Photon strength distributions in stable even-even molybdenum isotopes.

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Abstract. Electromagnetic dipole-strength distributions up to the particle separation energies are studied for the stable even-even nuclides \(^{92,94,96,98,100}\)Mo in photon scattering experiments at the superconducting electron accelerator ELBE of the Forschungszentrum Dresden-Rossendorf. The influence of inelastic transitions to low-lying excited states has been corrected by a simulation of \(\gamma\) cascades using a statistical model. After corrections for branching ratios of ground-state transitions, the photon-scattering cross-sections smoothly connect to data obtained from (\(\gamma, n\))-reactions. With the newly determined electromagnetic dipole response of nuclei well below the particle separation energies the parametrisation of the isovector giant-dipole resonance is done with improved precision.

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1. Introduction

The most prominent excitation mode in nuclei is constituted by the Isovector Giant Dipole Resonance (GDR) which can be interpreted macroscopically as the oscillation of proton matter against neutron matter. Nevertheless, the low-energy tail of the GDR strength at energies well below the maximum of the GDR has not been studied with high accuracy, so far. Theoretical predictions of the low energy tail of the GDR vary between pure Lorentzian distributions (constant width) and modified Lorentzian distributions (energy dependent width) \([\Pi]\). Additionally, at excitation energies of about 6 MeV, recent photon scattering experiments have shown extra strength commonly dubbed “pygmy resonance”. Since the accurate knowledge of the photoabsorption cross section close
In principle, the photoabsorption cross sections $\sigma_\gamma$ can be measured via $\gamma$ rays emitted after photoexcitation. However, the increasing density of nuclear states with increasing excitation energy results in de-excitation patterns which are combinations of direct ground-state decays and transitions via intermediate states. Due to the vast number of transitions observed in the deexcitation of medium-mass nuclei it reveals impossible to attach the observed transitions to nuclear states. Therefore, we developed an approach to unfold measured photon-scattering yields on the basis of a statistical model. Above the particle separation energies, the photoabsorption cross section has been determined previously in $(\gamma, n)$-reactions.

The experiments were carried out at the bremsstrahlung facility at the superconducting electron accelerator ELBE of the Forschungszentrum Dresden-Rossendorf. Bremsstrahlung was produced by electrons impinging onto a 3.4 mg/cm$^2$ thick Nb radiator. A narrow photon beam is formed by an aluminium collimator with a length of 2.6 m and a conical opening angle of 5 mrad while the electrons are deflected by a purging magnet. An absorber made of a 10 cm long Al cylinder between the radiator and the collimator attenuates the intense low energy part of the bremsstrahlung spectrum. The photon beam passed the target about 570 cm downstream inside an evacuated polyethylene beam pipe and was subsequently absorbed in a well shielded photon-beam dump. Scattered photons were registered in four high-purity Ge detectors (HPGe) with efficiencies of 100 % relative to a 3” × 3” NaI detector. In order to determine the multipole order of the scattered $\gamma$ rays two of the detectors were located at 127° and the other two at 90° with respect to the photon beam at distances of 32 and 28 cm to the target, respectively. The low-energy photons are suppressed by lead absorbers with thicknesses 0.8 and 1.3 cm at the two given angles, respectively, combined with 0.3 cm thick copper absorbers. The HPGe detectors are equipped with 3 cm thick escape-suppression shields made of BGO scintillation detectors. The detector resolution amounts to 5.0 keV (7.9 keV) at 5 MeV (9 MeV) photon energy. The bremsstrahlung facility of the ELBE accelerator is described in detail in Refs. [3, 4].

We performed all measurements at identical experimental conditions and the same electron-beam energy $E_{\text{kin}}^{\text{kin}} = 13.2$ MeV. Samples of elementary $^{92,94,96,98,100}\text{Mo}$ isotopically enriched to more than 97 % with masses of 2036 mg, 1998 mg, 2003 mg, 2952 mg, and 2916 mg, respectively, were used as targets. The spectra of photons scattered at 127° from $^{92,94,96,98,100}\text{Mo}$ measured for 51 h, 105 h, 95 h, 59 h, and 57 h, respectively, are presented in Fig. [11]. The detector response function is obtained using simulations based on the GEANT3 Monte-Carlo code and calibrated radiation standards. The incident
photon flux is determined by photon scattering from well-known transitions in $^{11}$B and is shown in Fig. 1 as well.

3. Determination of photon strength functions

The electric dipole photon strength for photon absorption is defined as the average reduced transition width

$$f_{E1} (E_\gamma) = E_\gamma^{-3} \frac{\langle \Gamma^{E1}_0 (E_\gamma) \rangle}{D},$$

with the average level width $\langle \Gamma^{E1}_0 (E_\gamma) \rangle$ at energy $E_\gamma$ and the average level spacing $D$. The dipole photon strength can be translated into the average photon absorption cross section $\langle \sigma_\gamma \rangle$ with the ground state spin $J_0$ and the spin of the excited state $J$:

$$f_{E1} (E_\gamma) = \frac{2J_0 + 1}{2J + 1} \frac{\langle \sigma_\gamma (E_\gamma) \rangle}{(\pi \hbar c)^2 E_\gamma}.$$ (2)

The magnetic dipole strength can be determined accordingly. We obtained the $M1$ strengths in $^{92,98,100}$Mo from discrete transitions and calculated an average photon absorption cross section of about 1 mb at excitation energies from 7 - 8 MeV [5] which is the region of spin-flip excitations. The contribution of $M1$-strength is taken into account in the determination of the dipole strength later on.

The intensity distribution obtained from the measured spectra after a correction for detector response and a subtraction of atomic background in the target contains a continuous part in addition to the resolved peaks which accounts for about 70% of the total strength. Fig. 2 shows the spectra of scattered photons close to the neutron separation energies which demonstrates the significant amount of unresolved strength as compared to strength in resolved transitions. In order to estimate the intensities of inelastic transitions to low-lying levels we have applied statistical methods [6, 7, 8]. By means of simulations of $\gamma$-ray cascades intensities of transitions to low-lying states could be removed from this intensity distribution and the intensities of ground-state transitions could be corrected for their branching ratios $\Gamma_0/\Gamma$ leading to the determination of the photoabsorption cross section $\langle \sigma (E_\gamma) \rangle$.

4. Parametrisation of the GDR for triaxially deformed nuclei

The chain of stable molybdenum isotopes is a good example for a study of the dipole strength distributions at the onset of (triaxial) deformation. The ground state deformations evolve from a deformation parameter $\beta = 0.04$ for the closed neutron-shell nucleus $^{92}$Mo via $\beta = 0.05(0.08, 0.18)$ for the transitional nuclei $^{94}$Mo ($^{96}$Mo, $^{98}$Mo) to $\beta = 0.24$ for $^{100}$Mo [5]. The experimentally deduced shapes of the considered Mo isotopes are soft where the triaxiality parameter $\gamma$ for $^{98}$Mo is 32° [10]. Therefore, the properties of the investigated Mo isotopes are dominated by quadrupole deformation and triaxial shape. The influence of deformation on the E1 strength at the low energy tail of the GDR has been studied microscopically for medium-mass nuclei in [11].
According to the hydrodynamical model, the GDR is represented as a vibration of the proton system against the neutron system. For nuclei with stable deformation in the ground state, the GDR splits into independent vibrations along the principal axes of the nucleus conserving the total strength. The integrated photoabsorption cross section corresponding to vibrations along one of the axes is given by the Thomas-Reiche-Kuhn dipole-sum rule \[ S_{\text{TRK}} = \int \sigma_\gamma(E_x) dE_x = 60ZN/A \text{ mb MeV} \] while the resonance energies \( E_i \) are inversely proportional to the length of the axis:

\[
E_i = E_0 \exp \left( -\sqrt{\frac{5}{4} \pi \beta \cos(\gamma - \frac{2}{3} \pi i)} \right),
\]

\( E_0 \) is the energy of the maximum of the GDR of a spherical nucleus. The Hill-Wheeler parameters \( \beta \) and \( \gamma \) used in Eq. (3) can be taken from Ref. [5].

We attempt to parametrise the low-energy tail of the GDR by a sum of three Lorentzians. Considering the wide range of excitation energy spanned by the combined data, a test of a Lorentzian with energy-dependent total width \( \Gamma(E_x) \) is indicated:

\[
\sigma_\gamma(E_x) = \frac{2C \cdot S_{\text{TRK}}}{3\pi} \sum_{i=1}^{3} \frac{E_i^2 \Gamma(E_x)}{(E_i^2 - E_x^2)^2 + E_i^2 \Gamma(E_x)^2},
\]

The parameter \( C \) measures the conformance of the integrated \( E1 \) strength with the Thomas-Reiche-Kuhn sum-rule. We use the parametrisation \( \Gamma(E_x) = \Gamma_S \cdot (E_x/E_i)^{\delta} \) of the energy dependence of the width with \( \delta \) as a parameter to be defined by a fit to the combined data.

The coupling of the particle-hole states to more complex configurations leads to an effective damping and consequently a wider Lorentzian shape. Nevertheless, a long standing question on a proposed energy dependence of the damping width [13, 14] was never finally answered due to the lack of precise and systematic data on the photon strength function. In this work, we obtain \( \delta = 0.0(4) \), i.e., no energy dependence of the width within the uncertainty. Fig. 3 shows two different parametrisations using a linear energy dependence width as compared to a constant width. In accordance to our findings in the neighbouring nucleus \( ^{88}\text{Sr} \) [15] and to the systematics of the GDR widths [14] we use \( \Gamma_S = 4 \text{ MeV} \). For the parameter \( C \) we find values of 1.08(1), 0.77(1), 0.83(1), 0.92(2), 0.90(1) from the fit of the \( (\gamma,n) \) data of \( ^{92}\text{Mo}, ^{94}\text{Mo}, ^{96}\text{Mo}, ^{98}\text{Mo}, \) and \( ^{100}\text{Mo}, \) respectively. The results of the parametrisation are presented in Fig. 4.

By the proposed clear-cut separation of the two causes for the widening of the GDR (deformation and damping), we obtain an expression of use also when no GDR-data are available, i.e. for nuclei far off stability entering nucleosynthesis calculations. Without much influence on the off-resonance cross section the GDR-energy can then be taken from systematics [16], and by using \( C = 1 \) and calculated deformation parameters [5], the dipole strength from 4-5 MeV up to threshold can be predicted.

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Figure 1. Experimental spectra of $\gamma$-rays scattered from $^{92,94,96,98,100}$Mo and the distribution of the incident bremsstrahlung produced by an electron energy of 13.2 MeV. The spectra are taken at an angle of $127^\circ$ relative to the photon beam. Transitions marked by stars belong to the calibration standard $^{11}$B, while crosses mark $\gamma$ rays from $^{73}$Ge($n, \gamma$) reactions.

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Figure 2. Spectra of $\gamma$-rays scattered from $^{94,96}$Mo (left) and $^{98,100}$Mo (right) around the neutron separation energies (labelled by arrows) divided by the incident photon flux and the respective number of target atoms.

Figure 3. Comparison of photoabsorption cross sections for $^{100}$Mo determined in the photon scattering experiment and in ($\gamma, n$)-reactions [17] with two different parametrisations of the Giant Dipole Resonance. The parametrisation consists of a superposition of three Lorentzians according to the triaxial deformation of $^{100}$Mo using a linear energy dependence of the width (left) and an energy-independent width (right). Data obtained in neutron capture experiments are shown as red (color online) triangles.
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Figure 4. Photoabsorption cross sections for all stable even-even molybdenum isotopes derived from photon scattering (filled symbols) and $(\gamma, n)$-reactions (open symbols)\[17\]. The solid lines indicate the parametrisation using the sum of up to three Lorentzians (dashed lines).