FIRST STUDY OF THE PYGMY DIPOLE RESONANCE VIA NEUTRON INELASTIC SCATTERING AT GANIL-SPIRAL2/NFS: BENCHMARKING THE METHOD ON THE ^{12}C 2^{+} EXCITED STATE*

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The Pygmy Dipole Resonance is an exotic excitation mode whose microscopic nature is not yet fully understood. By using different probes in inelastic scattering reactions, it is possible to obtain complementary information on the character of excited structures. For this reason, the very first study of the Pygmy Dipole Resonance using a neutron probe has been performed. The experiment, focused on the ^{140}Ce nucleus, took place in 2022 at the NFS facility at GANIL-SPIRAL2. The PARIS and MONSTER arrays were used for the γ-ray and scattered neutron detection, respectively. As the first step of the analysis, the elastic and inelastic scattering channels on a $^{\rm nat}$C target were investigated with a focus on the well-known first 2^+ excited state of ^{12}C. The obtained results validate the analysis procedure, which will be applied to investigate the Pygmy Dipole Resonance in ^{140}Ce.

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1. Motivation

The Pygmy Dipole Resonance (PDR) is an exotic excitation mode that emerges in the dipole response of nuclei as the neutron-to-proton number ratio increases. Compared to the Giant Dipole Resonance — a collective vibration mode of nuclei which exhausts the majority of the dipole strength — the pygmy states are located at lower excitation energies around the neutron separation energy threshold. Studies of PDR are of great interest for nuclear structure [1], have possible implications in nuclear astrophysics [2], and can provide constraints for the symmetry-energy parameter [3] of the nuclear equation of state. As of today, available experimental data do not provide an accurate picture of the fine structure of the PDR and open questions on its nature still need to be addressed, in particular regarding the collectivity and the isospin character of the E1 states in the PDR energy region [1].

Scattering experiments are commonly used to extract information on the structure of nuclear states. As the response of nuclei is sensitive to the nature of the external field, different probes may provide complementary insights into the characteristics of the excited states [4]. In the experiment presented here, a new experimental approach, namely neutron inelastic scattering, has been used to extract information on the microscopic structure of the PDR. The study benefited from unique neutron beam fluxes available at the Neutron For Science (NFS) facility [5] at GANIL-SPIRAL2 [6]. The experiment took place in September 2022 and focused on the PDR in the ^{140}Ce nucleus, observed in the energy region between 3 and 8 MeV. As the dipole excitations of ^{140}Ce were previously studied via different reactions [7], it will be possible to compare the results of the present study with those obtained using other complementary probes in order to get a deeper insight into the character of the PDR in this nucleus.

2. The ^{140}Ce(n, n') experiment at GANIL-SPIRAL2/NFS

2.1. Neutron beam at NFS

The NFS facility produces high-flux neutron beams via interaction of protons, accelerated by the SPIRAL2 LINAC up to 33 MeV energy, with a converter. In the present experiment, a 1.5 mm-thick lithium converter was used to generate a quasi-monoenergetic neutron beam of 30.8 MeV energy via the ^{7}Li$(p, n)^7$Be charge-exchange reaction. The neutron beam energy spectrum was measured with the Time-Of-Flight (TOF) technique using a detector placed 30 m from the converter. General characteristics of the neutron beam are given in Fig. 1. The measured neutron flux, integrated over the full-energy peak at 30.8 MeV, was equal to $(1.41 \pm 0.03) \times 10^9$ n/sr/μC, in agreement with Ref. [5]. This corresponded to $(1.41 \pm 0.04) \times 10^6$ n/s on the target.

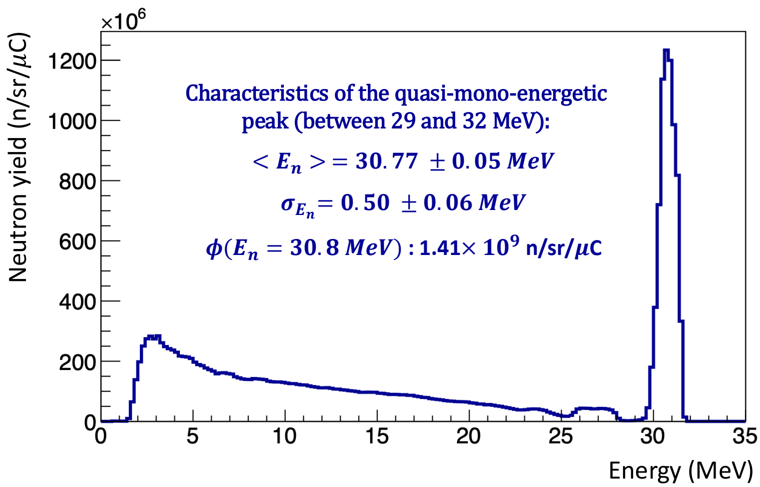

Fig. 1. Measured neutron beam energy distribution with its general characteristics and the value of the neutron flux at 30.8 MeV. The obtained values are in agreement with Ref. [5].

2.2. Experimental setup

The targets were placed 5 m from the converter in the TOF hall of NFS, surrounded by the detection setup shown in Fig. 2 (also presented in Ref. [8]). For the ^{140}Ce study, a 3 cm thick $^{\mathrm{nat}}$Ce target of 2 cm radius was used, with the natural abundance of the ^{140}Ce isotope equal to 88%. As the cerium metal easily oxidises, the target was wrapped in an aluminum foil. A second target of $^{\mathrm{nat}}$C with the same dimensions, also wrapped in aluminum, was used as a benchmark. The MONSTER (MOdular Neutron time-of-flight SpectromeTER) [9] and PARIS (Photon Array for studies with Radioactive Ion and Stable beams) [10, 11] detectors were used for the detection of, respectively, the scattered neutrons (n') and the γ rays coming from the deexcitation of ^{140}Ce* (or ^{12}C*) in the reactions of interest: $^{140}\mathrm{Ce}(n,n')^{140}\mathrm{Ce}^*(\gamma)^{140}\mathrm{Ce}$ and $^{12}\mathrm{C}(n,n')^{12}\mathrm{C}^*(\gamma)^{12}\mathrm{C}$.

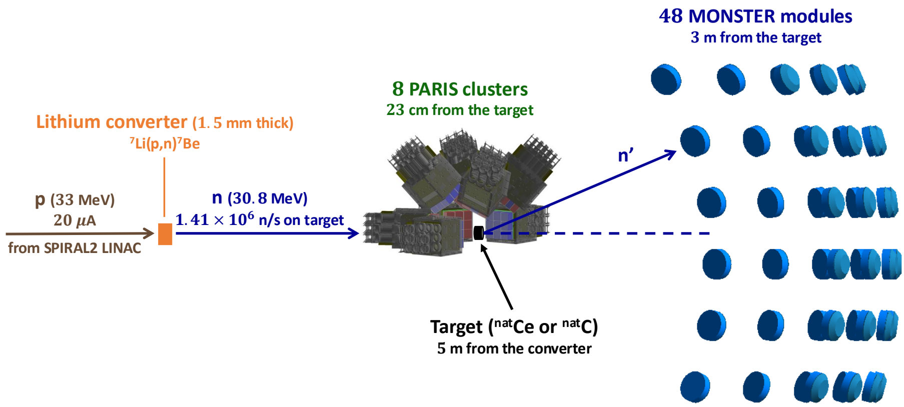

Fig. 2. Experimental setup used for the present study of the PDR in ^{140}Ce.

During the experiment, 8 PARIS clusters of 9 phoswiches each ($LaBr_3$ or $CeBr_3$ scintillators coupled to NaI crystals) were placed 23 cm from the target. An addback procedure was applied to the data from each cluster in order to reconstruct Compton-scattering events. The PARIS setup offers good efficiency in the PDR energy region (around 3% after addback), and an angular coverage from 45° to 164° in the laboratory frame with respect to the beam direction. The MONSTER modules are based on liquid scintillators (BC501A and EJ301) offering good neutron-γ discrimination via the Pulse-Shape Discrimination (PSD) method. The scattered neutron energies were reconstructed from the TOF over the average 3 m distance between the target and the MONSTER modules. This distance was chosen as the best compromise between the geometrical efficiency and the energy resolution. The MONSTER setup covered the angular range of 3°–36° in the laboratory frame. The experimental setup had a very good timing resolution, with a typical σ of 360 ps for PARIS and of 600 ps for MONSTER. The data were acquired using the FASTER (Fast Acquisition SysTem for nuclEar Research) acquisition with the CARAS digitizer [12].

3. Results of the study with the $^{\rm nat}$C target

3.1. Elastic scattering $^{nat}C(n,n)^{nat}C$

The first part of the analysis was focused on the elastic scattering channel measured with the $^{\rm nat}$C target, and specifically the extraction of the angular differential cross section. The energy spectra of the scattered neutrons were extracted for each MONSTER module from *(i)* the TOF between the neutron detection and the LINAC RF and *(ii)* the target-MONSTER module distance. The outgoing fluxes for the elastic channel were computed from the integral of the 30.8 MeV peak in each MONSTER module after background subtraction. Background runs were taken with the neutron beam bombarding the aluminum target shell at the standard target position. An efficiency of 10% at 30.8 MeV was assumed based on simulations performed by the MONSTER Collaboration. A correction for the neutron beam attenuation in the 3 cm-thick target was also applied. The deduced experimental angular differential cross section in the center-of-mass frame is shown in Fig. 3. The uncertainties of the angle correspond to the angular aperture of the MONSTER modules, and those of the cross-section result from the standard propagation of the uncertainties of the neutron beam intensity, target properties and the number of scattered neutrons detected in MONSTER. No uncertainty on the MONSTER efficiency was considered. A very good agreement is observed between the experimental values and the data from the TENDL-2019 evaluation library, see Fig. 3. This provides a validation of the analysis procedure applied to the scattered neutron data.

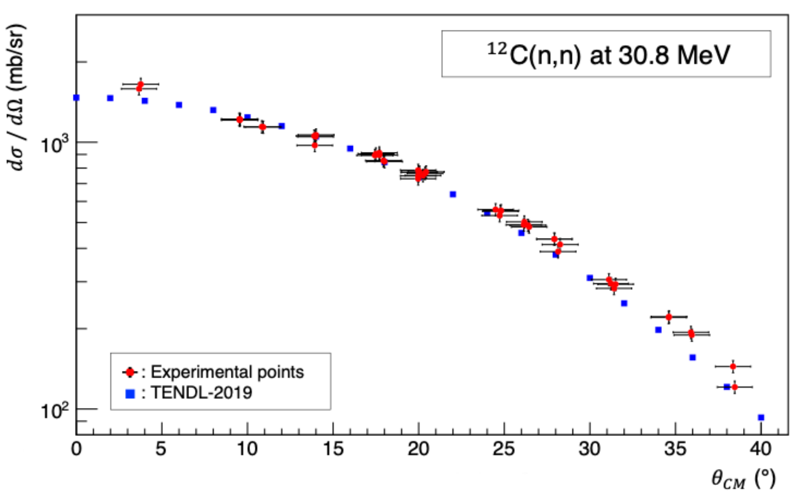

Fig. 3. Angular differential cross section for the neutron elastic scattering on a $^{\rm nat}$C target after background subtraction. The experimental points are compared to the data from the TENDL-2019 evaluation library.

3.2. Inelastic scattering on the ^{nat}C target

The analysis of data from the inelastic scattering channel on $^{\mathrm{nat}}$C was focused on the properties of the first 2^+ excited state of ^{12}C at 4.4 MeV. Since the energy of this state is within the PDR energy region for the ^{140}Ce nucleus, the analysis of which will rely on the same method, this step of the analysis provides a benchmark of the procedure. The γ rays resulting from the scattering of 30.8 MeV incident neutrons, referred to as prompt γ rays, are selected via tagging of the incident neutron energy using a gate on the TOF in PARIS, measured with respect to the accelerator RF signal. A γ–n' coincidence condition is then applied in order to keep only events with at least one prompt γ ray in PARIS and at least one scattered neutron in MONSTER. The coincidence matrix built from those events is shown in Fig. 4, top panel, where the horizontal axis corresponds to the excitation energy reconstructed from the measurement of the scattered neutron energy in MONSTER, and the vertical axis is the measured γ-ray energy in PARIS. The two-dimensional cut used to select the 4.4 MeV excited state corresponds to $\pm\,3\sigma$ on both axes ($\sigma_{E^*} = 730.0 \pm 4.1$ keV and $\sigma_{E_{\gamma\mathrm{prompt}}} = 52.5 \pm 0.2$ keV). Applying this cut results in a suppression of random coincidences coming from 1.6 neutrons per bunch (on average) interacting in the target, as well as from cross-talk between MONSTER modules.

The γ-ray angular distribution of the decay of the 4.4 MeV excited state measured in PARIS (after background subtraction) is shown in Fig. 4, bottom panel. The background subtraction and error evaluation follow the description in Section 3.1. The distribution is fitted with Legendre polynomials: $\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)$. The experimental points follow well the expected angular distribution for a quadrupole excitation [13]. The cross section in Fig. 4 (bottom panel) accounts only for the absolute efficiency of the MONSTER setup. The total experimental cross section obtained in this way was compared with theoretical predictions [14] to extract the efficiency of the PARIS setup at 4.4 MeV. The obtained value of $2.93 \pm 0.73\%$ (after addback) was in agreement with the simulations performed with the STоGS toolkit [15], and confirmed the validity of the RADWARE fit [16] used for the efficiency curve up to the PDR energy region. The coherent results of the presented analysis for the inelastic channel on ^{12}C validate the method used for random-coincidence suppression using a two-dimensional cut on the $(E_{\gamma\mathrm{prompt}}, E^*)$ matrix. The same method will be applied in the study of the PDR in ^{140}Ce. In particular, γ-ray and neutron angular distributions will be analysed to verify the dipole multipolarity of the populated excited states and, consequently, their PDR nature.

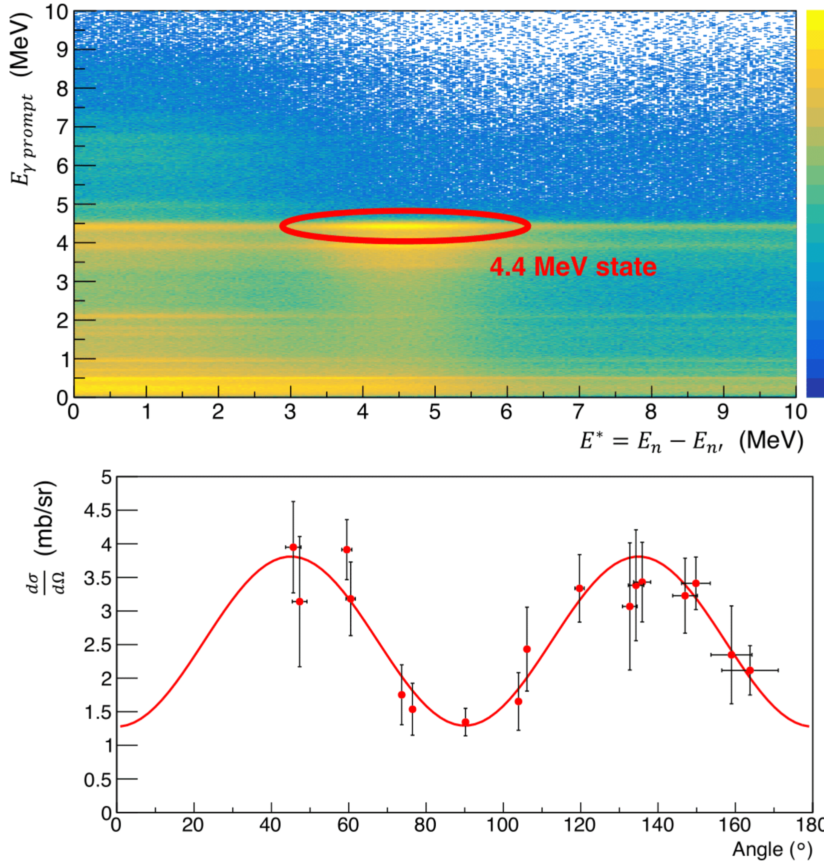

Fig. 4. (Colour on-line) Top panel: γ-ray energy measured in PARIS, after addback, as a function of the ^{12}C excitation energy deduced from the scattered neutron TOF, Bottom panel: γ-ray angular distribution measured in PARIS after application of the cut presented in the top panel and after background subtraction (see the text for details). The red/black curve presents a fit with Legendre polynomials using a_2 and a_4 as free parameters (see the text for details).

4. Conclusion and perspectives

The first study of the PDR using neutron inelastic scattering was performed at GANIL-SPIRAL2/NFS in 2022. The main aim of the experiment was to study the PDR in ^{140}Ce, but data with a carbon target were also taken to benchmark the method. The analysis of ^{12}C data has been completed. The deduced neutron angular distribution for the elastic scattering reaction channel $^{12}\mathrm{C}(n,n)^{12}\mathrm{C}$ were found to be in agreement with the data from the TENDL-2019 evaluation library. The γ-ray angular distribution of the decay of the 2^+ state in ^{12}C, populated in the inelastic scattering reaction channel $^{12}\mathrm{C}(n,n')^{12}\mathrm{C}^*(\gamma)^{12}\mathrm{C}$, was obtained. Its fit using Legendre polynomials confirmed the quadrupole nature of the analysed γ-ray transition. These results have validated the analysis procedure that will be applied to ^{140}Ce in the future. The analysis of the elastic and inelastic scattering reaction channels measured for ^{140}Ce is ongoing. The neutron angular distribution for the elastic scattering on ^{140}Ce will be, to our knowledge, obtained for the first time at this neutron energy. This result, together with the study of the PDR in ^{140}Ce, will be presented in a follow-up article.

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