances built upon such states. Isomers in these nuclei have yet to be identified. On the other hand, the inherently prolate entrance channel makes heavy-ion radiative capture a rather selective tool in the search for these unusual states. There are in fact, specific predictions for the $^{16}\text{O}(^{16}\text{O}, \gamma)^{32}\text{S}$ reactions leading to an isomer at 8-MeV in ^{32}S .¹⁶⁾ We have investigated this reaction. However, no unusually strong transitions were observed in the predicted energy range (11 to 13-MeV c.m.).¹⁷⁾ The symmetry of the entrance channel does preclude dipole radiation, but a giant quadrupole resonance might still be observable. Nonetheless, the capture cross sections were no larger than the $^{12}\text{C}(^{12}\text{C}, \gamma)$ data shown in Fig. 3. Since the available dipole radiative width will always be much larger than

that for quadrupole radiation, capture through a $T \neq 0$ heavy-ion channel would be a much more sensitive probe for such an isomer search. As a possible example of this, a spectrum from the $^{16}\text{O}(^7\text{Li}, \gamma)^{23}\text{Na}$ reaction is shown in Fig. 9.2) Here the γ_0 and γ_1 transitions are completely dwarfed by the much stronger decays to a doublet of levels at 7.1- and 7.7-MeV in ^{23}Na . These data are suggestive of a GDR built upon a prolate shape-isomer, although as yet there are no calculations for such levels in this nucleus. If such calculations can be extended to ^{23}Na and other s-d shell nuclei, heavy-ion radiative capture may prove an exceptionally well-suited probe.

Fig. 9. A high-energy gamma-ray spectrum from the $^{16}\text{O}(^7\text{Li}, \gamma)^{23}\text{Na}$ reaction.

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