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Target dependence in the study of collective modes in stable and exotic \( {\text{Ni}} \) nuclei

T. Le Bleis\(^1,2,3\), D. Rossi\(^4\), A. Klimkiewicz\(^1,5\), P. Adrich\(^1\), K. Boretzky\(^1\), F. Aksouh\(^1\), H. Alvarez-Pol\(^6\), T. Aumann\(^1\), J. Benlliure\(^6\), M. Boehmer\(^7\), E. Casarejos\(^6\), M. Chartier\(^8\), A. Chatillon\(^1\), D. Cortina-Gil\(^8\), U. Datta Pramanik\(^9\), H. Emling\(^1\), O. Ershova\(^1,3\), B. Fernandez-Dominguez\(^8\), H. Geissel\(^1\), M. Gorska\(^1\), M. Heil\(^1\), H. Johansson\(^1,10\), A. R. Junghans\(^11\), O. Kiselev\(^1,4\), J.V. Kratz\(^4\), N. Kurz\(^1\), M. Labiche\(^12\), R. Lemmon\(^13\), Y. Litvinov\(^1\), K. Mahata\(^1\), P. Maierbeck\(^7\), T. Nilsson\(^10,14\), C. Nociforo\(^1\), R. Palit\(^15\), S. Paschalis\(^8\), R. Plag\(^1,3\), R. Reifarth\(^1,3\), H. Simon\(^1\), K. Sümmerer\(^1\), A. Wagner\(^11\), W. Walus\(^5\), H. Weick\(^1\), M. Winkler\(^1\).

\(^1\) GSI, Darmstadt, Germany,
\(^2\) IPHC, Strasbourg, France,
\(^3\) Uni. Frankfurt, Germany,
\(^4\) University of Mainz, Germany,
\(^5\) Jagelonian Uni., Krakow, Poland,
\(^6\) Uni. Santiago de Compostela, Spain,
\(^7\) Tech. Uni. Munich, Germany,
\(^8\) Uni. Liverpool, United Kingdom,
\(^9\) SINP Kolkata, India,
\(^10\) Chalmers Göteborg, Sweden,
\(^11\) FZ Dresden Rosendorf,
\(^12\) Univ. Paisley, United Kingdom,
\(^13\) Daresbury, United Kingdom,
\(^14\) Tech. Uni. Darmstadt, Germany,
\(^15\) TIFR Mumbai, India,

E-mail: t.lebleis@gsi.de

Abstract. The appearance of the pygmy-dipole-resonance is a recently observed phenomenon that can be related to neutron-matter properties. Its study can be a tool to determine the nuclear symmetry-energy parameters and thus can contribute constraining neutron star models. We present the \( \gamma, n \) cross sections for different \( {\text{Ni}} \) isotopes obtained from a measurement in inverse kinematics at about 500 MeV/u in the LAND reaction setup at GSI. The question of the disentanglement of the Coulomb and nuclear contributions is addressed.

1. Introduction
In the early 1990s, a new collective dipole mode, usually referred to as pygmy-dipole-resonance (PDR), was predicted for neutron-rich nuclei [1, 2]. Random-phase-approximation calculations for medium-heavy and heavy nuclei [3–6] attribute the concentration of strength located below the giant dipole resonance (GDR) region to the formation of a neutron or a proton skin in
neutron or proton-rich nuclei, respectively. Since such a skin depends on the nuclear symmetry energy \[7, 8\], experimental observation of the PDR strength can lead to valuable information about the parameters of the symmetry energy and on the evolution of the neutron-skin thickness. Experimental PDR strength measurements using Coulomb dissociation of exotic secondary beams at kinetic energies of about 500 MeV/u were reported in the \(^{132}\)Sn region \[9, 10\] and compared with available data for stable nuclei from \[11–15\] and \((\gamma, \gamma')\) measurement for \(^{68}\)Ni from \[16\].

From that experiment, neutron skin thicknesses of 0.23 ± 0.04 fm and 0.24 ± 0.04 fm were determined for \(^{130}\)Sn and \(^{132}\)Sn, respectively \[10\]. Values for the symmetry-energy in pure neutron matter \(a_4 = 32.0 ± 0.04\) fm and the symmetry energy pressure \(p_0 = 2.3 ± 0.8\) MeV/fm\(^3\), both at saturation densities, were obtained from the determination of the PDR strength.

Neutron stars are described as composed of a neutron solid crust that surrounds liquid neutronic matter. The solid-liquid phase transition depends on the pressure of the neutron-rich matter, which led Horowitz and Piekarewicz \[17\] to propose a study of neutron star observable by means of studying neutron-rich matter pressure and neutron skin. The study of PDR is then an effective tool to perform such studies.

Another experiment in stable and exotic Ni isotopes has been performed to study the PDR and is presented in Section 2. First results are presented and further discussed, particularly in the context of the target-charge and target-mass dependence of the excitation processes in Section 3.

2. Experimental observation

We carried out an experiment using beams of stable and exotic \(^{56–72}\)Ni isotopes at about 500 MeV/u delivered from the GSI facility. The secondary beams were selected after fragmentation reactions using the Fragment Separator (FRS). The dipole response of the beam projectiles is studied via relativistic heavy-ion induced electromagnetic excitation at beam energies around 500 MeV/u, where excitation energies up to about 15 MeV can be reached effectively \[18\]. Both dipole modes, the PDR and GDR are excited with relatively large cross sections. Other multipolarities are excited with much smaller cross sections. After interaction in the reaction target, the decay products from the excited nuclei are detected using the kinematically complete LAND reaction setup. The neutron detector LAND, the large acceptance dipole ALADIN, and the CsI crystals-based \(\gamma\) detector are the most notable. We study the neutron-decay channels, which are the dominant channels for excitations above the neutron threshold, in particular for neutron-rich nuclei. For \(^{68}\)Ni, for instance, the proton threshold is much higher at 15.5 MeV, which is additionally hindered due to the Coulomb barrier.

One of the main difficulties in such measurements is to distinguish between the electromagnetic dissociation (ED) and the very peripheral nuclear dissociation (ND). For that purpose, we have used three different targets with different charges namely C (187 mg/cm\(^2\)), Sn (1515 mg/cm\(^2\)) and Pb (519 mg/cm\(^2\)).

The data are under analysis and the results presented in the following are preliminary.

3. Discussion

For the study of PDR and GDR, we are interested in the ED part of the dissociation cross sections and thus need to subtract the ND contribution. The dependence of the neutron-removal cross section on the charge and the mass of the nuclei have previously been studied \[19–21\]. From these one can conclude that (a) the nuclear and electromagnetic interaction can be added incoherently as interference effects are small. We can thus write \(\sigma = \sigma_{ND} + \sigma_{ED}\). (b) the separation depends highly on a critical impact parameter \(b_c\). For impact parameters \(b < b_c\) the nuclear contribution is predominant, whereas for \(b > b_c\), only the electromagnetic interaction applies.
Since the ED grows with the charge of the target, we want to extract our values from the measurements with the Pb target. Assuming the ED cross section is very small (negligible) with a C target, we are looking for a scaling factor \( \alpha = \frac{\sigma_{ND}^{Pb}}{\sigma_C} \), in order to describe the nuclear contribution to the cross section in Pb using the total cross section measured in C. We illustrate this study using the case of the one-neutron removal from \(^{68}\)Ni as presented in Figure 1. ED cross sections were calculated in a semiclassical approach [22] for the three targets, using minimum impact parameters as proposed in [21]. An effective Z-dependence of \( \sigma_{ED} \propto Z^{1.57} \) is found for the one-neutron removal.

![Figure 1](image_url). Integrated cross sections for one-neutron removal from \(^{68}\)Ni. The curves represent the fit results as described in the text for the black disk approach (solid lines) and the soft-sphere approach (broken lines). The upper curves represent the sum of the ED and ND contributions whereas the lower curves show the ND cross section only.

However, the nuclear part is more complex. We will consider two different approaches to represent the nuclear contribution. The first one is the black disk method: the nuclei are not transparent to each other. Therefore the interaction is simplified to a geometrical picture of two disks interacting with each other. It then only depends on the radii of the nuclei, giving \( \sigma_{ND} \propto (A_T^{1/3} + A_P^{1/3}) \). A second approach is the soft-sphere model. It is detailed in [21] and represents the fact that the interaction occurs at the surface of the nuclei. It is then proposed to be of the form \( \sigma_{ND} = 2\pi \left[ b_c - \Delta b \right] \Delta b \), where \( \Delta b \) represents the width of impact parameters for which the reaction occurs on the surface of the nuclei. Benesh et al. suggest, following Glauber calculations over a rather wide range of nuclei, to use \( \Delta b = 0.5 \) fm. They also propose \( b_c = r_0(A_T^{1/3} + A_P^{1/3} - x(A_T^{-1/3} + A_P^{-1/3})) \) with \( r_0 = 1.34 \) fm and \( x = 0.75 \).

We have fitted our integrated cross sections for the one-neutron removal from \(^{68}\)Ni with the functions \( \sigma = p_1\sigma_{ED} + p_2\sigma_{ND} \), where the mass and charge dependence of \( \sigma_{ED} \) and \( \sigma_{ND} \) are taken from semiclassical calculations and our two models for the nuclear dependence, respectively. \( p_{1,2} \) are taken as free parameters for the fit. The results are shown in Figure 1. The solid line was obtained using \( \sigma_{ND} \) from the black disk model and the broken line from the soft sphere model. The fits show remarkable agreement for both the total and the nuclear cross sections. From these fits, we determine the scaling factors \( \alpha_{disk} = 1.29 \) and \( \alpha_{sphere} = 1.38 \).

For previous experiments, we used a factorisation approach as presented by Mercier et al. [19], there we determined a factor of \( \alpha = 1.38 \), which is in good agreement.

Using the \( \alpha_{sphere} \) parameter, an ED cross section (including \( 1n \) and \( 1n1p \)) of \(^{58}\)Ni of 108(10) mb is extracted, which is in agreement with the published value of 127(12) mb derived from [23] by folding with the virtual photon spectrum.
Conclusion
The low-lying dipole strength has been recently studied in both experimental and theoretical approaches. It appears to be a tool to investigate the nuclear symmetry energy as well as the neutron star structure. The LAND-FRS setup proves to be an effective means to study the dipole response of exotic nuclei in the energetic regime of the PDR and GDR. The difficulty to disentangle the nuclear from the electromagnetic contributions to the neutron removal cross section of neutron-rich Ni nuclei has been addressed. We have shown that the black disk and the soft-sphere description of the nuclear contribution to the integrated cross section lead to similar results, and allows us to determine a scaling factor from the cross section of carbon to the nuclear contribution to the cross section of lead of about 1.38.

As the analysis progresses we will be able to verify this scaling factor, investigating, e.g., decay channels with thresholds above the energetic range of ED, like the three-neutron removal channel.

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