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Photon scattering off ^{94}Zr and ^{96}Zr

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Abstract. Photon-scattering experiments off the nuclei ^{94}Zr and ^{96}Zr were performed at the 10-MeV bremsstrahlung facility DHIPS at the super-conducting electron linear accelerator S-DALINAC at Darmstadt. The dipole excitation-strength distributions were determined in an energy range between 2 and 8 MeV, including the 1^- quadrupole-octupole coupled Two-Phonon-State and parts of the Pygmy Dipole Resonance. In total 74 transitions in ^{96}Zr were observed and for most of the excited states the spin quantum number could be firmly assigned to $J = 1$. Calculations within the Quasiparticle Phonon Model show a good agreement.

1. Introduction

The Nuclear Resonance Fluorescence (NRF) method is sensitive to dipole and quadrupole excitations [1]. For that reason, the NRF is an excellent tool to investigate the so-called "*Pygmy Dipole Resonance*" (PDR) and the $\left[2^+_1 \otimes 3^-_1\right]_{1^-}$ state [2]. The latter originates from a coupling of the low-energy 2^+ quadrupole phonon and the 3^- octupole phonon which leads to a quintuplet of states with spin and parity quantum numbers ranging from 1^- to 5^-. Furthermore, magnetic dipole excitations [3] such as the scissors mode [4] and spin flip-excitations can be observed in NRF.

The stable Zr isotopes (Z = 40, N = 50 - 56) exhibit a pronounced proton subshell closure towards the empty $\pi(1g_{9/2})$ subshell with the Fermi level just above the $\pi(2p_{1/2})$ orbital. For this reason, it is very interesting to investigate the PDR in these nuclei, because, until now, the PDR is mainly investigated in nuclei at or near well-developed shell closures (see e.g. [5, 6, 7]). In a geometrical picture, the PDR is described by an oscillation of a neutron skin against an isospin saturated N = Z core. The PDR is also described in an hydrodynamic model [8]. The centroid can be calculated by the expression $E_{\mathrm{PDR}} = 31 \cdot A^{-1/3}$ MeV.

Experiments performed at the Kernfysisch Versneller Instituut (KVI) in Groningen (NL), using the isoscalar probe in an α-scattering experiment suggest a fragmentation of the PDR in an isoscalar and an isovector part. While the first one is observed in $(\alpha, \alpha'\gamma)$ reactions, the isovector part becomes dominant in (γ, γ') experiments [9].

Indications of the PDR appear in many nuclei in the excitation energy range between 6 and 10 MeV. Dipole excitation cross sections in this energy region may have a large impact on the neutron-capture cross sections and, consequently, on the astrophysical reaction rates, that are

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relevant for the r-process [10].
Below the energy region where the PDR is observed, multi-phonon excitations (MPE) can be found. The best studied examples are given by the coupling of the low-lying quadrupole excitations in spherical nuclei forming the two-quadrupole phonon triplet of states with spin and parity quantum numbers 0^+, 2^+ and 4^+ [11]. MPEs may even result of the coupling of two phonons built on different nucleon configurations. In the case of ^{96}Zr the phonon of the octupole vibration built on the ground state might be able to couple to the phonons of the quadrupole excitations built on top of the ground state or on top of the low-lying 0^+ intruder state. The properties of MPEs depend on correlations induced by the nuclear forces between several nucleons and the fermionic nature of the latter. Therefore, multi-phonon states are very sensitive to the underlying shell structure. Nuclear multi-phonon structures represent fascinating objects of research at the heart of nuclear structure physics.
Beside the mentioned electric dipole transitions, NRF offers the possibility to observe magnetic dipole transitions. The scissors mode of deformed nuclei [12] and spin-flip excitations belong to this kind of M1 excited states. The latter describe the excitation of at least one nucleon from a subshell $j\pm1/2$ to its spin-orbit partner in a $j\mp1/2$ shell with a change of the spin orientation.

2. Experiments
The photon scattering experiments have been performed using the Darmstadt High Intensity Photon Setup (DHIPS) [13] at the super-conducting electron linear accelerator S-DALINAC at the Technische Universität Darmstadt, Germany.
The injector of the S-DALINAC can accelerate the electrons up to 10 MeV with beam currents up to 40 μA. These electrons are completely stopped in a thick copper radiator and converted into bremsstrahlung. The maximum energy of the continuous-energy bremsstrahlung corresponds to the energy of the electron beam. The photons are collimated with a copper collimator with a diameter of 2.5 cm and 3 cm, respectively, at two target positions. The whole setup is passively shielded against background stemming from the radiator and natural sources by Lead.
In order to detect the scattered photons at the first target position, three High-Purity Germanium detectors (HPGe) equipped with active Anti-Compton shields are available. In the case of the experiments on ^{96}Zr, one detector was placed at 90° and two detectors at 130°. Approximately 4 g of the very expensive target material (ZrO_2 enriched to 96 % in ^{96}Zr) was loosely packed in an Aluminum container, to which the calibration standard ^{11}B was mounted. In the measurement on ^{94}Zr, one detector was placed at 90°, a second at 95° and the third one at 130°. The target was composed of 300 mg of metallic Zr enriched to 91.2 % in the isotope ^{94}Zr and 800 mg of ZrO_2 enriched to 92.6 %. In addition, about 180 mg of the calibration standard ^{11}B was added to the target.

3. Results
The dipole-strength distributions resulting from the measurements are presented in Figure 1. For ^{96}Zr calculations within the Quasiparticle Phonon Model [14] were performed. These are shown in the lower panel of Figure 1.
The comparison of the dipole-strength distributions of ^{94}Zr and ^{96}Zr up to an energy of 5 MeV exhibits that in ^{96}Zr the transitions are stronger and the level density is lower. In the energy range of 4.7 and 5.2 MeV, the two isotopes exhibit a similar structure. There appears a group of states in the respective isotope with almost identical transition strengths. Furthermore, the measurement on the isotope ^{96}Zr with an end-point energy of 7.7 MeV shows an accumulation of dipole strength starting from an energy of 5.5 MeV. This is characteristic for the E1 Pygmy Dipole Resonance. However, in the experiments presented here, the parity quantum numbers cannot be determined. Therefore, it is not for sure that all shown transitions are of E1 character.

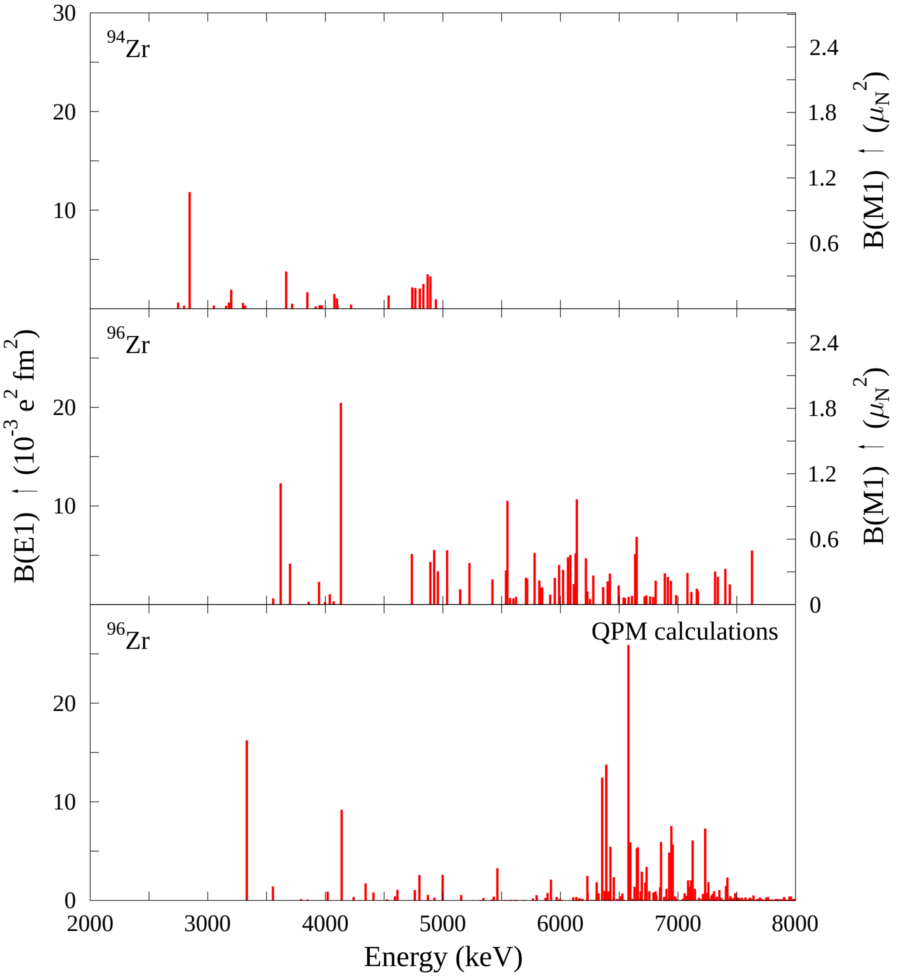

Figure 1. Preliminary dipole excitation strength distributions of ^{94}Zr and ^{96}Zr: The upper panel shows the observations on ^{94}Zr. The panel in the middle presents the measured dipole strength distribution of ^{96}Zr, while the lower panel shows the one calculated within the QPM (see text). The data analysis is still on-going.

The E1 strength distribution calculated within the QPM shows a resonance-like structure above an energy of about 6 MeV. To compare the calculations with the data, the centroid energies for the resonance-like part of the distributions were estimated as strength-weighted averages from an energy of 5.4 MeV to 7.63 MeV. The resulting value for the QPM calculation is $\bar{E}_{theo} = 6.59$ MeV while the experimental one is $\bar{E}_{exp} = 6.33$ MeV. The hydrodynamical model predicts a value of about 6.77 MeV. Furthermore, the latter predicts the full transition strength to 0.141 e^2fm^2 while the QPM calculates the summed E1 strength to 0.186 e^2fm^2. The preliminary experimental value is 0.131(17) e^2fm^2. Infact, the given experimental value can be considered as a lower limit for the total strength. Because of the limited sensitivity there may be unresolved strength hidden in the non-resonant background. Furthermore, in the summation M1 and E2 excited states could have been included.

The low-energy part of the strength distributions in both isotopes is dominated by strong dipole excitations at 2846 keV in ^{94}Zr and 4132 keV in ^{96}Zr, respectively. Both states are strong candidates for the 1^- state of the $2_1^+ \otimes 3_1^-$ quintuplet. The parity of the 4132 keV state in ^{96}Zr was determined to be negative [18] and we tentatively assign a negative parity for the 2846 keV

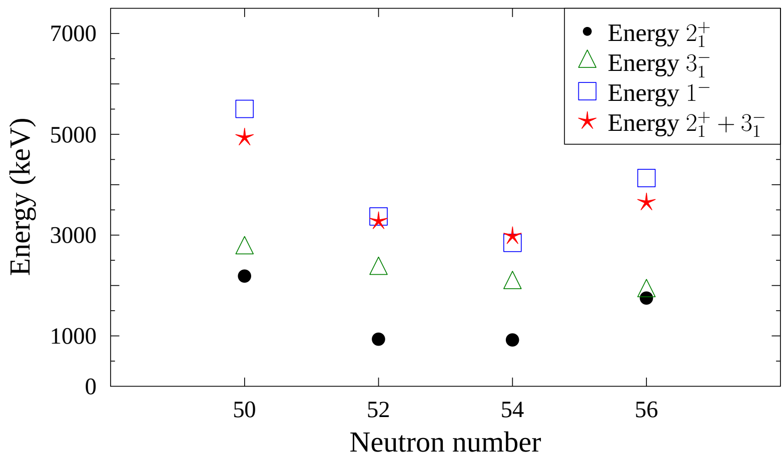

Figure 2. Systematics of the values of the sum energy of the 2_1^+ and the 3_1^- state and the energy of the prominent low-energy 1^- states in the even-even Zirconium isotopes: The excitation energies of the doubly-closed shell isotopes ^{90}Zr and ^{96}Zr is higher than in the two other isotopes. Data for ^{90}Zr are taken from [2] and those for ^{92}Zr from [15]. The energy of the 3_1^- state for ^{94}Zr is taken from [16] and for ^{96}Zr from [17].

state in ^{94}Zr from systematics, because it appears in the region of the sum energy of the 2_1^+ and the 3_1^- state. In Figure 2 the systematics of the deviation of the values of the sum energy of the 2_1^+ and the 3_1^- state and the energy of the observed 1_1^- states in the even-even Zirconium isotopes is shown.

The two isotopes ^{90}Zr and ^{96}Zr have high excitation energies of the 2_1^+ state. The latter indicates, once more, the doubly-magic character of ^{96}Zr. For that reason, the excitation energy of the 1^- states is high as well. The difference between the sum energy of the 2_1^+ and the 3_1^- state and the energy of the prominent low-energy 1^- state in these two isotopes might be explained by blocking effects.

Figure 3 shows the comparison of the quadrupole-octupole coupled E1 excitation strength in nuclei in the Z = 38 - 50 region. Especially the transition from the 1^- to the ground state in ^{96}Zr is much stronger than the common trend in this mass region. One reason might be the large octupole collectivity of this isotope. This octupole collectivity is expected to be dominated by the available low-energy $\Delta L = 3, \Delta J = 3$: $\pi \left(p_{3/2} \rightarrow g_{9/2}\right)$ and $\nu \left(d_{5/2} \rightarrow h_{11/2}\right)$ particle-hole excitations [19]. Hence, a strongly excited $[2^+ \otimes 3^-]_{1^-}$-state is expected in ^{96}Zr. The excitation should get weaker with decreasing neutron number. These expections can be confirmed as shown in Figure 3.

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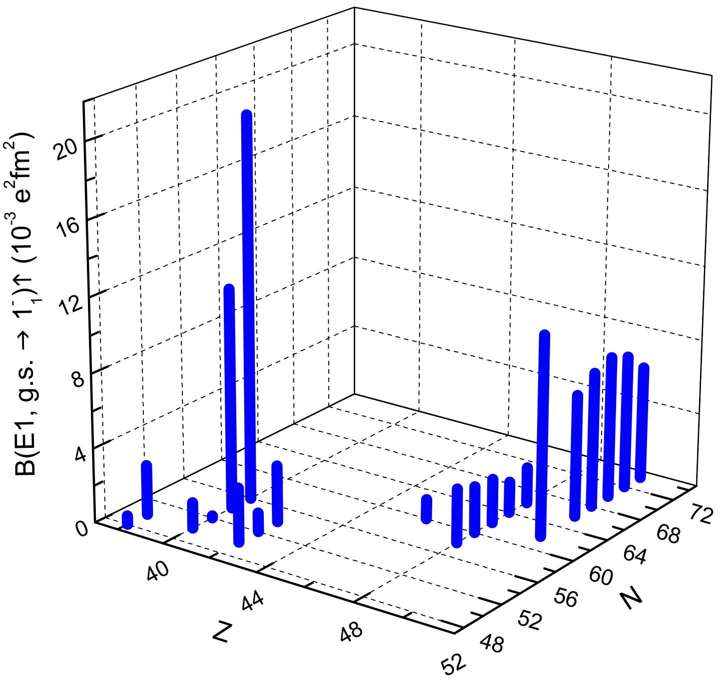

Figure 3. Systematics of the B(E1, g.s. $\rightarrow 1_1^-$)-transition strengths in the Z = 38 - 50 mass region: The isotopes ^{94}Zr and ^{96}Zr have the strongest transitions. This fact might be caused by their large octupole collectivity. Data for ^{86,88}Sr, ^{90}Zr, ^{92,94}Mo, ^{110,112,114}Cd and ^{116,118,120,122,124}Sn have been taken from [2] and for ^{92}Zr from [15]. Furthermore the transitions strengths for ^{96}Mo, ^{106}Pd, ^{106}Cd, ^{108}Cd and ^{112}Sn have been taken from [20] - [24].

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