The pygmy dipole resonance in $^{68}$Ni and the neutron skin

O. Wieland$^{a,*}$, A. Bracco$^{a,b}$

$^a$ INFN Sezione di Milano, I-20133 Milano, Italy
$^b$ Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy

A search of the pygmy resonance in $^{68}$Ni was made using the virtual photon technique. The experiment was carried out using the radioactive beam $^{68}$Ni at 600 A MeV, produced with fragmentation of $^{86}$Kr at 900 A MeV on a $^{9}$Be target. The $^{68}$Ni beam was separated by a fragment separator, and the $\gamma$-rays produced at the interaction with the Au target were detected with the RISING and FRS set-up at the GSI laboratory in Germany, also including the HECTOR array. The measured $\gamma$-ray spectra show a peak centered at approximately 11 MeV, whose intensity can be explained in term of an enhanced strength of the dipole response function (pygmy resonance). A pygmy structure of this type was also predicted by different models for this unstable neutron-rich nucleus. Correlations between the behavior of the nuclear symmetry energy, the neutron skins, and the percentage of energy-weighted sum rule (EWSR) exhausted by the pygmy dipole resonance (PDR) are investigated by using different random phase approximation (RPA) models.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Giant resonances are among the basic building blocks of nuclear structure. Because they dominate the nuclear response, particularly above the particle binding energies, investigations of their main features such as centroid and widths have been carried out for many years in experimental nuclear physics. In the case of the simplest mode, the giant dipole resonance (GDR), a reasonable knowledge of its systematic features has been achieved. However, its fine structure, which carries unique information on the underlying nature of the mode and on the decay mechanisms, is not generally known. A very interesting long-standing question is the nature of the so-called electric pygmy dipole resonance close to the neutron threshold in medium-to-heavy nuclei. When the pygmy strength is rather collective, it is also predicted that it might result from a neutron excess density vibration relative to the $N \approx Z$ core. A good understanding of the properties of soft E1 (or pygmy) modes is important, particularly in connection with exotic neutron-rich nuclei, because in that case the corresponding strength is expected to be higher than in stable nuclei. Furthermore, the presence of a resonance of E1 character close to particle threshold has important astrophysical implications, because it considerably modifies the equilibrium of $(\gamma, n)$ and $(n, \gamma)$ reactions occurring in explosive nucleosynthesis scenarios [1]. A powerful tool to study the low-lying E1 strength of unstable neutron-rich nuclei is the scattering of high-energy radioactive beams in inverse kinematics. At beam energies of several hundred MeV/nucleon, the rapidly varying electromagnetic field of a high-Z target experienced by the fast-moving projectile generates dipole transitions with relatively large cross sections up to excitation energies of the order of 20 MeV, and thus opens the possibility of studying the dipole response of exotic nuclei. So far, experimental information on the E1 response in unstable nuclei is rather limited, and the existing results are based on neutron break-up measurements [2–4]. A complementary approach is the virtual-photon-scattering method so far employed to study $^{20}$O up to excitation energy of 7 MeV [5]. Here, a report is given of the first measurement made for $^{68}$Ni that uses the virtual-photon-scattering method.

* Corresponding author.

E-mail address: oliver.wieland@mi.infn.it (O. Wieland).

0146-6410/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.ppnp.2011.01.037

Please cite this article in press as: O. Wieland, A. Bracco, Progress in Particle and Nuclear Physics (2011), doi:10.1016/j.ppnp.2011.01.037
at much higher energy than that of $^{20}$O in order to excite with the Coulomb field the region well above the nucleon binding energy. An important point is also that at this bombarding energy the excitation of vibrations of electric dipole character dominates over other excitation modes [6]. The unstable nucleus $^{68}$Ni represents a good case to search for pygmy structures, this nucleus being located in the middle of the long isotopic Ni chain having at the extremes the doubly magic $^{56}$Ni and $^{78}$Ni. In addition, different theoretical predictions of the pygmy dipole strength are available for this mass region [7–9].

2. The experiment

The experimental method consists in the scattering of a high-energy radioactive beam on a high-$Z$ target and in detecting $\gamma$-rays in coincidence with the scattered particles at angles smaller than that corresponding to grazing collision. A schematic drawing of the experimental set-up is shown in Fig. 1. The radioactive $^{68}$Ni beam was produced by fragmentation of a primary $^{86}$Kr beam delivered by the SIS synchrotron at GSI at 900 MeV/u and focussed on a Be target. The $^{68}$Ni ions were selected and transported with the fragment separator FRS. The settings of the FRS were chosen to accept secondary fragments with a magnetic rigidity corresponding to a certain mass-over-charge ratio, and that provided a beam cocktail containing in large fraction $^{68}$Ni ions. The different nuclei contained in the secondary beam were identified uniquely according to their nuclear charge and mass number on an event-by-event basis. The $^{68}$Ni ions constitute the most intense component (33% of the beam cocktail) impinging on the Au target (2 g/cm$^2$ thick). The particle identification after the Au target was performed using a calorimeter (CATE) [10] placed at 0°. This calorimeter consisted of nine thin position-sensitive Si detectors placed in front of four 6 cm thick CsI scintillator detectors, arranged symmetrically with respect to the beam direction. The opening angle $\theta$ of the calorimeter CATE was $\pm 2.0^\circ$, which is much larger than the grazing angle of this reaction. The grazing angle, corresponding to the maximum angle at which the interaction is strongly dominated by the Coulomb interaction, is in this case equal to $0.43^\circ$. At larger angle, the contribution of hadronic interaction becomes more important, and therefore also other multipole can be excited. The total energy and energy loss correlation of events in the CATE calorimeter corresponding to $^{68}$Ni ions were measured; the results had an FWHM which was found to be approximately 1%. Therefore the present resolution is sufficient to discriminate between different masses of the outgoing nuclei. The $\gamma$-ray emission at the target location was measured using a specific configuration of the RISING set-up [11]. $\gamma$ rays were detected at different angles: at 16°, 33° and 36° with the 15 HPGe clusters of the RISING array, at 51° and 88° with 7 HPGe segmented clusters of the Miniball array and at 88° and 142° with 8 BaF$_2$ of the HECTOR array [12,13]. The good timing properties of the BaF$_2$ detectors were exploited to discriminate against $\gamma$ events originating at different locations along the beam line, using the time of flight measurement. The energy spectra of BaF$_2$ detectors are therefore characterized by a much smaller background, particularly at low energy, in comparison with the HPGe of the RISING set-up. Conversely, the latter, having a much better energy resolution, have allowed us also to measure the B(E2) of the first 2$^+$ state.
3. The measurement of the pygmy dipole states

In Fig. 2 (right panel), the cross section for the $\gamma$ decay of $^{68}$Ni at $E_\gamma > 7$ MeV measured with the BaF$_2$ detectors is shown. The measured cross section is compared with predictions obtained making different assumptions for the E1 strength function. In particular, the ingredients of the calculations are shown in the left panel of Fig. 2. In this panel, an electric dipole response function with a small peak at 11 MeV with 5% of the energy weighted sum rule (EWSR) strength is shown. The corresponding function when modified by the virtual photon number is shown with the dotted line. The additional and very important effect of the $\gamma$ branching ratio $R_\gamma$ is displayed with a dashed line. This latter contribution depends on the nuclear level density. For the present calculation, the adopted level density is based on Shell Model Monte Carlo calculations [14]. Using this level density, the total $\gamma$ branching ratio is found to vary from 0.4% to 4% going from the region of the GDR to the region of the pygmy resonance. For a proper comparison of the calculation to the data, the detector response function was folded. A more detailed description of these calculations is given in [13]. There is a remarkable agreement of the calculated cross section with the data (without any normalization factor) both in size and shape when one assumes an electric dipole strength function with 5% of EWSR strength at 11 MeV (the corresponding B(E1) value being 1.2 e$^2$ fm$^2$). At present, two different predictions are available for the pygmy resonance in Ni isotopes, one based on relativistic random phase approximation [7] and the other based on quasi-particle relativistic random phase [8], both predicting at 9–10 MeV a pygmy structure, with an EWSR strength of 4% and 10%, respectively. In Fig. 3, the RPA predictions with SKI2 Skyrme force are used as an input to reproduce the experimental data.

4. The neutron skin

At present, there is an interesting discussion on the possibility of extracting information on the neutron skin from the pygmy resonance [2,15,16]. In fact, this is related to the isospin-dependent part of the nuclear equation of state (EOS), which, in turn, has relevant implications for the description of neutron stars. For this reason, there is an enormous effort aimed at determining the parameters that govern the asymmetric matter EOS, using both experimental and theoretical tools. The energy per particle in a nuclear system characterized by a total density $\rho$ (sum of the neutron and proton densities $\rho_n$ and $\rho_p$)
and $\rho_p$, and by a local asymmetry $\delta \equiv (\rho_n - \rho_p) / \rho$, is usually written as

$$E_A(\rho, \delta) = E_A(\rho, \delta = 0) + S(\rho)\delta^2.$$  

Odd powers of $\delta$ are forbidden by the isospin symmetry, and the term proportional to $\delta^4$ is found to be negligible. The above equation defines the so-called symmetry energy $S(\rho)$. One can find constraints on the symmetry energy from the dipole response of stable and unstable nuclei if there is a strong correlation between the slope parameter $L$ and $\Delta R$ (the neutron skin thickness) as previously proposed [17–19]. This might not be a general concept [16], but could depend on the interaction and on the collectivity of the pygmy state [15]. The analysis uses this correlations for a large set of different Skyrme forces and RMF (meson exchange) Lagrangians that give different predictions of the strength of the PDR and consequently of the derivative of the symmetry energy at saturation. The derivative of the symmetry energy at saturation is related to the widely used “slope” parameter $L$ by

$$S'(\rho)|_{\rho=\rho_0} = \frac{L}{3\rho_0}.$$  

The symmetry energy at saturation, $S(\rho_0)$, is denoted by $a_4$ or $J$. No measurement of the neutron skin is available which is accurate enough to constrain the slope parameter $L$. The results of the predicted strength for the pygmy dipole state calculated with a large set of RPA calculations using different Skyrme forces as a function of the slope parameter $L$ are shown in Fig. 4. One can note a rather good correlation between the parameter $L$ and the measured fraction of EWSR associated with the PDR. In the theoretical calculations, we consider the whole part of the low-energy region where the strength is not negligible. One should remark that the correlation found is based on a large set of a variety of theoretical models, both nonrelativistic and relativistic. Both classes of mean-field model are successful in describing the nuclear ground states and many of the excited states.

Our result is that the slope parameter $L$ is constrained to be in the interval 50.3–89.4 MeV or 29.0–82.0 MeV, if we use either the $^{68}\text{Ni}$ results, or the $^{132}\text{Sn}$ results (left panel of Fig. 5). The weighted average gives $L = 64.8 \pm 15.7$ MeV. The next step is to use the $L$ value obtained from the PDR data points for $^{68}\text{Ni}$ and $^{132}\text{Sn}$ in order to deduce the neutron skin thickness $\Delta R$. First, one can note that the correlation between $L$ and $\Delta R$, when the two quantities are calculated using the models already described, is quite good (Fig. 5 left panel). If one imposes the value of $L$ to be in the interval 64.8 ± 15.7 MeV, one obtains for the skin thickness $\Delta R = 0.200 \pm 0.015$ fm for $^{68}\text{Ni}$, $\Delta R = 0.258 \pm 0.024$ fm for $^{132}\text{Sn}$, and $\Delta R = 0.194 \pm 0.024$ fm for $^{208}\text{Pb}$. The approach presented here is in good agreement with other methods used so far to constrain $L$ and $S(\rho_0)$ (see Fig. 5 right panel). The other results reported in Fig. 5 are based on isospin diffusion data (vertical lines in Fig. 5 derived from quantum molecular dynamics calculations [20]), heavy-ion collisions, and energy of the isobaric analogue state [21] (for a more complete list, see the references in [15]).

5. Conclusions

The first experimental search of the pygmy resonance in the neutron-rich $^{68}\text{Ni}$ nucleus using the virtual photon scattering technique has been reported here. The data are taken with the RISING set-up and a beam with 600 MeV/nucleon. Evidence is found for the presence of a pygmy component in the E1 response energetically located below the GDR and centered at $\approx 11$ MeV.
Fig. 5. The left figure displays the correlations between the neutron skin thickness $\Delta R$ and the slope parameter $L$, in the case of $^{68}\text{Ni}$, $^{208}\text{Pb}$ and $^{132}\text{Sn}$. Under the constraint for $L$ emerging from our analysis, the values displayed for the neutron skin thickness in the three nuclei are obtained as a function of the slope parameter $L$. The right figure (based on a figure from [20]) shows the correlation between $L$ and $S$ for different experimental methods. The square in the center shows the results discussed here, and the other graphs report the results for the method using isospin effects in heavy-ion collisions (HIC) [20] and the method using the energy of the isobaric analogue state (IAS) [21].

MeV with $\approx 5\%$ of the EWSR strength. This result is in rather good agreement with theoretical predictions. Analysis based on RPA calculations has been made to deduce the relevant information which connects the neutron skin and nuclear symmetry energy [2]. In the near future, measurements of the pygmy dipole state in other nuclei are planned with an improved and more efficient set-up to go further away from stability. Within mean-field models, one can find a correlation between the PDR strength and one of the important parameters governing the density dependence of the symmetry energy, namely the first derivative at $S(\rho_0)$. In this way one can extract a constraint on this parameter, denoted as $L$. In addition, with more data, one can establish whether or not this approach to deduce the neutron skin is general or not. It should be noted that data with increased resolution such as those provided from $\gamma$ tracking arrays like AGATA and GRETA are expected to disentangle the fine structure of the PDR, which should help us to select more realistic interactions. Therefore, more work should be made to allow us to make firm conclusions on the important question of neutron skin and nuclear equation of state.

Acknowledgements

This work was partially supported by the Italian Istituto Nazionale di Fisica Nucleare.

References