Fine structure of the giant $M1$ resonance in $^{90}$Zr

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Abstract. $M1$ excitations in the $^{90}$Zr nucleus have been studied in a photon-scattering experiment with monoenergetic and 100% linearly-polarized beams from 7 to 11 MeV. More than 40 $J^\pi = 1^+$ states were identified for the first time from the observed ground-state transitions revealing the fine structure of the giant $M1$ resonance with center of gravity of 9 MeV and sum strength of 3.8(3) $\mu^2_N$. The results of the present work are compared with predictions from the shell model and the quasi-particle random-phase approximation.

1. Introduction

Experiments searching for $M1$ excitations in $^{90}$Zr were performed using different nuclear probes. A broad resonance structure at $E_x = 8.9$ MeV has been observed in inelastic proton scattering at $E_p = 200$ MeV [1]. High-resolution electron-scattering experiments revealed that a significant part of the observed structures in heavy nuclei is due to $M2$ excitations [2]. For the case of $^{90}$Zr, the total $M1$ strength from $(e,e')$ experiments was found to be $\sum B(M1) \uparrow \leq 2.5 \mu^2_N$ and to be distributed over three states at excitation energies $E_x = 8.233, 9.000$ and 9.371 MeV [3]. Poor detector resolution in both experiments, proton- and electron-scattering, constrained probing of any fine structure in $^{90}$Zr. Photon-scattering experiments, with partly-polarized tagged photons, determined the strength of the giant $M1$ resonance to be $\sum B(M1) \uparrow \approx 6.7 \mu^2_N$, and located it between 8.1 and 10.5 MeV [4]. The scattered $\gamma$ rays were registered with a NaI detector, which due to its poor resolution, did not allow for the identification of the individual excitations of the $M1$ resonance.

Study of the structure of the giant $M1$ resonance requires involvement of a reaction which selectively populates dipole states and one which allows for an unambiguous assignment of the spin and parity of the levels. Photon-scattering experiments with polarized beams meet these conditions. The High-Intensity Gamma-ray Source (HI$\gamma$S) facility of the Triangle Universities...
Nuclear Laboratory produces 100% linearly-polarized and nearly monoenergetic photon beams with selectable energy spread from 0.5 to 5% using inter-cavity Compton backscattering of free-electron laser (FEL) photons from electrons stored in the Duke storage ring. Presently, the energy of the backward-scattered photons can be tuned in a wide energy range, from about 1 MeV to 60 MeV, by changing the energy of the electron beam and the FEL wavelength. The polarization of the FEL photons, defined by the magnetic field of the undulators, is mostly preserved during the Compton back-scattering due to a negligible recoil effect, leading to the production of intense photon beams with nearly 100% polarization. The HI\(\gamma\)S facility is described in detail in Ref. [5].

2. Spin and parity assignment

The angular distribution of the scattered \(\gamma\) rays relative to the direction of the beam (\(\theta\)) and the vector of polarization (\(\phi\)) depends on the multipole order and the type (electric or magnetic) of the transition. According to the angular distribution for spin combinations \(0 \rightarrow 1 \rightarrow 0\) and \(0 \rightarrow 2 \rightarrow 0\) [6] a photon beam with 100% linear polarization provides distinguishable distributions for \(E1\), \(M1\) and \(E2\) transitions for scattering from an even-even nucleus. These distributions are shown in Fig. 1. Clearly, it can been seen that there are three specific directions of the intensity distributions of \((\theta, \phi) = (90^\circ, 0^\circ), (90^\circ, 90^\circ)\) and \((135^\circ, 0^\circ)\), given in Table 1, which provide unambiguous assignment of the type of transition, spin, and parity of the excited level. Therefore, experiments with 100% polarized, monoenergetic photon beams provide the opportunity to (i) excite low-spin levels, mainly \(\Delta J = 1\), (ii) assign spin and parity of those levels and (iii) distinguish between ground-state and branching transitions, i.e. determine the level scheme. Spectra from the present experiment measured at the three angles just mentioned are shown in Fig. 2.

3. Experimental results

We performed high-resolution, photon-scattering experiments on \(^{90}\)Zr at the HI\(\gamma\)S facility at beam energies from 7 to 11 MeV in order to reveal the fine structure of the \(M1\) resonance. The beam was collimated by a lead collimator with a length of 30.5 cm and a cylindrical hole with diameter of 1.9 cm. The target was positioned downstream in an evacuated plastic tube which was made of poly-methyl-meta acrylic. We used a cylindrical \(^{90}\)ZrO\(_2\) target with diameter of 2 cm, mass of 4054.22 mg and enriched to 97.7% in \(^{90}\)Zr. The scattered \(\gamma\) rays were measured with

### Table 1. Angular distribution \(W(\theta, \phi)\) for pure dipole and quadrupole transitions for an even-even nucleus relative to the vector of polarization \((90^\circ, 0^\circ)\).  

|       | \((90^\circ, 0^\circ)\) | \((90^\circ, 90^\circ)\) | \((135^\circ, 0^\circ)\) |
|-------|------------------------|-------------------------|------------------------|
| \(0^+\ E1\) \(1^-\ E1\) \(0^+\)   | 0.00                   | 1.50                   | 0.75                   |
| \(0^+\ M1\) \(1^+\ M1\) \(0^+\)   | 1.50                   | 0.00                   | 1.50                   |
| \(0^+\ E2\) \(2^+\ E2\) \(0^+\)   | 2.50                   | 0.00                   | 0.00                   |
Figure 2. Spectra of γ rays scattered from the $^{90}$ZrO$_2$ target at angles ($\theta, \phi$) = (90°, 90°), (135°, 0°) and (90°, 0°) labelled “vertical”, “backward” and “horizontal”, respectively. The spectra were collected in measurements using photon beams with energies of 6.8 (left panel) and 8.0 MeV (right panel).

four high-purity germanium (HPGe) detectors with 60% efficiency relative to a 3 in. × 3 in. NaI detector. All detectors were equipped with passive shields made of 3 mm copper and 2 cm thick lead cylinders. Lead and copper absorbers with thickness of 5 mm and 3 mm, respectively, were placed in front of the detectors in order to reduce the counting rate from low-energy background. Two detectors were positioned horizontally at 135° relative to the beam, one horizontally at 90° and one vertically at 90°. The detectors at 90° and 135° were positioned at 10 and 14 cm from the target, respectively, providing a similar detection efficiency at each angle. Spectra measured at beam energies of 6.8 and 8.0 MeV are presented in Fig. 2. At each energy, a measurement was performed for about 5 h with total photon flux of about $5 \times 10^7$ s$^{-1}$.

The energy distribution of the incident photon beam was measured with a large volume HPGe detector with an efficiency of 123% placed in the beam. Four copper blocks with thicknesses of 8 cm each, were placed in the beam near the exit of the FEL, in order to reduce its intensity. A photon-beam spectrum at 9.2 MeV is presented in Fig. 3. The spectrum was corrected for the detector response, full-energy peak efficiency and the attenuation in the copper blocks. The absolute photon flux was deduced from the cross sections of strong $E1$ transitions in $^{90}$Zr with known strengths [7]. The resulting beam-energy distribution, which was normalized to the flux determined from the discrete transitions, is shown in Fig. 3. The average photon flux density was typically of $2 \times 10^7$ s$^{-1}$ cm$^{-2}$. The absolute efficiency of the detector setup was simulated with GEANT3 and normalized at the low-energy part (< 3.5 MeV) to the efficiency obtained from calibrated sources. The integrated cross sections of the newly observed deexcitations were
The calculations were performed for effective models for the above 6 MeV excitation energy. This gives a possibility to test the predictions of various models. The present experiment provides precise information for the first time about the distribution of 1+ states in 90Zr. This normalization method omits the need for use of the absolute flux and absolute efficiency. The transition type was found from the angular distributions of the scattered γ rays discussed above, such that M1 deexcitation is assigned if a peak is seen in the horizontal detectors at θ = 90° and 135° and not in the spectrum of the vertical detector. However, small peaks (which correspond to strong E1 transitions) are observed in the spectrum measured in the horizontal plane at θ = 90°, due to the finite opening angle of the detectors. If a peak is present in the spectra measured at θ = 90°, the peak area in the spectrum of the horizontal detector was corrected by 5% of the area of the peak observed in the spectrum of the vertical detector. See Ref. [8] for more details. A comparison between the spectra measured at the two angles in the horizontal plane allows us to distinguish between M1 and E2 radiation. Note that the first 2+ excited level in 90Zr is at $E_x = 2186.3$ keV, and all observed peaks with energies in the range of the incident photon beam correspond to ground-state transitions. Therefore, according to the selection rules for γ-ray transitions, multipole mixing between M1 and E2 radiation is excluded.

We observed more than 40 peaks which correspond to M1 transitions. The experimental results for the $B(M1)$ strength are presented in Fig. 4. The resonance has a strength of $\sum B(M1) \uparrow \approx 3.8(3) \mu_N^2$ and a center of gravity at 9 MeV.

4 Discussion

The present experiment provides precise information for the first time about the distribution of 1+ states and the magnetic dipole (M1) strength in the hitherto inaccessible energy region above 6 MeV excitation energy. This gives a possibility to test the predictions of various models for the M1 strength. Predictions from the shell model are presented in Fig. 5 (a). The calculations were performed for effective g factors of $g_s = 0.7g_{s}^{\text{free}}$ in the model space of $\pi(0f_{5/2},1p_{3/2},1p_{1/2},0g_{9/2}) \nu(0g_{9/2},1d_{5/2},0g_{7/2})$ allowing at most two protons to be lifted from the fp orbits to the 0g_{9/2} orbit and up to two neutrons to be lifted from the 0g_{9/2} orbit to the 1d_{5/2} and 0g_{7/2} orbits. The calculations, restricted to a maximum excitation energy of 9 MeV, predict a summed strength of $\sum B(M1) \uparrow = 6.37 \mu_N^2$ and a center of gravity at 7.7 MeV. The main part of the strength originates from three states around 8 MeV which are dominated by the neutron $g_{9/2} \rightarrow g_{7/2}$ spin-flip configuration. Whereas the experimental strength is considerably fragmented. This raises the question whether advanced nuclear structure models such as the

![Figure 3](image-url)
quasi-particle random phase approximation (QRPA) or the multi-configuration Shell Model (SM) can explain this pronounced fragmentation of the $M1$ strength. In the following, the results of our theoretical investigation are described briefly. First, we use the QRPA formalism applied in Ref. [9] to the $M1$ strength observed in even-mass Mo below $E_x = 4$ MeV. In the present calculation the basic $1^+$ two-quasiparticle (2qp) excitations are constructed from a spherical Woods-Saxon potential and coupled via QRPA with a repulsive residual spin-spin ($\sigma \cdot \sigma$) interaction. In Fig. 5 (b), the measured excitation spectrum is compared to the calculated one, taking the same $\sigma \cdot \sigma$ strength constant and also the standard $M1$ transition operator as in Ref. [9]. The QRPA yields two strong peaks around 7.7 MeV, the strength of which is produced by transitions between the spin-flip partner states $0g_{7/2} \rightarrow 0g_{9/2}$ and $1d_{5/2} \rightarrow 1d_{5/2}$ of the $n = 4$ oscillator shell. Taking an effective g-factor of $g_s = 0.7g_{free}^{\text{free}}$, the summed $B(M1)$ strength is $2.2\mu_N^2$ as compared to the measured value of $3.3\mu_N^2$. However, the spherical QRPA misses also the strong fragmentation and the centroid of the measured $M1$ distribution.
5. Conclusion
The capability of the HIRaS facility and the low-background detector system allowed us to unambiguously identify the $M1$ excitations in $^{90}\text{Zr}$ in a photon-scattering experiment. We observed more than 40 $M1$ transitions for the first time in the energy range from 7 to 11 MeV revealing the fine structure of the $M1$ resonance in this nucleus. In a future analysis we will extract the total $M1$ strength considering the continuous intensity below the peaks analogously to the analysis done for experiments with bremsstrahlung beams [7, 10].

The experimental results were compared with model predictions. In summary, the observation of the sizeable, but strongly fragmented $M1$ strength is a challenge to theory, because neither the configuration space of the 2qp excitations considered in QRPA nor the one in our SM calculations is sufficient for an explanation of these findings.

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