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DIRECT EXCITATION OF HIGHER MULTIPOLE RESONANCES IN HEAVY NUCLEI

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Résumé - Nous revoyons les études récentes de résonances géantes de haute multipolarité dans les noyaux lourds. Nous discutons la résonance octupolaire géante à haute énergie, puis les composantes de haute multipolarité dans la région d'excitation de 2νω. Enfin nous présentons les premiers résultats d'expériences sur le fond continu dont on peut déduire des enseignements sur le mécanisme d'excitation et la multipolarité moyenne.

Abstract - A review is given on recent giant resonance studies in heavy nuclei investigating higher multipole excitations. Three topics are discussed: the high lying giant octupole resonance, higher multipole components in the region of 2νω excitations, and first investigations of the continuum background which can yield information about excitation mechanism and average multipolarity.

I - INTRODUCTION

During the last decade a rapid development of the field of giant resonances took place. Whereas in the seventies mainly the isoscalar giant quadrupole resonance (GQR) was studied in hadron scattering experiments, at present the main interest lies in two points: first the study of compressional modes of excitation with multipolarity L=0 and 1 (this is discussed in detail in the talk by M. Buenerden), and second higher multipole excitations which are discussed in this talk. Nuclear shape oscillations of higher multipolarity are expected to be important also in heavy ion collisions. Of special interest is the damping mechanism of these surface vibrations related to the question whether it is due to one-body or two-body dissipation.

To a large extent the recent progress in studies of giant resonances was due to large improvements of experimental techniques mainly through the possibility to study inelastically scattered particles at extremely small angles including 0°. This is feasible only by extremely good beam quality and magnetic spectrometer systems in combination with rather sophisticated detector devices. Here the pioneering work of the Texas and Grenoble groups [1] should be mentioned. The importance of small angle experiments is shown in fig. 1 which gives differential cross sections for collective excitations of different multipolarity calculated for 172 MeV α scattering from 208Pb. These cross sections are calculated within a DWBA approach using folding type form factors (see ref. 2). The advantage of using this folding method is that hadronic cross sections are derived consistent with electromagnetic properties. Further, an absolute comparison can be made between results from different scattering systems. At extremely small angles θ ≤ 30° only low multipole excitations are important whereas at somewhat larger angles also higher L excitations contribute. In the angular region 0° < θ < 80° all multipolarities can be distinguished unambiguously. This is not the case at larger angles.

In this talk I want to discuss mainly multipole excitations with L ≥ 3 although in the case of Pb (where some confusion has existed) also the L=2 strength is briefly discussed. Already for a number of years the low lying 1νω octupole excitation (E_x ~ 30 MeV) has been investigated [3]. Recently, by improved energy resolution and decay experiments this interesting excitation has been studied quite extensively.
II - EXCITATION OF THE GIANT OCTUPOLE RESONANCE (GOR)

Around 1980 from rather different scattering experiments, 130 MeV $^3$He scattering /4/ 172 MeV $\alpha$ scattering /5/ and 800 MeV p scattering /6/ evidence has been presented for the GOR. Spectra from these experiments for the case of $^{208}$Pb are shown in fig. 2. A rather broad structure is observed at a high excitation energy of about 20 MeV well above the giant quadrupole and monopole resonances. A summary of different experiments is given in table 1. In all these experiments /4-10/ the GOR is clearly observed. Whereas mostly one resonance is observed our Jüllich results indicate at least two resonances, the GOR and the isoscalar dipole resonance /5/, a compressional mode of excitation.

In the analysis of the different data (fig. 2) rather different background shapes have been subtracted. In the $^3$He and $\alpha$ work attempts were made to estimate the continuous background below the giant resonance whereas in the analysis of the $(p,p')$ spectra only a flat tail from the quadrupole and monopole resonances was subtrac-

Figure 1: Angular distributions for giant resonance excitations of different multipolarities calculated within a microscopic DWBA approach using folding type form factors.

I will concentrate on three points:
- Excitation of the giant octupole resonance ($3\hbar\omega$ excitation)
- Higher multipolarity excitation in the $2\hbar\omega$ resonance region
- Studies of the inelastic continuum background underlying the giant resonances. Here experiments are discussed which can give information on the reaction mechanism and the multipolarity distribution of the continuum.
Figure 2: Comparison of spectra from the scattering of different projectiles.
Table 1: Evidence for new isoscalar giant resonances at higher $E_x$ in hadron scattering.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>$E_{\text{inc}}$</th>
<th>Exp.</th>
<th>Multipolarity</th>
<th>Targets</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>130</td>
<td>Osaka 1979,80</td>
<td>L=3</td>
<td>$^{90}\text{Zr},^{116,118,120}\text{Sn},^{144}\text{Sm},^{208}\text{Pb}$</td>
<td>4</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>172</td>
<td>Jülich 1980</td>
<td>L=3,1</td>
<td>$^{208}\text{Pb},^{232}\text{Th},^{238}\text{U}$</td>
<td>5</td>
</tr>
<tr>
<td>p</td>
<td>800</td>
<td>LAMPF 1980</td>
<td>L=3</td>
<td>$^{40}\text{Ca},^{116}\text{Sn},^{208}\text{Pb}$</td>
<td>6</td>
</tr>
<tr>
<td>p</td>
<td>200</td>
<td>TRIUMF 1981</td>
<td>L=3</td>
<td>$^{90}\text{Zr},^{120}\text{Sn},^{208}\text{Pb}$</td>
<td>7</td>
</tr>
<tr>
<td>p</td>
<td>200</td>
<td>Orsay 1981</td>
<td>L=1(3)</td>
<td>$^{208}\text{Pb}$</td>
<td>8</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>340,480</td>
<td>Saclay 1981,82</td>
<td>L=3</td>
<td>$^{116}\text{Sn},^{208}\text{Pb}$</td>
<td>9</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>172</td>
<td>Jülich 1982</td>
<td>L=3</td>
<td>$^{120}\text{Sn}-^{238}\text{U}$</td>
<td>10</td>
</tr>
</tbody>
</table>

In the following the mass systematics of the GOR /10/ is discussed, particularly in view of deformation effects. It is well known that the giant dipole resonance in deformed nuclei splits into the $K=0^-$ and $1^-$ components. For resonances of higher multipolarity one expects a broadening of the resonance rather than a splitting because of a larger number of $K$ components, the energy of which are more closely spaced. For the GQR in deformed nuclei only a rather small broadening of the order of 0.4-1 MeV has been observed. This quantity has large uncertainties due to separation of the neighbouring giant monopole resonance (GMR) which also shows deformation effects.

The GOR can be studied very nicely in 172 MeV $\alpha$ scattering in the angular range 3-5°. At these angles the GOR is the only strong excitation in the $3\hbar\omega$ excitation region (fig. 3). Spectra taken at 4° from our Jülich work are given in fig. 4 for different target nuclei between $^{120}\text{Sn}$ and $^{238}\text{U}$. They show rather clearly the GOR peak in addition to the GQR and GMR resonances. Extracted resonance parameters and sum rule strengths are summarized in fig. 5 and compared with other investigations /4,6,7/. A clear deviation in width and excitation energy from a smooth $A$ dependence is obtained for deformed nuclei. We observe an increase in
width up to about 2 MeV. Somewhat surprising, also the excitation energy shows deformation effects which are opposite in rare earth and actinide nuclei. In general a good agreement of our results with other data is obtained. A strength in the order of 40-70 % of the EWSR strength has been extracted. Adding the $1\hbar \omega$ octupole excitations /3/ practically the whole isoscalar $L=3$ strength is observed. From 800 MeV (p,p') a much smaller sum rule strength has been reported /6/. This is due to a too high background subtraction, further an inelastic form factor was used which does not give reliable sum rule strengths.

From the quite large increase in resonance width from $L=2$ to $L=3$ giant resonances (for $^{208}$Pb from $2.6 \pm 0.2$ MeV to $5.0 \pm 0.9$ MeV) it is obvious that higher $L$ resonances at high excitations have quite large widths and are therefore extremely difficult to detect experimentally. Using a macroscopic damping model /13/ the width of the giant hexadecapole resonance is estimated to be at least 9-10 MeV. Experimental attempts to find higher multipole resonances at large excitation energies have been made so far only by the Saclay group using higher energy $\alpha$ particles /9/.
Within a shell model picture higher multipole excitations are not expected only at high energies but also at lower excitation. For a closed shell nucleus like $^{208}$Pb collective $L=4$ excitations are expected in the region of $2\hbar\omega$ energies and at $4\hbar\omega$, $L=6$ excitations at $2\hbar\omega$, $4\hbar\omega$ and $6\hbar\omega$. Similarly, the odd parity $L=3$ excitation has contributions at $1\hbar\omega$ and $3\hbar\omega$ (discussed in the last section). Of large interest in the moment is the question whether higher multipole components contribute to the cross section in the $2\hbar\omega$ region (GQR and GMR). As in the $2\hbar\omega$ region structures are not expected to be as broad as at high excitations it may be advantageous to study these effects. This question is related to the problem of the $L=2$ isoscalar sum rule strength in the GQR of $^{208}$Pb which was found to be very small in low energy electron scattering /14/ in disagreement with hadron scattering data (see e.g. ref. 2) and also higher energy $(e,e')$ /15/. Therefore I will mainly concentrate on the case of $^{208}$Pb.

Indications for $L$ contributions different from $L=2$ in the GQR region were first obtained from angular distributions. In several different scattering systems differential cross sections for the GQR were measured which did not show a pronounced diffraction pattern characteristic for pure multipolarity. Particularly, in $\alpha$ and $d$ scattering /2/ rather flat angular distributions were observed which indicate clearly a mixture of different $L$ values (fig. 6). Attempts to fit the data with an additional $L=4$ component only were not satisfactory. For $d$ scattering $L=4$ contributions give rise to a significant smearing out of the diffraction pattern as observed experimentally /2/ whereas in $172$ MeV $\alpha$ scattering $L=4$ angular distributions are not much out of phase with that of $L=2$ and thus create too much structure. Therefore, a consistent description of the data in fig. 6 are obtained only by assuming $L=2$, 4 and 6 excitation /2/. Alternatively, the data could be described also by a $L=2$, 4 and a strong...
L=3 excitation. However, this is not consistent with the result of a concentrated GOR at higher excitation (previous section). Our indications for a strong L=6 component in the GQR region are supported by results of a $^{208}\text{Pb}(\alpha,\alpha')$ correlation experiment /16/ in which a strong decay into the $13/2^+$ state of $^{207}\text{Pb}$ has been observed. This decay can only be favourably populated from a L=6 excitation.

Now I will discuss recent small angle $^{208}\text{Pb}(\alpha,\alpha')$ experiments from Jülich which yield more detailed information. The angular region studied was 1.5 - 8°. In fig. 7 small angle spectra are given. The background subtraction was done in the following way: the shape was fixed at 4° as discussed in sect. 2. This background shape was used also for the other smaller angle spectra. In addition a high energy background was assumed (dashed line) due to the tail of the elastic peak. This was adjusted to the 2° spectrum and scaled for the other angles with the elastic cross section. Towards smaller angles a decrease of the 10.9 MeV resonance (GOR) is observed with a cross section minimum of about 70 mb/sr. As for these angles higher L components are small this determines quite well the L=2 strength. It corresponds to about 60 % of the isoscalar EWSR consistent with older results /2/. This is a factor of two more than extracted from lower energy electron scattering /14/.

As discussed in fig. 4 the spectra at 3-4° are well described by three Gaussian peaks which represent GQR, GMR and GOR. In fig. 8 a comparison is made between 4° spectrum and those taken at larger angles of 6-8°. In this region we expect larger contributions of higher multipolarity (fig. 1). Indeed, by comparing the 4° spectrum with the
spectra at 6 and 8° we observe significant differences. This is seen on the left side of fig. 8 in which the same three-Gaussian fit which describes well the 40° spectrum is applied to the 6 and 80° spectra. Deficiencies of these fits are observed at three excitations indicated by the dashed arrows. At the excitation energy above the GOR the extra yield is interpreted to be due to the high lying L=1 excitation /5/ which is weakly excited at 40°. At the other two positions, at \( E_X = 12.5 \) MeV and 16 MeV, new structures were introduced in order to obtain a good fit to the spectra (right side, fig. 8). For larger angles the yields show a decrease of the 12.5 MeV structure and a rise at 16 MeV. The differential cross sections given in fig. 9 are described by \( L=4 \) \( (E_X = 12.5 \text{ MeV}) \) and \( L=6 \) \( (E_X = 16 \text{ MeV}) \) with EWSR strength of 14 and 15 %, respectively. The high lying structures are well described by \( L=3 \) and 1, respectively. The 16 MeV structure, which has an angular distribution quite similar to that of \( L=3 \) at larger angles, is responsible for the fact that in the earlier \( (\alpha,\alpha') \) study (ref. 5) the GOR was extracted at too low an excitation energy. The fact that in the region overlapping with the GMR a rather strong \( L=4 \) contribution was found explains why in \( \alpha \) scattering too large monopole cross sections have been extracted /2/.

Summarizing the different \( L \) components from peaks assumed at 10.9, 12.5, 13.8 and 16 MeV we obtain the multipole strength distributions given in fig. 10. These distributions are quite different from Gaussian or Lorentzian shapes with a rather narrow width for \( L=2 \) excitation \( (\Gamma = 2.7 \text{ MeV}) \), a larger width for \( L=4 \) \( (\Gamma = 4.5 \text{ MeV}) \) and a large width for \( L=6 \) \( (\Gamma \sim 7.8 \text{ MeV}) \). One should not forget to mention that in such a complicated analysis involving many data there are sizable uncertainties mainly due to the used resonance shapes, multipolarity ambiguities (mainly for \( L=0 \) and 2) and also the used background shape. For \( L=0 \) and 2 isoscalar sum rule strengths of 90 ± 20 % and 70 ± 20 % have been derived, respectively. Those for \( L=4 \) and 6 were in the order of 30 %. These results are in good qualitative agreement with RPA calculations /12/. The \( L=2 \) and 4 strength distributions are in good agreement with the results from higher energy \( \alpha \) scattering /9/.

There are very recently published data /17/ for GQR and GMR excitation in \( ^3\text{He} \) scattering stressing the importance of \( L=4 \) contributions. However, possible \( L=6 \) strength which was crucial to describe \( \alpha \) scattering data (fig. 6) was not mentioned at all. Based on our \( \alpha \) scattering results discussed above we calculated the corresponding \( ^3\text{He} \) scattering cross sections which are given together with the data /17/ in fig. 11. For a check we calculated also absolute cross sections for the low lying \( 3^+ \) excitation which are in excellent agreement with the data in fig. 11. Using our multipole assignments we obtain a perfect description for the GMR region (13.7 MeV), for the GQR region the estimated cross section (dashed line) is slightly below the data. Using additional strength of \( L=4 \) and 6 (6 % EWSR strength each) yields also in this case a
Figure 8: Comparison of $4^\circ$ spectrum with the measured spectra at larger angles $6^\circ-8^\circ$. Left hand side: three Gaussian fits to the giant resonances with the energies indicated. Excitation regions with large deficiencies of the fits are marked by dashed arrows. Right hand side: fits to the resonances including additional structures at 12.5, 16 and 21.3 MeV.
Figure 9: Differential cross sections for different resonances in the angular region 5-8° in comparison with DWBA calculations. The upper lines are due to excitation of the giant monopole resonance with some additional contributions of higher multipolarity.

Figure 10: Relative multipole strength distributions for even multipolarities obtained from the analysis of the resonances at 10.9, 12.5, 13.8 and 16 MeV.
Figure 11: Differential cross sections for excitation of the low lying $3^-$ state and the giant resonances at 10.9 and 13.7 MeV in 140 MeV $^3$He scattering (data are from ref. 17) in comparison with microscopic DWBA calculations with multipole strengths consistent with $\alpha$ scattering results.

good account of the data (solid line). The fact that somewhat smaller cross sections are predicted for the GQR from our $\alpha$ scattering data is presumably due to a somewhat different background subtraction in the two experiments analysed completely independent. The fits to the data in fig. 11 based on our $\alpha$ scattering results are much better than those given in ref. 17. Different from the conclusions of the authors they support our results of a strong L=2 excitation and the importance of L=6 contributions. There are also new (p,p') experiments which support our results of concentrated L=4 strength around 12 MeV /18/. As compared to $\alpha$ scattering (fig. 1) the situation in 200 MeV proton scattering is somewhat different in so far that higher multipole excitations have large cross sections only at much larger scattering angles at which low multipole excitations have already dropped off considerably (see fig. 12). Indeed, the large angle proton spectra in fig. 13 could be fitted only assuming a L=4 resonance peak at 12 MeV.

A few attempts have been made also to study the details of the $2\pi\omega$ excitations in lighter nuclei. In higher energy $\alpha$ scattering /9/ L=4 strength has been found in the Sn region quite consistent to that in $^{208}$Pb. In contrast, in the same mass region proton scattering angular distributions /7/ gave indication for only very small L=4 yield.
IV - STUDY OF THE INELASTIC CONTINUUM UNDERLYING THE GIANT RESONANCES

In the giant resonance peaks discussed in the previous sections large sum rule strengths are found only for low multipolarities up to $L=3$. This is only a small fraction of the total inelastic yield which involves excitations up to large multipolarities. The larger part of the inelastic strength is found in the continuous background below the sharp giant resonances. To get information about the features of high multipole vibrations one has to study the properties of the background, this is also of general interest.

At the beam energies used in the experiments reviewed we expect that the inelastic continuum is to a large extent due to direct excitation. Under this assumption we can calculate the background continuum using microscopic or macroscopic models/12,13/. Using the macroscopic model of ref. 13 a continuum is obtained as shown by the dashed line in fig. 14. In this calculation only surface vibrations (multipolarity $L=2-10$) were assumed. The centroid energies increase with increasing multipolarity, also the widths are strongly $L$ dependent. The resonance widths were calculated using two-body dissipation, this gives a quite remarkable agreement with our experimental findings for the widths of $L=2$ and $3$ resonances. In fig. 12 these results (dashed line) are compared with an $\alpha'$ spectrum taken at $15^\circ$ which extends up to higher excitation energies. Although the absolute magnitude is off by a large amount a qualitative agreement with the experimental spectral form is obtained, in particular in the higher excitation region. At lower excitations the yield is rather small. This can be significantly improved by adding to the macroscopic model/13/ features of the shell model as discussed in section III. These are $L$ contributions at lower energies, as e.g.
L=4 strength at 2\hbar\omega excitation and not only at 4\hbar\omega. The results of such a schematic model calculation are shown by the lower solid line in fig. 12 which shows a spectral form quite similar to those used experimentally. The widths of the high lying broad resonances were assumed to be the same as in the macroscopic model, those at lower excitation were taken from RPA calculations /12/ or directly from our experiment. Still the problem of the absolute background height is not solved. In the calculations presented only excitations up to L=10 were included, further compression modes were not assumed. Both effects can give rise to a significant increase of the direct yield.

At the end I like to discuss two types of experiments from which information on the nature of the background can be obtained. The first is related to the question of direct excitation, the second type of experiments probes the average multipolarity of the continuum.

The first question may be answered in correlation experiments. As an example I want to discuss a fission decay coincidence experiment studied at Jülich. We measured angular correlations of fission fragments in the $^{238}\text{U}(\alpha,\alpha'f_{1}f_{2})$ reaction. The idea of this experiment was to measure the linear momentum transferred to the nucleus, this gives rise to an angle between the fission products of less than 180°. The fission products were measured by two position sensitive parallel plate detectors coincident with inelastically scattered \(\alpha\) particles detected at 11°. Fission angle spectra are shown in fig. 15. For different outgoing $\alpha'$ energies they peak rather close to 180°. This is very different from the inclusive $^{238}\text{U}(\alpha,f_{1}f_{2})$ reaction. In the lower part the average fission angle and the transformation to the momentum parallel to the beam direction is plotted versus the outgoing $\alpha'$ energy. The parallel momentum transfer calculated in two-body kinematics is shown by the upper line. Deviations from this line are observed which are due to fast nucleon emission during the scattering process. In the data there is little deviation from the two-body kinematical line up to

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**Figure 14:** Higher multipole continuum for \(\alpha\) scattering (lower dashed and solid lines) calculated by use of macroscopic models (see ref. 13) in comparison with experimental data from ref. 5.
Figure 15: Fission angle spectra from the reaction $^{238}\text{U}(\alpha,\alpha'f_1f_2)$ and momentum transfer parallel to the beam axis $(p||)$ and corresponding average fission angle as a function of outgoing $\alpha'$ energy. Two-body and three-body kinematical lines are indicated.

Figure 16: Spectral form and angular distribution of the continuum calculated in a quasifree scattering model (solid lines) in comparison with 800 MeV proton scattering /19/.
30-40 MeV of excitation, this supports the picture of a large direct excitation in the background yield in the region of the observed giant resonances. Other type of correlation experiments detecting different secondary particles may give similar or complementary information.

A second type of experiment is the investigation of the background behaviour at extreme small angles. At larger angles the background behaviour shows an exponential slope. This is expected to change at small angles due to the fact that for the dominant large angular momenta small momentum transfer is strongly reduced in direct scattering. A first experiment was performed at Los Alamos utilizing 800 MeV proton scattering which indicates a reduction of the background yield at small angles (see fig. 16). Both, spectral form of the background and the angular distribution are well described using a quasifree scattering model. By these calculations and those presented in fig. 14 the usual background shape subtracted (discussed in sect. II) appears to be justified a posteriori. Preliminary results of giant resonance studies in and also at Jülich show the same trend but a rather flat small angle behaviour. From these angular distributions the average multipolarities in the excitation of the background continuum can be deduced.

**SUMMARY**

Giant resonance excitations in hadron scattering experiments have been reviewed which give information on higher multipole excitations. Apart from the giant quadrupole resonance studied for almost all stable nuclei the giant octupole resonance is the only rather concentrated resonance of higher multipolarity for which a systematic study is possible. Resonances with \( L \geq 4 \) are expected to have widths of the order of 10 MeV or more, which appear to be extremely difficult to detect experimentally. Such high \( L \) excitations have components in the lower excitation region; these could be studied in the case of \( ^{208}\text{Pb} \) for \( L=4 \) and \( L=6 \) excitations. It is certainly of large interest to study these type of excitations also for other nuclei. To learn more about excitations of high multipole structures it is important to study the inelastic continuum below the narrow resonances. Two examples of such experiments were discussed, correlation experiments and small angle studies which can give information on mechanism and average multipolarity. The comparison of experimental background shapes with theoretical estimates confirms the importance of high \( L \) contributions at lower excitation energies. Further it may give insight into the nuclear damping mechanism in the regime of high multipolarities.

In this talk experimental results only from proton and light ion scattering were covered which give very useful complementary results. Specific aspects of heavy ion scattering were not discussed; this is the subject of several contributions to this meeting.

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