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Low-energy dipole modes in the heavy deformed nucleus ^{154}Sm via inelastic polarized proton scattering at 0°

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Abstract. A high resolution proton scattering experiment has been performed on the heavy deformed nucleus ^{154}Sm at extreme forward angles with 300 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 showing a double-humped structure 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 deformed nuclei at about 1 $\hbar\omega$ excitation energies appears the so called spin-$M1$ resonance. In years of intense studies it has been found out that the centroid energy of this resonance scales approximately with $40 \cdot A^{-1/3}$ [1,2]. Figure 1 shows that the 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 shown in figure 1 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 2 demonstrates

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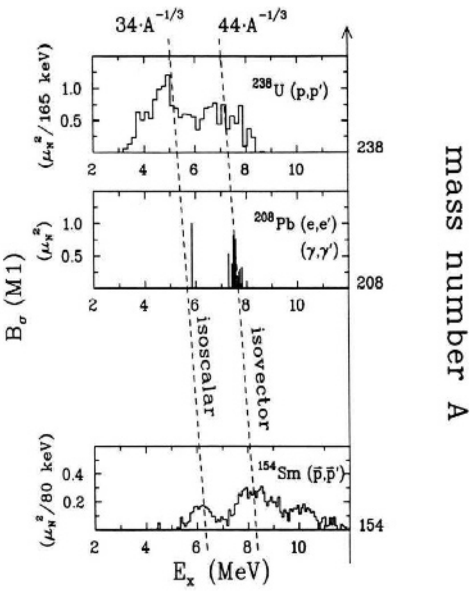

Fig. 1. Systematics of the spin-$M1$ resonance in heavy deformed nuclei measured at TRIUMF [3].

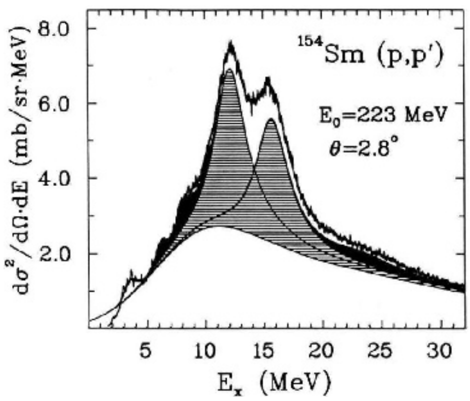

Fig. 2. Double-differential cross section of the ^{154}Sm($\mathbf{p}, \mathbf{p}'$) reaction measured at $\theta = 2.8°$ at TRIUMF [3,4]. A decomposition of the spectrum into contributions of the IVGDR (horizontally hatched) spin-$M1$ resonance (black, low E_x) and the IVGQR (black, high E_x) and a background from quasifree scattering (lower smooth line) is shown. From Ref. [3].

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 huge background that originates from quasifree scattering due to the fact that the experiment has been performed at non-zero 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].

Recently the method of polarized proton scattering at exactly 0° has become available and this provides a new tool to investigate this intriguing physics with a clearer view. At the Research Center for Nuclear Research (RCNP) in Osaka one is able to perform polarized proton scattering at 0° at an intermediate energy of 300 MeV which is optimal for spin-isospin excitations because the central term of the nucleon-nucleon cross section shows a minimum. Combined with a very good energy resolution of 25 keV at a proton energy of 300 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 with the method of polarization transfer observables.

As a reference case of a heavy nucleus these types of analyses have been performed for the nucleus ^{208}Pb and they show good agreement [9–11].

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

In this section the experimental method is briefly described. For detailed information we refer to [12]. In figure 3 one can see, that 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 0°, only two polarization transfer coefficients, D_{NN} which corresponds to D_{SS} at 0°, and D_{LL}, are nonzero and independent. The total spin transfer Σ is defined as

$$\begin{aligned} \Sigma &= \frac{3 - (D_{NN} + D_{SS} + D_{LL})}{4} \\ &= \frac{3 - (2D_{SS} + D_{LL})}{4} \qquad \text{at } 0°. \end{aligned} \tag{1}$$

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 produced and 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 in the experimental setup shown in figure 3 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

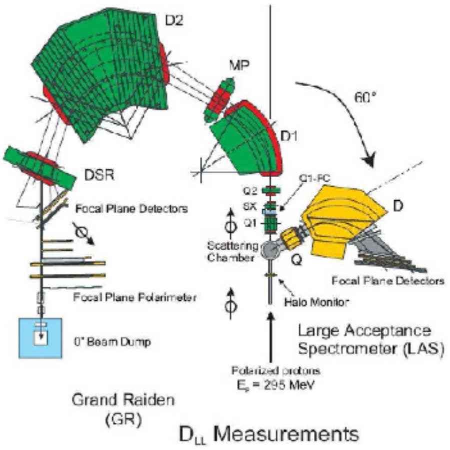

Fig. 3. (color online) The experimental setup at the RCNP in Osaka as it has been used for the D_{LL} measurement [9]. For the D_{NN} measurement the DSR Magnet has been used for rotating the spin of the protons.

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 run of ^{154}Sm-data which took two hours, a short calibration run with a ^{26}Mg target has been performed. Prominent 1^+ states in ^{26}Mg in the energy region of interest have been used for an excitation energy calibration since in the ^{154}Sm spectra no clear lines have been observed. The ^{26}Mg data has also been used to test the analysis of the polarization transfer coefficients because the prominent peaks should show a pure $M1$ character. The preliminary analysis of the polarization transfer coefficients with the FPP data has been carried out using the method of unbiased effective estimators [14].

3 Discussion of preliminary results

Figure 4 shows the first results of the polarization transfer coefficients in ^{26}Mg in the excitation energy range between 8 and 14 MeV where several clear peaks can be clearly distinguished. In the upper panel of the figure the total spin transfer Σ is displayed whereas the lower panel shows the observed cross sections as a function of the excitation energy. The strongest line at 10.65 MeV has been used to correct spectra for small variations of the beam energy. The fact that almost all peaks in this energy region except the weak transitions around 12.5 MeV show either a pure spinflip or a pure non-spinflip character proves the reliability of the analysis. The excitation energy spectrum of the ^{154}Sm data set (figure 5) shows that no resolved lines can be seen because of the high level density. In the excitation energy region between 10 and 16 MeV one can clearly observe the typical structure of the giant dipole resonance which is double-humped for a prolate deformed nucleus. Σ is exactly zero in this region because of the $E1$ nature of the giant dipole resonance. At 6 and 8 MeV a double-humped structure can be seen and the total spin transfer Σ shows an enhancement of the spinflip cross section in this region. This is a good indication for the spin-$M1$ resonance. The combination of the polarization transfer coefficients and the angular distribution data where the analysis is still in progress will help to extract the spin-$M1$ cross section and

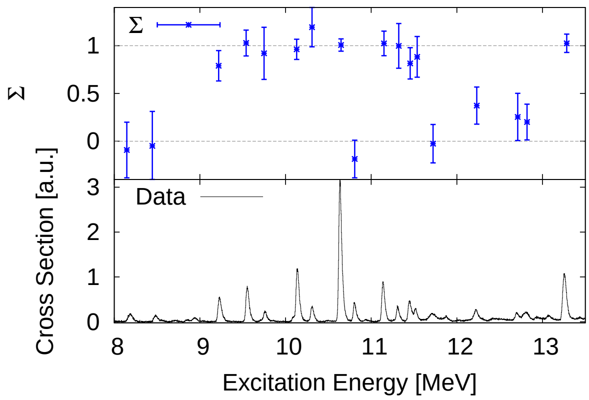

Fig. 4. (color online) Total spin transfer Σ (upper panel) and the corresponding peaks in the excitation energy spectrum (lower panel) for the reaction ^{26}Mg($\mathbf{p}, \mathbf{p}'$) at a proton energy of 295 MeV at 0°.

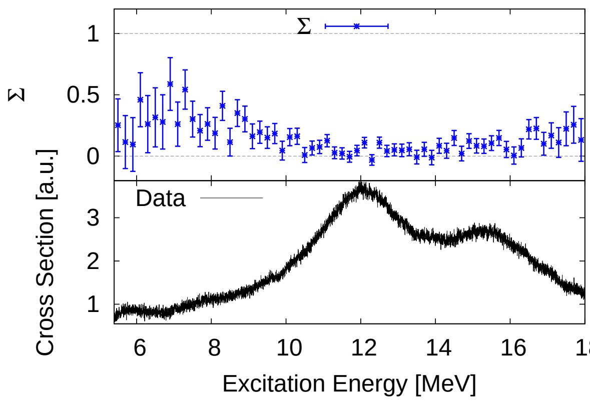

Fig. 5. (color online) Total spin transfer Σ (upper panel) and the corresponding energy bins (width of 200 keV) in the excitation energy spectrum (lower panel) for the reaction ^{154}Sm($\mathbf{p}, \mathbf{p}'$) at a proton energy of 295 MeV at 0°.

the pygmy dipole strength which lies in the same excitation energy region. The comparison with calculations in the quasi-particle phonon model [15] will allow a multipole decomposition analogous to the one described in [9, 11]. It will also be interesting to investigate the role of the deformation for the pygmy dipole resonance when combining the results with measurements of ^{144}Sm [16] that have been performed during the same beam time.

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