# Investigation of the Dipole Response in Exotic Nuclei — Experiments at the LAND-$R^3B$ Setup

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We present experimental results on the electromagnetic excitation of neutron-rich nickel isotopes, making use of the $R^3$B-LAND setup at GSI. Exotic beams were produced at approximately 500 MeV/u and their reactions were studied in inverse kinematics. Integral cross sections for $^{58}$Ni are discussed and compared to previous data, providing a validation of our experimental method. The E1 excitation-energy distribution of the unstable $^{68}$Ni is presented as well, showing an excess in cross section in the 1n decay channel when compared only with a typical Giant Dipole Resonance.

## §1. Introduction

For decades, the study of the collective response of atomic nuclei was limited to stable or very long-lived isotopes. The emergence of radioactive ion-beam facilities has broadened the possible range of investigation towards the limits of existence of nuclei, providing an access to proton-neutron asymmetries that could not be achieved before. In the particular case of dipole response, the Giant Dipole Resonance (GDR) is accompanied by a soft dipole mode — the so-called Pygmy Dipole Resonance (PDR) — when the neutron excess is large enough. The appearance of the PDR is related to the thickness of the neutron skin, which in turn strongly correlates with the symmetry energy in pure neutron matter and with the symmetry energy pressure,[1),2)] two important quantities of the nuclear equation-of-state. The measurement of PDR strength in exotic nuclei provides a constraint of these parameters at saturation density, which have an influence for instance on the behavior of neutron stars. The PDR also plays a role in r-process nucleosynthesis scenarios,[3)] since it provides additional strength at energies below the GDR. Depending on the selected astrophysical conditions such as temperature, neutron density and duration of neutron irradiation, the PDR can have a more or less large impact on the calculated r-abundances.

Experimental data on Pygmy Dipole Resonances in exotic nuclei is still only available for a limited number of species due to the great complexity of such measurements. In a previous experiment carried out at the LAND setup at GSI, PDR strength was observed in neutron-rich Sn isotopes,[4)] leading to the determination of the $a_4$ and $p_0$ parameters of the nuclear symmetry energy and to neutron-skin radii in $^{130}$Sn and $^{132}$Sn using an RQRPA approach.[5)] The PDR has also been measured in $^{68}$Ni more recently by means of ($\gamma$,$\gamma$') virtual photon scattering and appears with approximately 5% of the E1 energy-weighted sum rule strength,[6)] leading to equation-of-state parameters in good agreement with those obtained for $^{132}$Sn.[7)]

In the following discussion, we present preliminary results of the dipole response in $^{68}$Ni, measured via Coulomb dissociation ($\gamma$,xn) at the LAND-R$^3$B setup.

## §2. Experimental setup

The present experiment has been carried out at the LAND-R$^3$B setup located at GSI in Darmstadt, as shown in Fig. 1. Various radioactive ion beams, containing $^{56}$Ni to $^{72}$Ni at energies around 500 MeV/u, have been prepared using the fragment separator FRS.[8)] Due to the use of so-called cocktail beams, the identification of the particles on an event-by-event basis is vital and is shown in Fig. 2. This was achieved by measuring the time-of-flight of the ions between the final focal plane of the FRS and the experimental setup and their energy loss in front of the reaction target. In order to separate the individual ion masses, an additional position measurement in the dispersive focal plane of the FRS is required, providing a correction to the nominal magnetic rigidity setting of the fragment separator.

When using heavy-ion-induced electromagnetic excitation to measure the dipole response of a nucleus, its excitation energy is not known unless the invariant mass of

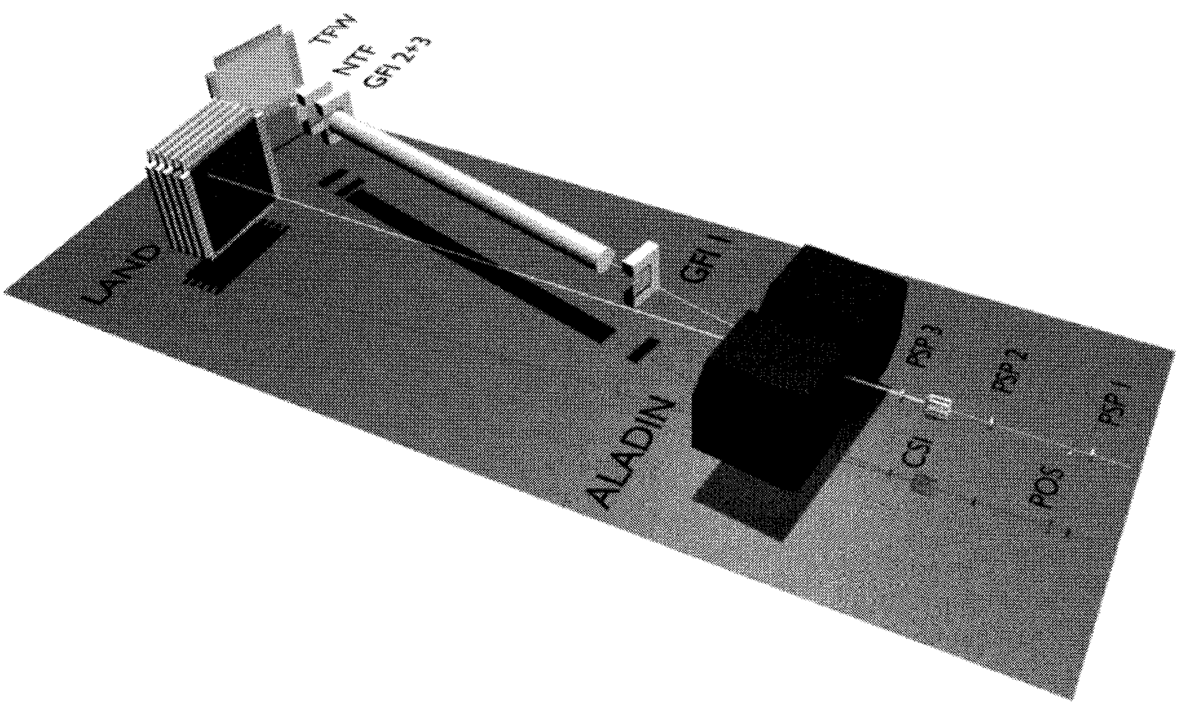


Fig. 1. (Color online) LAND-R$^3$B setup at GSI. The incoming exotic beam enters the setup at the lower right side in the figure and is directed onto the reaction target located directly in front of the CsI gamma detector (CSI). Various tracking detectors measure the momentum and identify the exotic nuclei (PSP, POS). The charged fragments are deflected by the ALADIN dipole magnet into the ion branch of the setup, equipped with scintillating fiber detectors (GFI) and a plastic scintillator time-of-flight wall (TFW). The decay neutrons are detected at angles close to 0° in the Large Area Neutron Detector (LAND).

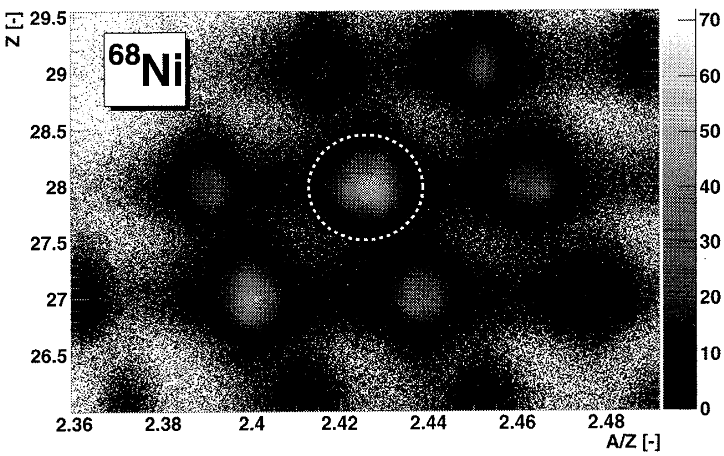


Fig. 2. Identification plot of the cocktail beam in the $^{68}$Ni region. The $^{68}$Ni ions are selected with a two-dimensional cut along the dotted circle.

the system before and after the excitation is measured. When dealing with neutron-rich nuclei, as is the case in the present experiment, the expected reaction products are several evaporated neutrons, photons and one heavy fragment. Therefore, the main detectors of the LAND-R$^3$B setup for this experiment were the Large Area Neutron Detector (LAND),[9] located at 0° and responsible for the momentum measurement of the neutrons, a $2\pi$ CsI gamma detector (144 crystals arranged in a barrel geometry) placed directly behind the reaction target, a series of scintillating fiber detectors[10] intended for the tracking of the remaining ion fragments and a plastic scintillator time-of-flight wall for their identification and momentum measurement. Due to the relativistic energy of the incoming beam, all reaction products experience strong kinematic forward-focusing, allowing high-acceptance measurements with relatively small detectors. In addition to the various detector systems, the setup relies on the large acceptance ALADIN dipole magnet to deflect the heavy ions, allowing the measurement of their mass after tracking their individual trajectories.

The electromagnetic excitation of the nuclei of interest is most efficient when using a high-Z target, such as Pb. However, even when using strict conditions on the data to pin down the desired reaction channel, very peripheral reactions involving the strong interaction cannot be fully excluded. Therefore, each beam setting is also measured with a C target, in order to provide data from nuclear interactions. After adjusting the measured differential cross sections for the difference in size of the Pb and C nuclei,[11] the unwanted reactions can be subtracted quantitatively from the Pb data. An additional measurement without target also allows the subtraction of non-specific background also present in the Pb data, mainly originating from reactions in the various detectors.

## §3. $^{58}$Ni test case

One of the main goals of the present experiment was the measurement of dipole strength in unstable Ni isotopes. One of the beam settings, however, delivered a stable nickel isotope, namely $^{58}$Ni. This allows us to compare our present results on this nucleus with previously published data,[12),13] providing a valuable opportunity to validate our experimental method.

The decay of the GDR in $^{58}$Ni is expected to involve the emission of protons, since its proton and neutron thresholds are located at 8.17 MeV and 12.2 MeV, respectively. However, the setup of the present experiment was not fully suited for the investigation of such a nucleus, since relativistic protons were not detected. This leads to a significant reduction in observed dipole strength. An additional feature of the data of Fultz et al. is the presence of the ($\gamma$,np) channel above excitation energies of 19.6 MeV in the photoneutron data, since the charged reaction products were not detected. In the present case, we are able to clearly separate the ($\gamma$,n) and ($\gamma$,np) channels, which are evaluated individually.

The $^{58}$Ni photoabsorption data of Fultz et al.[13] was converted into an integral Coulomb-excitation cross section for a projectile energy of 501 MeV/u impinging on a Pb target, corresponding to the experimental conditions of the $^{58}$Ni setting in the present experiment. Table I presents the integral cross sections for the ($\gamma$,n)

Table I. $^{58}$Ni Coulomb-excitation cross sections. The statistical errors are indicated between brackets for each cross section value. The last row contains the estimated systematical error on the combined n+np cross sections. The mean value for each error source is taken into account for the Fultz et al. data.[13)]

| Data set | $\sigma$(n) [mb] | $\sigma$(np) [mb] | $\sigma$(n+np) [mb] | Syst. error [mb] |
|---|---|---|---|---|
| Fultz et al.[13)] | – | – | 123(6) | 15 |
| Present experiment | 111(4) | 25(4) | 136(8) | 8 |

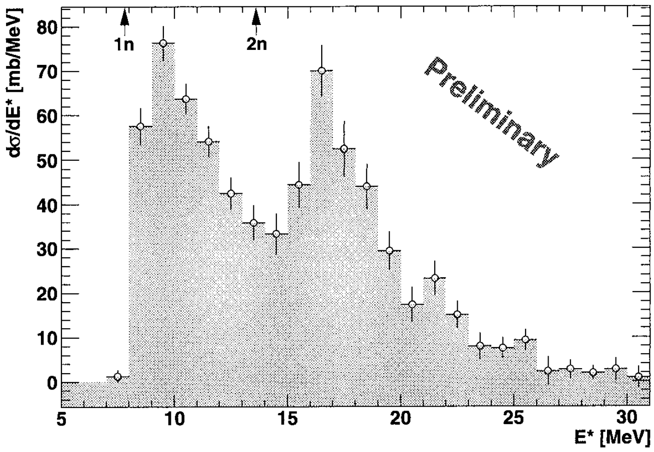


Fig. 3. Preliminary Coulomb-excitation energy distribution of $^{68}$Ni at approximately 500 MeV/u obtained from the ($\gamma$,n) and ($\gamma$,2n) channels.

and ($\gamma$,np) channels of $^{58}$Ni. Fultz et al.[13)] report also a series of systematical errors. Since the photons are generated by positron annihilation, the bremsstrahlung subtraction is reported with an error of at most 4%. The error on the photon flux is of the order of 5–10%, and the efficiency of the neutron detector varies from 1% to 5%, depending on the neutron energy. In the present experiment, a systematical error of 6% is attributed to the efficiency correction, originating from a small discrepancy in the neutron hit distributions in the experimental and simulated data. These effects lead to the systematical errors indicated in Table I. The combined $\sigma$(n+np) cross sections of both measurements are in good agreement within the respective statistical errors, validating the present experimental method.

## §4. Dipole strength of $^{68}$Ni

Among several experimental settings containing exotic nickel isotopes, the case of $^{68}$Ni is of particular interest, since this nucleus has been studied in a different experiment[6)] using the technique of virtual photon scattering, providing another valuable opportunity for comparison. Figure 3 presents the reconstructed Coulomb-excitation energy distribution from the analysis of the ($\gamma$,n) and ($\gamma$,2n) channels at a beam energy of about 500 MeV/u. The spectrum as shown here contains a strong detector response induced by the neutron and gamma detectors, which is partially responsible for the pronounced double-peak structure. The 1n and 2n decay channels have been measured with preliminary integral cross section values of 386(16) mb and 263(14) mb, respectively.

In order to evaluate an eventual PDR in this data, the GDR must first be accounted for. We assume that the GDR follows a systematical trend in energy and width in this mass region and use the parametrization proposed by Junghans et al.[14] According to this model, the GDR in $^{68}$Ni has an energy of 18.17 MeV and a width of 5.17 MeV. Using simulations to account for the setup response in the measurement, we use the calculated GDR parameters to fit the experimental data above the 2n threshold, leaving the GDR strength as only free parameter. Eventual PDR strength is not expected to be present at such high energies, thus justifying the attribution of the total strength in the 2n channel to the GDR. The fit yields a preliminary E1 strength exhausting 91(5)% of the E1 energy-weighted sum-rule. Subtraction of the total GDR strength provided by the fit yields a preliminary cross section excess of 168(31) mb in the 1n decay channel. This additional E1 strength is a first hint for the presence of a PDR in $^{68}$Ni in our data.

## §5. Outlook

The analysis of the E1 strength distribution of $^{68}$Ni will be pursued in order to understand quantitatively the cross section excess observed in the 1n decay channel, defining the centroid energy, width and strength of this PDR. This task will require precise knowledge of the experimental detector response of the setup, which needs to be determined. Other possible explanations for the additional strength will be investigated as well, such as the influence of the Giant Quadrupole Resonance or a non-statistical decay component of the GDR.

Besides the data on neutron-rich nickel isotopes, the analysis of experimental data on neutron-deficient argon isotopes is currently in progress. Theoretical calculations predict a proton-related PDR in $^{32}$Ar[15] analogous to the Pygmy Resonances observed so far only in neutron-rich nuclei. Such measurements at extreme isospin values provide a valuable contribution to the deeper understanding of this exotic collective excitation.

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