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Investigation of low-energy dipole modes in the heavy deformed nucleus ^{154}Sm via inelastic polarized proton scattering at zero degree

A. Krugmann[1,a] D. Martin[1], P. von Neumann-Cosel[1], N. Pietralla[1], and A. Tamii[2] for the E350 Collaboration

[1] *Institut für Kernphysik, TU Darmstadt, Germany*
[2] *Research Center for Nuclear Physics, Osaka, Japan*

Abstract. A high resolution proton scattering experiment has been performed on the heavy deformed nucleus ^{154}Sm at extreme forward angles with 295 MeV polarized protons at RCNP, Osaka. Our scientific goal is to investigate the impact of ground state deformation on the properties of the pygmy dipole resonance and on the spin-$M1$ resonance in heavy deformed nuclei. The (p,p') cross sections can be decomposed into $E1$ and $M1$ parts in two independent ways based either on a multipole decomposition of the cross sections or on spin-transfer observables as has been demonstrated for the case of ^{208}Pb. We present the method and preliminary results from the analysis of polarization transfer observables.

1 Introduction

In heavy nuclei at about 1 $\hbar\omega$ excitation energies the so called spin-$M1$ resonance appears. Its centroid energy scales approximately with $40 \cdot A^{-1/3}$ [1, 2]. In deformed nuclei the $M1$ strength is distributed in a double hump structure with an isoscalar part at lower excitation energies and an isovector part at higher excitation energies [3]. The experimental data for the systematics for heavy deformed nuclei have been taken in the early 1990s in a proton scattering experiment with polarized protons at a bombarding energy of 223 MeV at forward angles up to 2.8° performed at the TRIUMF facility in Canada. Figure 1 demonstrates the difficulties of the analysis [4]. One assumption made was that the entire $E1$ strength entering the analysis is described by the giant dipole resonance i.e., the possible existence of a pygmy dipole resonance was neglected. The other problem was that the resonance structures are built on top of a significant background that originates from quasi-free scattering due to the fact that the experiment has been performed at finite scattering angles. A decomposition of the spectrum into contributions of the isovector giant dipole resonance (IVGDR, horizontally hatched), spin-$M1$ resonance (black, low E_x) and the isovector giant quadrupole resonance (IVGQR, black, high E_x) and a background from quasifree scattering (lower smooth line) is shown. The interpretation of the double-hump structure of the spin-$M1$ resonance is contradictory. While some calculations suggest an explanation based on a separation of the proton and neutron 1p-1h states, others explain it as a separation into isoscalar and isovector strength [5–8].

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[a] e-mail: krugmann@ikp.tu-darmstadt.de

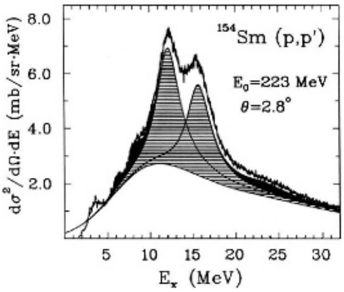

Figure 1. Double-differential cross section of the ^{154}Sm($\vec{p}$, $\vec{p}'$) reaction measured at $\theta = 2.8°$ at TRIUMF [3, 4]. A decomposition of the spectrum into contributions of the IVGDR (horizontally hatched) spin-$M1$ resonance (black, low E_x) and the IVGQR (black, high E_x) and a background from quasifree scattering (lower smooth line) is shown. From Ref. [3].

Recently the method of polarized proton scattering at exactly 0° has become available and this provides a new tool to reinvestigate this intriguing physics with a clearer approach. At the Research Center for Nuclear Research (RCNP) at Osaka one can study polarized proton scattering at 0° at an energy of 295 MeV. This is optimal for spin-isospin excitations because the central term of the nucleon-nucleon cross section shows a minimum at that energy. Combined with a very good energy resolution of 25 keV at a proton energy of 295 MeV it is possible to do two independent experiments. At first a separation of $E1$ and $M1$ contributions to the cross section can be done by comparing the experimentally extracted angular distributions. In addition a spinflip/non-spinflip separation of the cross section can be performed using polarization transfer observables. As a reference case for a heavy nucleus these types of analyses have been performed for the nucleus ^{208}Pb and they show good consistency [9–11].

2 Experimental method and the 0° setup at RCNP at Osaka

In this section the experimental method is briefly described. For detailed information we refer to [12]. In case of inelastic scattering at 0° the primary proton beam is transported into the scattering chamber of the Grand Raiden spectrometer. For a clean measurement, a halo-free beam as well as lateral and angular dispersion matching is necessary and the beam tuning takes up to several days. For achieving both, good scattering angle resolution and low background scattering rates, the medium under-focus mode of the Grand Raiden spectrometer is employed.

At exactly polar scattering angles of 0°, only two polarization transfer coefficients, D_{NN} or D_{SS} which correspond at 0°, and D_{LL} are non-zero and independent. The total spin transfer Σ at $\theta = 0°$ is defined as

$$\Sigma = \frac{3 - (D_{NN} + D_{SS} + D_{LL})}{4} = \frac{3 - (2D_{SS} + D_{LL})}{4}. \tag{1}$$

For non-spinflip excitations (including Coulomb excitation) $\Sigma = 0$ and for spinflip excitations $\Sigma = 1$ [13]. This model-independent relation is used to decompose the spinflip and non-spinflip parts of the cross section.

The polarized proton beam has been preaccelerated up to 54 MeV in the AVF cyclotron and after that accelerated to an energy of 295 MeV in the RING Cyclotron. The polarization axis of the beam has been controlled by employing two solenoid magnets located in the injection line of the RING cyclotron. It has been adjusted to the normal (longitudinal) direction for the D_{NN} (D_{LL}) measurement. The two coefficients D_{NN} and D_{LL} were measured using a focal plane polarimeter (FPP) system. The double scattering efficiency of the FPP system is 0.04 and the effective analyzing power is 0.37. During the experiment a beam intensity of 4 nA and an average beam polarization of 0.7 has been achieved. Differential cross sections at 0° have been measured at the same time during the polarization transfer measurements. After each two-hour run of ^{154}Sm-data, a short calibration run with a ^{26}Mg target has been performed. Prominent 1^+ states of ^{26}Mg in the energy region of interest have been used for an excitation energy calibration since in the ^{154}Sm spectra no resolved transitions are observed because of the high level density. The ^{26}Mg data set has also been used to check the analysis of the polarization transfer coefficients because the prominent peaks should show a pure $M1$ character which, indeed, was observed. The analysis of the polarization transfer coefficients with the FPP data has been carried out using the method of unbiased effective estimators [14].

3 Discovery of the pygmy dipole resonance in ^{154}Sm

Within the above described framework, one can deduce the total spin transfer Σ as a function of the excitation energy. It is plotted in the lower panel of figure 2. As expected, Σ vanishes in the region of the IVGDR because of its pure non-spin flip E1 character. From the quantity Σ one easily obtains the spinflip and non-spinflip cross sections as shown in the upper panel of figure 2. In the lower energy region one can see one clear bump at 6 MeV on top of the low-energy tail of the IVGDR. The non-spinflip cross sections stem from Coulomb excitation of $E1$ transitions. The spinflip strength corresponds to $M1$ transitions showing a broader bump at 6-11 MeV. The low lying dipole strength is clearly dominated by E1 strength and the structure at 6 MeV originates from electric excitations. This indicates that the strength observed in [3, 4] results, at least partially, from $E1$ excitations. This is in conflict with the old TRIUMF data that did not extend to exactly 0° and, hence, the low-energy E1 strength in the deformed nucleus ^{154}Sm escaped detection. To our best knowledge we observed for the first time the so called pygmy dipole resonance (PDR) in a heavy deformed nucleus.

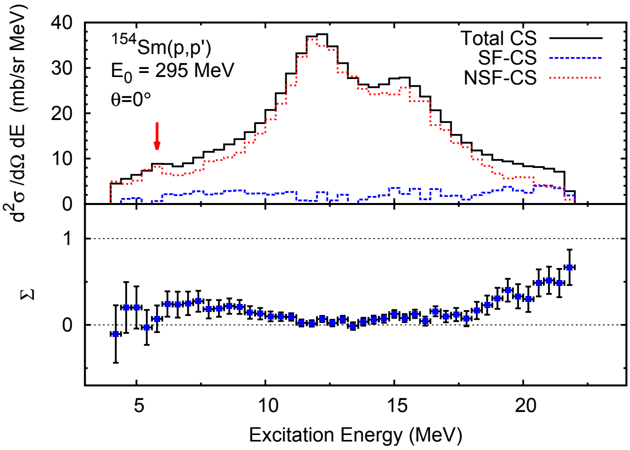

Figure 2. (color online) Upper panel: The solid line shows the total cross section in bins of 400 keV. The dashed line in blue corresponds to the spinflip cross section and the dashed line in red shows the non-spinflip cross section obtained by using polarization transfer coefficients. The arrow indicates a local enhancement of non-spinflip strength observed here for the first time. Lower panel: The experimentally obtained total spin transfer Σ.

4 Discussion and preliminary results

Figure 3 shows the photo-absorption cross section $\sigma_{Absorption}$ obtained in this experiment. The (γ,xn) cross section from [17] has been scaled to the height of the IVGDR. The two datasets are in a good agreement and for the first time we can show results for the photo-absorption cross section below the particle threshold in this nucleus. The previously mentioned (γ,xn) measurements are only capable to measure the cross section down to the neutron separation energy S_n. The deviation of the two datasets in the vicinity of the neutron separation energy is not clear yet and needs further investigation. Also the multipole decomposition analysis as it has been carried out in [9, 11] for the case of ^{208}Pb is currently in progress.

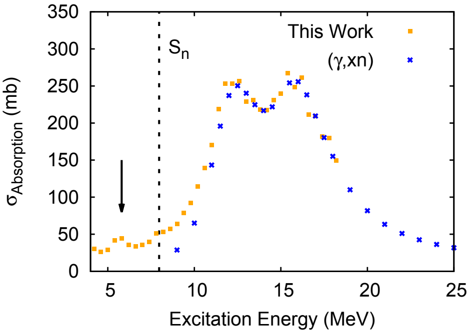

Figure 3. (color online) γ-absorption cross section extracted from this experiment compared to (γ,xn) measurements from [17]. The dashed line indicates the neutron separation energy for ^{154}Sm which lies at 7.97 MeV. The arrow indicates a local enhancement of $E1$ photo-absorption strength in the energy range of the pygmy dipole resonance.

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