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Colloquia: COMEX7

Study of the pygmy dipole resonance using neutron inelastic scattering at GANIL-SPIRAL2/NFS

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Summary. — The pygmy dipole resonance (PDR) has been the subject of numerous studies, both experimental and theoretical. Indeed, the study of the PDR has been and still is of great interest since it allows to constrain the symmetry energy, an important ingredient of the equation of state of nuclear matter that describes the matter within neutron stars. Moreover, the PDR is predicted to play a key role in the r-process via the increase of the neutron capture rate. However, despite numerous experiments dedicated to the study of the PDR, a consistent description is still missing. In this context, we have proposed to study the PDR using a new probe: the neutron inelastic scattering reaction (n,n'γ). An experiment to study the pygmy resonance in ^{140}Ce using the (n,n'γ) reaction has been performed in September 2022. This experiment has been made possible thanks to the high-intensity proton beam of the new accelerator SPIRAL2 at GANIL and the NFS (Neutron For Science) facility. The experimental setup was composed of the new generation multi-detectors PARIS, for the detection of γ-rays coming from the de-excitation of the PDR, and MONSTER, for the detection of scattered neutrons. In this article, the experiment motivation and description are presented.

1. – Studying nuclear excitations via the (n,n'γ) reaction

A basic approach to study the Coulomb or nuclear excitations is to investigate the response to external fields, *i.e.*, performing scattering experiments. These experiments give a direct access to observables —excitation energy spectra and cross sections— that can then be compared to microscopic calculations. The aim is then to identify the inputs of these models that will best reproduce the observables. In the framework of a microscopic structure model, transition densities are inputs which may help interpreting the nature of the phenomena under study: strength, collectivity, isoscalar/isovector nature, presence of a neutron/proton skin, surface or volume excitation... and they are independent of the probe that is used to study this excitation. But, according to the energy and nature of the projectile used in the scattering experiment, the surface and volume densities of neutrons and protons will be probed differently. Thus, complementary experimental approaches need to be used to shed light on the role of protons and neutrons involved in an excitation and further challenge the nuclear structure properties predicted by the models.

At the new NFS [1] facility at GANIL/SPIRAL2 [2], high-flux neutron beams up to an energy of 30 MeV are now available. This offers an opportunity to study the nature of excited states using neutron inelastic scattering, a reaction which is more sensitive to protons than to neutrons [3] and that will probe the surface of the nucleus. The neutron probe has the advantage to be *i)* an elementary probe from the nucleonic point of view: comparison with results obtained using proton inelastic scattering reaction is thus particularly instructive, and *ii)* a pure nuclear probe for which Coulomb correction is not necessary. The intensities and energies of the neutron beams delivered by NFS now make it possible to study excited states with higher excitation energies than what was previously possible using inelastic neutron scattering.

Among the "higher" excitation energy states that are now accessible in inelastic neutron scattering at NFS, the electric dipole (E1) excitations are of particular interest.

The well-known isovector giant dipole resonance (IVGDR), which corresponds to the oscillation of the neutron fluid against the proton fluid, is a broad resonance with mean energy between 12 and 24 MeV and a width in the range of 2.5 to 6 MeV exhausting almost 100% of the isovector electric dipole strength. Additional E1 strength has been observed at lower energy in neutron-rich nuclei, near the neutron separation threshold. This small-size structure, in comparison to the IVGDR, is commonly known as the pygmy dipole resonance (PDR) and can be described as the oscillation of a neutron skin against a symmetric proton/neutron core. The PDR has been the subject of numerous studies, both experimental and theoretical, and results are compiled, for example, in recent reviews [4-6]. The study of collective dipole modes has raised a lot of interest since they are related to the neutron-proton interactions and thus can constrain the symmetry energy, an important ingredient of the equation of state [7]. The enhancement of the E1 strength close to the neutron separation energy is expected to impact the astrophysical r-process by increasing the neutron capture rates [8-10]. Almost all the macroscopic and microscopic models are able to reproduce E1 strength at lower energy than the IVGDR but with various interpretation of the intrinsic nature. In this context, the availability of a new probe like the neutron inelastic scattering is welcome.

2. – Study of the PDR in ^{140}Ce using the (n,n'γ) reaction

In September 2022, we performed the first experiment dedicated to the study of the PDR using neutron inelastic scattering reaction. This experiment has been performed at NFS on ^{140}Ce(Z = 58). A proton beam with an intensity of 20 μA accelerated by the LINAC of SPIRAL2 to an energy of 33 MeV, was sent onto a 1.5 mm-thick lithium converter. The ^{7}Li(p,n)^{7}Be charge-exchange reaction provided a quasi-mono-energetic neutron beam peaked around 30.7 MeV. The energy distribution of this neutron beam was measured using a calibrated EJ309 scintillator based neutron detector. This spectrum is shown in fig. 1, the integrated flux in the peak being 1.2×10^{9} n/sr/μC for a light threshold of 400 keVee.

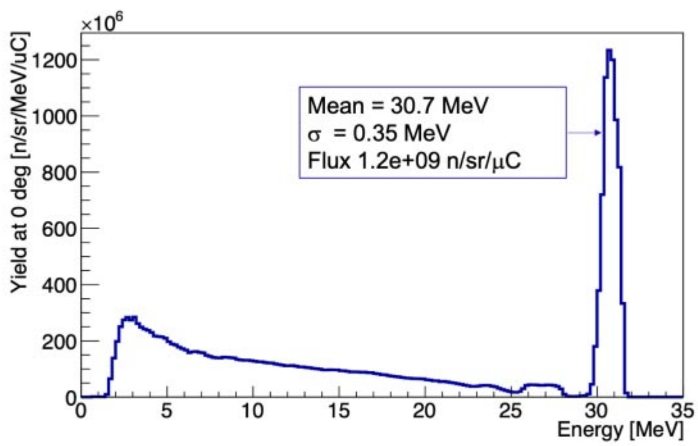

Fig. 1. – Rate of neutrons measured as a function of energy by the ^{7}Li(p,n)^{7}Be reaction for a light threshold of 400 keVee.

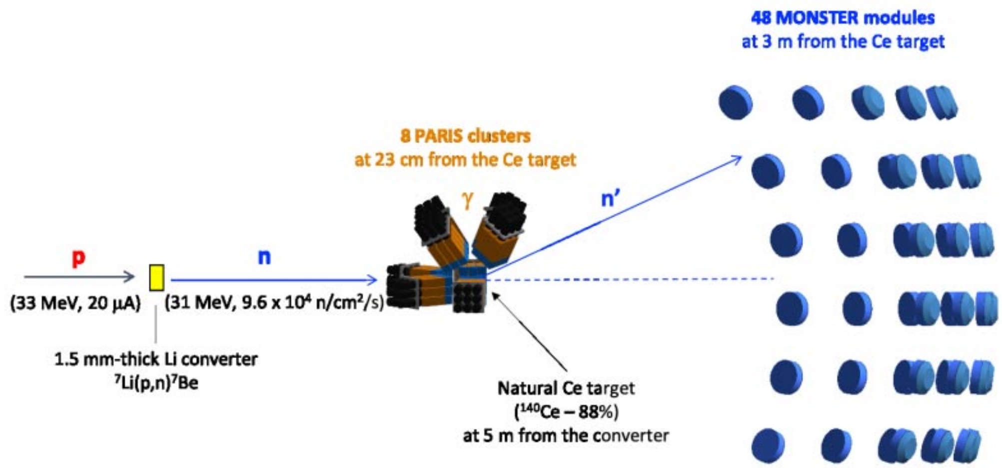

Fig. 2. – Scheme of the experimental setup used at NFS in September 2022 to study PDR in ^{140}Ce. Picture extracted from simulations performed using NPTOOL framework [14].

The produced neutron beam interacted with a natural cerium target (88% ^{140}Ce, 11% ^{142}Ce), with a diameter of 4 cm and a thickness of 3 cm, positioned 5 m downstream from the converter. The aim here is to excite the ^{140}Ce nucleus using neutron inelastic scattering reaction, and then to study γ de-excitation: ^{140}Ce(n,n')^{140}Ce$^{*}(\gamma)^{140}$Ce or, shorter, ^{140}Ce(n,n'γ). The PARIS detector (Photon Array for studies with Radioactive Ion and Stable beams) [11, 12] has been used for γ-ray measurement. 8 PARIS clusters were placed at 23 cm from the target, in pairs at 60°, 90°, 120° and 150° in respect to the beam axis, to provide angular coverage between 45° and 165°. For the detection of the scattered neutron, the MONSTER detector [13] has been used. The 48 modules were mounted on 8 vertical structures, each accommodating 6 modules. The structures were positioned 3 m downstream of the cerium target at −32°, −24°, −16°, −8°, 0°, 8°, 16° and 24° from the beam axis. On each structure, 6 detectors were mounted at y = −84 cm, −51 cm, −17 cm, +17 cm, +51 cm and +84 cm relative to the horizontal plane containing the beam axis. The solid angle coverage of the neutron/γ detectors is $\Omega = 0.17\,\mathrm{sr}/4.3\,\mathrm{sr}$. Figure 2 presents a scheme of the experimental setup and fig. 3 shows a picture of this experimental setup mounted at NFS. Angular coverage for scattered neutron detection ranged from 10° to 50°, covering in particular the angles where the effective E1 cross-section is highest (see fig. 5).

The analysis is ongoing. The goal is to identify excited states or excited energy range of 1^- nature. When this step will be reached, cross sections of these 1^- states will be compared to theoretical predictions. To extract information about the transition densities we can calculate the neutron and proton inelastic cross sections using the microscopic Jeukenne, Lejeune and Mahaux (JLM) folding model and QRPA transitions densities [15] and make a direct comparison with the experimental results. QRPA (Quasiparticle Random Phase Approximation) calculations with the Gogny D1M interaction have been carried out for ^{140}Ce. This mean-field method has proven its value in predicting the dynamical behavior of the nucleus [16]. The first excited state of 1^- nature is predicted at 9.1 MeV, and the proton and neutron transition densities associated with this state

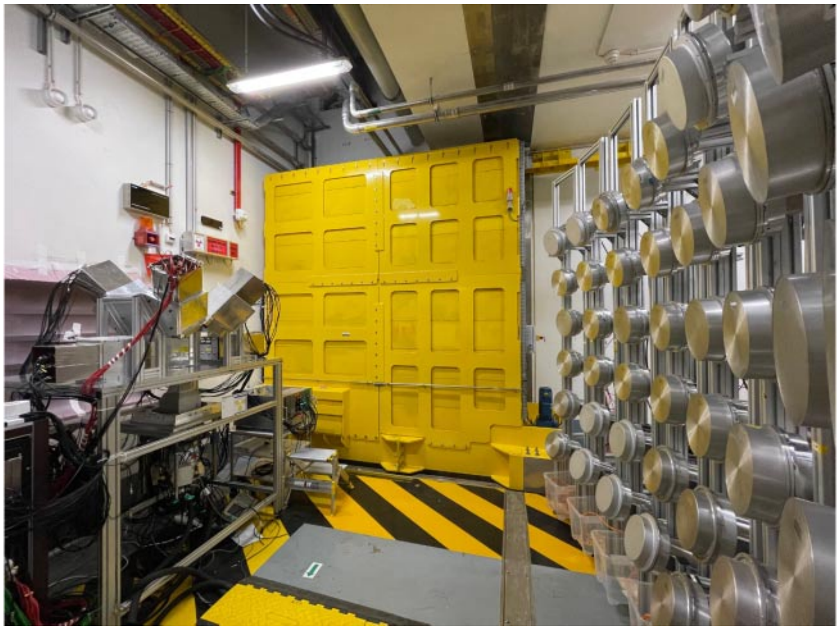

Fig. 3. – Photo of the experimental setup used at NFS in September 2022 to study PDR in ^{140}Ce.

are shown in fig. 4. DWBA calculations using the microscopic JLM folding model were then performed to predict the inelastic scattering cross sections (n,n') and (p,p') for this 1^- state at 9.1 MeV. Figure 5 shows the results of these calculations for inelastic neutron scattering in black and proton scattering in red. If we arbitrarily divide the amplitude of the proton (respectively neutron) transition density by a factor of 3, we obtain the result shown with the dotted line (fig. 5 left (resp. right)): the reaction cross-section (p,p') (resp. (n,n')) remains almost unchanged, while that associated with the reaction (n,n') (resp. (p,p')) decreases significantly (factor ∼3).

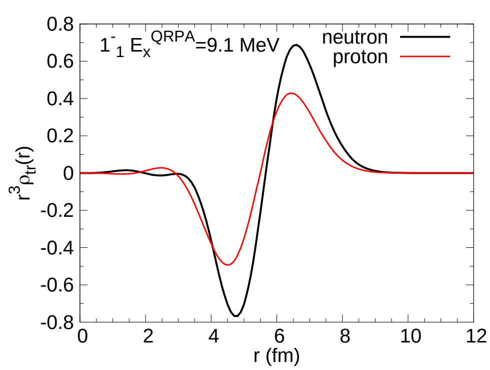

Fig. 4. – Proton (red) and neutron (black) transition densities multiplied by r^3 for the first 1^- state predicted in ^{140}Ce by the QRPA calculations using the Gogny D1M interaction.

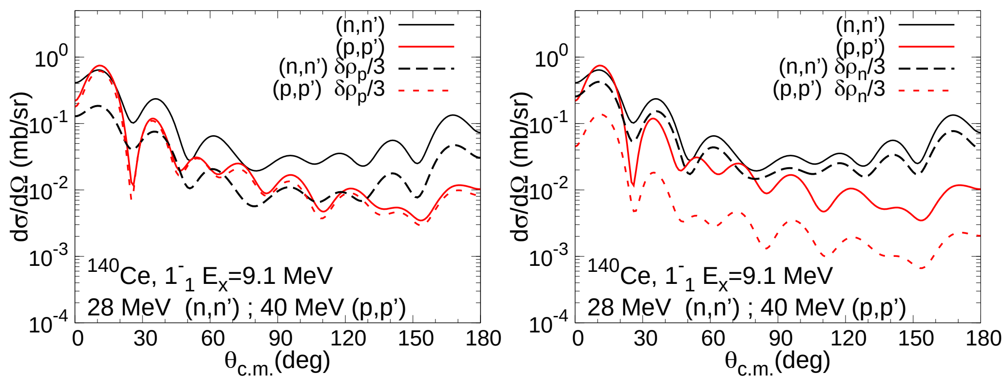

Fig. 5. – Left: cross sections for the first 1^- state in ^{140}Ce populated in the (n,n') reaction (black) and in the (p,p') reaction (red) as a function of the angle in the c.m. The calculations are done with the initial set of transition densities (solid line) and with the proton transition density reduced by 3 (dashed line). Right: same but with the neutron (instead of proton) transition density reduced by 3. The calculations are done for incoming neutron at 28 MeV and incoming proton at 40 MeV to take into account the Coulomb contribution in (p,p').

Figure 5 illustrates the principle of the method that motivated the experiment. The valuable quantities to discuss the transition densities would be the angular distributions to assess the transition strength and nature of the 1^- excitation mode. In practice, for each excited state which will be identified as 1^- thanks to the γ angular distribution, we will:

1) Extract the (n,n') cross section to populate these states;
2) Compare the (p,p') and (n,n') cross sections to populate these same excited states;
3) Discuss the transition densities (fig. 4) that are able to reproduce these observables, or even other reaction channels if experimental data exist.

At the time of writing this paper, the energy calibrations of the detectors and the time alignments were carried out and the efficiency of the PARIS detectors estimated. The current analysis focuses on the elastic scattering channel for which there are no published data at this incident neutron energy.

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