

## MAGNETIC DIPOLE STRENGTH DISTRIBUTION AT HIGH EXCITATION ENERGIES IN DEFORMED NUCLEI <sup>★</sup>

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The distribution of magnetic dipole strength in the two rare earth nuclei <sup>156</sup>Gd and <sup>168</sup>Er has been studied both theoretically, in the framework of deformed QRPA, and experimentally, by inelastic electron scattering. The calculation yields a large amount of spin strength at high excitation energies with a maximum at about 8 MeV. In the electron scattering spectra, however, no strong signal is found, which leads to the conclusion that M1 strength at high energies must be strongly fragmented and very uniformly distributed.

### 1. Introduction

The discovery of a new magnetic dipole mode in <sup>156</sup>Gd by inelastic electron scattering in 1983 [1,2] led to an intensive theoretical and experimental investigation of  $J^\pi = 1^+$  states in heavy deformed nuclei [3]. Until now these efforts mainly concentrated on the low-lying states ( $E_x \approx 3$  MeV) which are predominantly excited by the orbital part of the magnetic dipole operator. They are now commonly called scissors mode states<sup>#1</sup>.

Being aware of the fact that these low-lying transitions do certainly carry only part of the total M1 strength we were interested in the question what fraction of strength is situated at higher energies ( $E_x \geq 4$  MeV). Our efforts were motivated mainly by the following reasons:

(i) In light and medium heavy nuclei the giant M1 spin-flip resonance is known for a long time [5]. For

nuclei with  $A \leq 140$  it has been systematically studied by inelastic electron [6,7], proton [8,9] and photon [10] scattering. Its excitation energy is found to follow a  $40A^{-1/3}$  MeV scaling law which corresponds to a value of about 7.5 MeV for the rare earth nuclei. Its strength is strongly reduced in comparison to shell model calculations. This phenomenon of quenching of M1 spin strength has been discussed extensively in the literature [7].

For  $A > 140$  the only experimental data available is for <sup>197</sup>Au [6,11], <sup>206</sup>Pb [12,13] and <sup>208</sup>Pb [14]. Whereas in <sup>197</sup>Au a pronounced resonance is found, M1 strength in the Pb isotopes is much more fragmented. Up to now there are no experimental results on M1 strength at high excitation energies in heavy deformed nuclei.

(ii) A number of theoretical studies of M1 strength in the rare earth nuclei were carried out in the early seventies [15]. The calculations which used Tamm-Dancoff and random-phase approximations all predicted a large amount of strength at high excitation energies. Moreover, they all yielded a region of concentrated strength which was identified with the giant M1 spin-flip resonance.

Based on these observations our new approach to the question of high-lying M1 strength in the de-

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<sup>#1</sup> For a detailed discussion see ref. [4].

formed nuclei was twofold:

(i) A new calculation in the framework of the deformed QRPA with, in comparison to the earlier attempts, more realistic forces.

(ii) Precise measurements on the deformed nuclei  $^{156}\text{Gd}$  and  $^{168}\text{Er}$  with high-resolution inelastic electron scattering at backward angles, under which magnetic dipole transitions are most sensitively detected.

## 2. Model calculation

The calculations were carried out in the quasiparticle random-phase approximation (QRPA) with an interaction of the form  $H = H_{\text{sqp}} + V_q + V_\sigma$  where  $H_{\text{sqp}}$  is the hamiltonian for the single-quasiparticle motion,  $V_q$  takes into account the residual quadrupole interactions, and  $V_\sigma$  takes into account the residual spin-spin interactions. We followed the methods and notations of refs. [15,16] and they are similar to those used in refs. [17,18].  $V_q$  contains a sum of isoscalar and isovector terms  $\frac{1}{2}[\kappa(0)T^\dagger(0)T(0) + \kappa(1) \times T^\dagger(1)T(1)]$  where the  $T$  are given by the commutators of the hamiltonian  $H_{\text{sqp}}$  with the spherical components of the angular momentum operator:  $T(0) = [H_{\text{sqp}}(\pi) + H_{\text{sqp}}(\nu), J_x + iJ_y]$  and  $T(1) = [H_{\text{sqp}}(\pi) - H_{\text{sqp}}(\nu), J_x + iJ_y]$ . The coupling parameter  $\kappa(0)$  is determined by the condition that the lower RPA frequency for the isoscalar mode (the spurious mode) should vanish [16,18,19]. For the relative strength of the isovector and isoscalar interactions we used the ratio  $b = \kappa(1)/\kappa(0) = -0.6$  which was discussed in ref. [17]. For the spin-spin interaction we used the isovector form  $V_\sigma = \kappa_\sigma \sigma_1 \sigma_2 \tau_1^\dagger \tau_2^\dagger$ . We used  $\kappa_\sigma = 0.8A^{-1/3}$  MeV for the strength parameter as determined from an investigation of Gamow-Teller beta decays to odd mass deformed nuclei [20].

Constructing a hamiltonian for which the calculated energy of the spurious state is equal to zero would only remove all spurious components of the excited states if the single particle energies and the residual interaction were consistent. Only then the full hamiltonian would commute with the total angular momentum operator. Since this consistency is not guaranteed in the present approach, we have calculated the response to the operator  $J_\pi + J_\nu$  and found that it was vanishingly small for all excited states. This indicates that the followed procedure for removing

spurious components is indeed effective.

The Nilsson single-particle energies were obtained with the Warsaw deformed Woods-Saxon code [21]. The deformation parameters were fixed at the values determined from Coulomb excitation [22]. We used  $\beta_2 = 0.297$  and  $\beta_4 = 0.058$  for  $^{156}\text{Gd}$  and  $\beta_2 = 0.316$  and  $\beta_4 = -0.003$  for  $^{168}\text{Er}$ . The pairing parameters  $\Delta$  were taken from tables 4.2 and 4.3 of ref. [23]. For  $^{156}\text{Gd}$  these are 1.04 MeV for protons and 1.12 MeV for neutrons and for  $^{168}\text{Er}$  these are 1.09 MeV for protons and 0.88 MeV for neutrons. The calculations included 30 single-particle states around the Fermi surface for the protons and 30 for the neutrons. This results in typically several hundred two-quasiparticle states. (As a check, for  $^{156}\text{Gd}$  we also carried out the calculation with 60 single-particle states. Below 7 MeV excitation energy, the results changed only in detail. Above 7 MeV, the total strength increased by  $1.8 \mu_N^2$  and the centroid energy of the spin flip resonance shifted upward by about 1 MeV.) In order to take into account the well known quenching of magnetic spin strength we used effective spin  $g$ -factors  $g_s^{\text{eff}} = 0.7 g_s^{\text{free}}$  in our M1 operator.

For a comparison of the theoretical results with experiment it is important to know that the level density at these energies in heavy deformed nuclei is tremendously high. An estimate in a realistic backshifted Fermi gas model [24] yields for  $^{156}\text{Gd}$  at an excitation energy of 7.5 MeV a mean level spacing of  $1^+$  states of only 15 eV, a value which is far below any experimentally feasible resolution and also very much smaller than the spacing between the QRPA two-quasiparticle states ( $\approx 30$  keV). A comparison of theory with experiment should therefore rather refer to the overall strength distribution than to single states.

The calculated strength distribution for  $^{156}\text{Gd}$  is displayed in the upper part of fig. 1. As can be seen the calculation yields M1 strength in the whole range of excitation energy from 2 to 10 MeV with a broad maximum around 8 MeV which we identify with the giant M1 spin-flip resonance. The total strength in the range between 7 and 9 MeV is  $8.7 \mu_N^2$  for  $^{156}\text{Gd}$  and  $9.7 \mu_N^2$  for  $^{168}\text{Er}$ . As shown in the second part from above of fig. 1 the resonance becomes much more pronounced when free nucleon  $g$ -factors are used in the calculation. The two lower parts of fig. 1 show a decomposition of strength in its orbital and spin con-

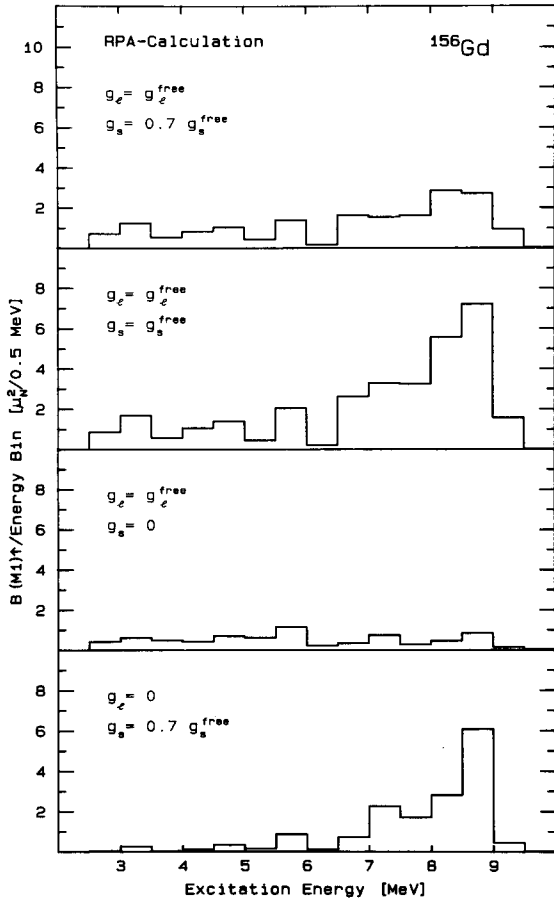


Fig. 1. M1 strength distribution for  $^{156}\text{Gd}$  calculated within the QRPA. From top to bottom: total strength using effective spin  $g$ -factors, total strength using free nucleon  $g$ -factors, pure orbital strength, pure spin strength (quenched).

tributions. It becomes very clear that the high-lying strength is mainly produced by the spin part of the M1 operator as is expected for the giant M1 spin-flip resonance and that the orbital strength is uniformly distributed over the whole range of excitation energy. These results are very much the same for  $^{168}\text{Er}$ .

### 3. Experiment

The experiments were performed at the Darmstadt Electron Linear Accelerator DALINAC [25]. The targets consisted of 10 mg/cm<sup>2</sup> thick metallic foils ( $^{156}\text{Gd}$  93.6%,  $^{168}\text{Er}$  97.7% enriched). For each nucleus four spectra at incident energies between 25 and

40 MeV and a scattering angle of 165° were taken. These are the kinematical conditions most sensitive for M1 transitions. In addition one forward angle measurement ( $\theta = 117^\circ$ ) was carried out to evaluate possible electric contributions to the form factor. The range of excitation energy covered was 3–10 MeV. Note that the thresholds for neutron emission are 8.531 MeV for  $^{156}\text{Gd}$  and 7.771 MeV for  $^{168}\text{Er}$ . The energy resolution achieved varied between 25 and 40 keV (FWHM) depending on the kinematical parameters of the experiment. The experiment consumed a total running time of about 80 days.

One spectrum for each nucleus is displayed in fig. 2 together with the corresponding theoretical strength distribution. The background of elastically scattered electrons (radiative tail) has been subtracted. The

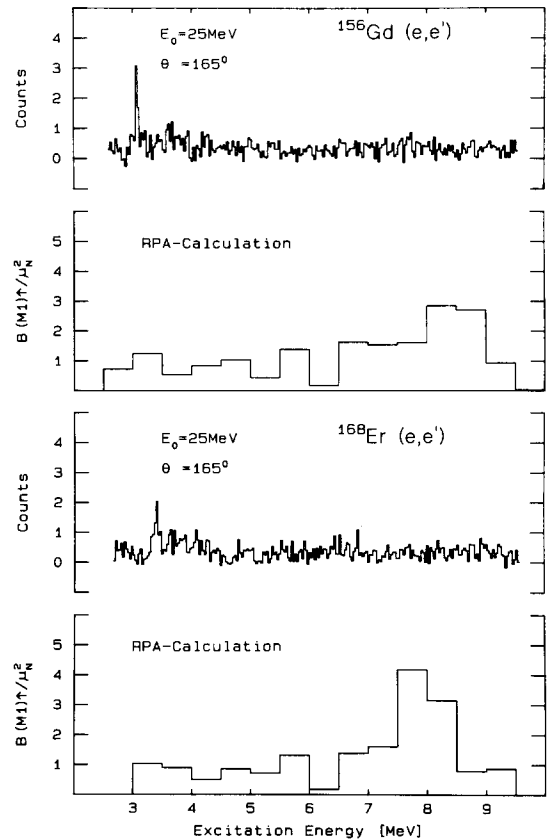


Fig. 2. Comparison of electron scattering spectra with the calculated strength distributions for  $^{156}\text{Gd}$  (top) and  $^{168}\text{Er}$  (bottom). For convenience in the experimental data eight channels have been summed up.

experimental findings are very similar for both nuclei. The spectra exhibit one prominent peak with  $E_x = 3.070$  MeV and  $B(M1)_{\uparrow} = 1.3 \pm 0.2 \mu_N^2$  for  $^{156}\text{Gd}$  and  $E_x = 3.395$  MeV and  $B(M1)_{\uparrow} = 1.0 \pm 0.2 \mu_N^2$  for  $^{168}\text{Er}$  which corresponds to the excitation of  $1^+$  states through the so-called scissors mode. In the vicinity of this peak the spectra show some fine structure due to weaker transitions. An exact analysis of the low energy spectra has been published earlier [2,26] and we shall restrict ourselves to the topic of this paper, e.g. the high energetic part.

As can be seen from fig. 2, at  $E_x > 4$  MeV the spectra lose most of their fine structure and in fact no single peak rises beyond the detection limit determined by the statistics which is  $B(M1)_{\uparrow} \leq 0.25 \mu_N^2$  for orbital dominated and  $B(M1)_{\uparrow} \leq 0.40 \mu_N^2$  for spin dominated transitions. The different values reflect the different behaviour of the form factor for the two types of excitations.

Moreover, the spectra give no indication for a region of concentrated strength at the anticipated excitation energy. To estimate the maximum strength within a possible resonance we tried to fit a gaussian with a width of 2 MeV and its center at 7.5 MeV, as predicted by the empirical rule, to the spectrum with the most favourable kinematic conditions ( $E_0 = 25$  MeV,  $\theta = 165^\circ$ ). Since the exact position of the

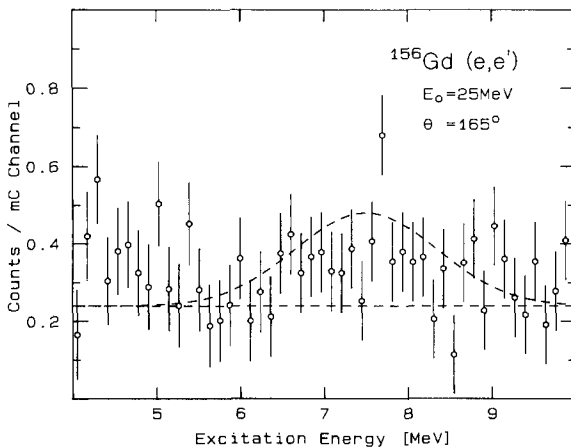


Fig. 3. Maximum size of a giant resonance at the anticipated energy of 7.5 MeV that is compatible with experiment. The dashed line indicates the 95% confidence limit for the height of a gaussian with an assumed width of 2 MeV. The area under the curve corresponds to a strength of  $B(M1)_{\uparrow} = 6.5 \mu_N^2$ . Experimental data points have been roughly summed up.

background is unknown it was let free in the fitting procedure. We varied the height of the curve until the  $\chi^2$  reached the critical value for a 95% confidence limit. This curve is shown in fig. 3. Simply by looking at the picture it is convincing that a possible resonance cannot be larger than the displayed line. The corresponding upper limit for the M1 strength, which is valid for  $^{156}\text{Gd}$  and  $^{168}\text{Er}$ , is  $B(M1)_{\uparrow \text{res}} \leq 6.5 \mu_N^2$ . (This value does not change significantly when the center of the gaussian is shifted up to 8 MeV. For a 3 MeV broad resonance we obtain in the same way an upper limit of  $9 \mu_N^2$ .)

#### 4. Discussion

How can we bring together the absence of a signal in our electron scattering spectra with the results of our QRPA calculation?

Firstly the fact that no strong single lines are observed can easily be explained by the high level density mentioned before. Presumably the strength of the RPA two-quasiparticle states is highly fragmented in the very dense multi-quasiparticle states so that none of them exceeds the detection limit mentioned above.

Secondly the limit given for a gaussian shaped peak refers only to that part of the strength that is concentrated in a pronounced resonance. If the strength is distributed more uniformly over the whole range of excitation energy and in addition highly fragmented it can very difficultly be detected. By adjusting the background in the lowest possible way and then simply summing up the cross section in a certain energy bin we can also in the case of such a uniform distribution give an upper limit for the total strength. We get  $\Delta B(M1)_{\uparrow} / \Delta E \leq 7.5 \mu_N^2 / \text{MeV}$ , a value, which to our annoyance is quite large but cannot be reduced due to the uncertainties in the height of the background.

Note the completely different meaning of the two numbers stated above. Whereas the value of  $B(M1)_{\uparrow \text{res}} \leq 6.5 \mu_N^2$  refers to the maximum height of a bump on top of the background, the value of  $\Delta B(M1)_{\uparrow} / \Delta E \leq 7.5 \mu_N^2 / \text{MeV}$  gives the upper limit for M1 strength hidden within the background.

This second upper limit is no longer in contradiction to the results of the QRPA when effective spin g-factors are used in the calculations (see fig. 1). In

contrast the strength calculated with free nucleon  $g$ -factors clearly exceeds the experimental upper limit which leads to the conclusion that also in heavy deformed nuclei a quenching of spin strength does occur. Hence the final result from the comparison of our experiments and calculations is that M1 spin strength in heavy deformed nuclei must be strongly fragmented, very uniformly distributed and quenched by an amount which is at least as high as in spherical nuclei.

Finally we want to make a brief comment on two very recent calculations. The one of ref. [27] is unfortunately erroneous [28], and their result can thus not be discussed. The QRPA calculation of ref. [29] yields the maximum strength between 4 and 5 MeV in  $^{156}\text{Gd}$  with a total value that exceeds our experimental upper limit (we refer to the upper part of fig. 3 in ref. [29]). So a strength distribution as proposed there can be ruled out by experiment.

From the experimental side there is certainly still much more work to do to clarify the question of M1 spin strength in heavy deformed nuclei. Two very promising ways to attack this problem could be:

(i) Inelastic proton scattering at forward angles which has proven to be very well suited for the investigation of spin-flip transitions [9].

(ii) Measurements with tagged photons which have the great advantage that they are practically free of background [13].

More help will also come from the new cw electron accelerators. They will allow for high-resolution electron scattering experiments with, in comparison to the present ones, much better statistics and reduced background.

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