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Neutron-Skin Thickness of ^{208}Pb from the Study of the Anti-Analog Giant Dipole Resonance

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Abstract. The γ-decay of the anti-analog of the giant dipole resonance (AGDR) has been measured to the isobaric analog state excited in the ^{208}Pb(p,$n\,\gamma\,\bar{p}$) ^{207}Pb reaction at a beam energy of 30 MeV. The energy of the transition was also calculated with state-of-the-art self-consistent random-phase approximation (RPA) and turned out to be very sensitive to the neutron-skin thickness (ΔR_{pn}). By comparing the theoretical results with the measured one, the ΔR_{pn} value for ^{208}Pb was deduced to be 0.190 $\pm$ 0.028 fm, which agrees well with the previous results, and can be used to constrain the symmetry energy part of the EoS.

1 Introduction

There is a renewed interest in measuring precisely the thickness of the neutron skin [1–4], because it constrains the symmetry-energy term of the nuclear equation of state. The precise knowledge of the symmetry energy is essential not only for describing the structure of neutron-rich nuclei, but also for describing the properties of the neutron-rich matter in nuclear astrophysics.

The symmetry energy determines to a large extent, through the Equation of State (EoS), the proton fraction of neutron stars [5], the neutron skin in heavy nuclei [6] and enters as input in the analysis of heavy-ion reactions [7, 8], etc. Furnstahl [6] demonstrated that in heavy nuclei there exists an almost linear empirical correlation between the neutron-skin thickness and theoretical predictions for the symmetry energy of the EoS in terms of various mean-field approaches. This observation has contributed to a renewed interest in an accurate determination of the neutron-skin thickness in neutron-rich nuclei [1, 3, 4, 9]. In this work, we are suggesting a new precise method for measuring the neutron-skin thickness.

Recently, we have shown that the energy difference between the anti-analog giant dipole resonance (AGDR) and the isobaric analog state (IAS) is very sensitively related to the corresponding neutron-skin thickness [10]. The energy of the AGDR has been calculated also for the ^{208}Pb isotope using the state-of-the-art fully self-consistent relativistic proton-neutron quasi-particle random-phase approximation and compared to the available experimental data after correcting them for the admixture of the spin dipole resonance (SDR) [11].

Yasuda *et al.* [12] separated the AGDR from other excitations such as the SDR by multipole decomposition analysis of the ^{208}Pb$(\vec{p},\vec{n})$ reaction at a bombarding energy of $E_p = 296$ MeV. The polarization transfer observables were found to be useful for carrying out this separation. The energy difference between the AGDR and the isobaric analog state (IAS) was determined to be $\Delta E = 8.69 \pm 0.36$ MeV, where the uncertainty includes both statistical and systematic contributions. Using our theoretical results [11] a neutron-skin thickness of $\Delta R_{pn} = 0.216 \pm 0.046 \pm 0.015$ fm, where the first and second uncertainties are the experimental and theoretical uncertainties, respectively.

The aim of the present work is to determine the above energy difference (ΔE) more precisely than ever before by measuring the energy of the γ-transition between them. The direct γ-branching ratio of the AGDR to the IAS is expected to be similar to that of the isovector giant dipole resonance (IVGDR) to the g.s. in the parent nucleus, which can be calculated from the parameters of the IVGDR [13].

2 The Anti-Analog Giant Dipole Resonance and Its γ-Decay

Due to the isovector nature of the (p,n) reaction, the strength of the E1 excitation is divided into T_0-1, T_0 and T_0+1 components, where T_0 is the ground-state (g.s.) isospin of the initial nucleus. Because of the relevant Clebsch-Gordan coefficients [14], the T_0-1 component (AGDR) is favored compared to the T_0 and T_0+1 one by about factors of T_0, and $2T_0^2$, respectively. According to the work of Osterfeld [14] the non-spin-flip/spin-flip ratio is favored at low bombarding energy, below 50 MeV.

Dipole resonances were excited earlier at such low energies in the ^{208}Pb(p,n) reaction by Sterrenburg *et al.* [15], and Nishihara *et al.* [16] at $E_p = 45$ MeV and 41 MeV, respectively. However, it was shown experimentally [17, 18] that the observed $\Delta L = 1$ resonance was a superposition of all possible SDR modes and the non-spin-flip dipole AGDR even at these low bombarding energies.

The expected γ-decay properties of the states excited in ^{208}Bi is shown in Figure 1 together with the proton-decay branching ratios of the IAS [19–21].

The observed γ-ray branching ratio of the IVGDR to the g.s. of ^{208}Pb is about 1% [13]. In contrast, in the investigation of the electromagnetic decay properties of the SDR to the low-lying Gamow-Teller states by Rodin and

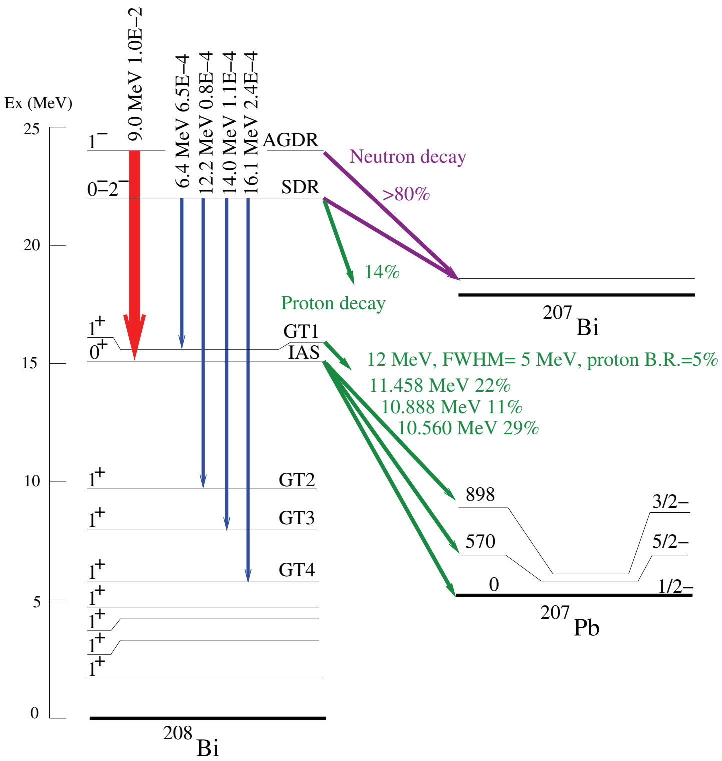

Figure 1. Energy levels excited in the ^{208}Pb(p,n)^{208}Bi reaction and their expected γ-decay branching ratios (red- and blue-colored arrows). The energies and branching ratios of the proton decay of the IAS to low-lying states in ^{207}Pb is also shown (green-colored arrows).

Dieperink [22] the γ-decay branching ratio was found in the range of 10^{-4}.

The proton-decay of the IAS [19–21] was used as a signature of the de-excitation of the IAS. The γ-transition expected from the decay of the AGDR was measured in coincidence with such proton lines.

3 Experimental Methods and Results

The experiments, aiming at studying the neutron-skin thickness of ^{208}Pb, were performed at the Oslo Cyclotron Laboratory (OCL) with 30 MeV proton beam bombarding a 5.5-mg/cm^2 thick ^{208}Pb self-supporting metallic target and a 1-mg/cm^2 thick C target for energy calibration.

Particle-γ coincidences were measured with the SiRi particle telescope and CACTUS γ-detector systems [23, 24]. The SiRi detectors were placed in the backward direction, covering eight angles from $\Theta = 126°$ to $140°$ relative to the

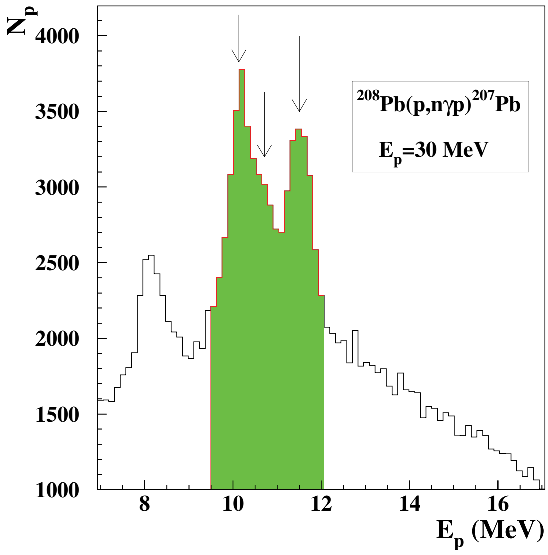

Figure 2. Proton energy spectrum measured in coincidence with the γ-rays.

beam axis. The ΔE and E detectors had thicknesses of 130 μm and 1550 μm, respectively.

A typical proton spectrum, identified according to the energy loss of the protons is shown in Figure 2. The proton transitions populating low-lying states in ^{207}Pb are marked by arrows and the region used for gating the γ-spectrum is shown in green.

The CACTUS array consists of 28 collimated $5'' \times 5''$ NaI(Tl) detectors with a total efficiency of 15.2% for $E_\gamma = 1.33$ MeV. The γ-ray energy spectrum measured in coincidence with the protons originating from the decay of the IAS in ^{208}Bi is shown in Figure 3.

The random coincidences were subtracted. A gate was also set above the green region in the proton spectrum and their contribution was subtracted from the γ-spectrum. We were expecting a broad transition ($\Gamma \approx 2.9$ MeV) from the decay of the AGDR, the centroid of which was shifted down in energy because of the decreasing efficiency of the NaI detectors. In order to correct that energy shift the spectrum was divided by the relative efficiency curve. The result of such transformations is shown in Figure 3 together with the error bars calculated for each point.

The double line at 4.44 MeV most probably comes from some carbon contamination of the target excited in the $(p,p\prime)$ reaction, while the broad line around 13.3 MeV may come from the decay of the IVGDR excited in ^{208}Pb also by the

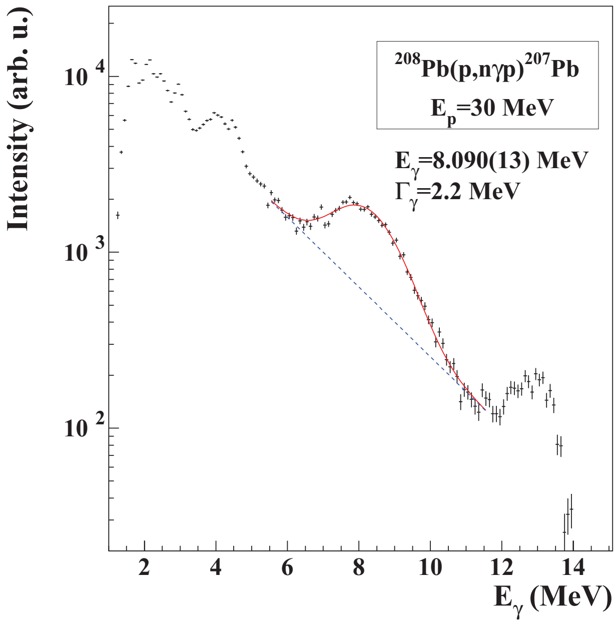

Figure 3. The γ-ray energy spectrum measured in coincidence with protons of energy $9.5 \leq E_p \leq 12$ MeV. The random coincidences were subtracted and the spectrum was corrected for the efficiency of the NaI detectors. The solid line shows the result of the fit described in the text.

(p,$p\prime$) reaction. As the IVGDR is broad ($\Gamma = 3.6$ MeV) the inelastically scattered protons should have a broad distribution. Unfortunately, the energy region of the γ-spectrum did not cover the whole distribution of the IVGDR.

It is well known, that the NaI detectors are sensitive not only to γ-rays, but also to neutrons [25]. Low-energy neutrons are captured mostly by iodine and the ^{127}I(n,γ) reaction produces γ-rays, which show up at 6.826 MeV in the spectrum and which interfere with the low-energy side of the AGDR $\rightarrow$ IAS transition. At higher neutron energies the cross section for capture on iodine drops, and the response of the NaI detectors for MeV neutrons is constant as a function of the detected energy.

The $5''$ long NaI detectors of the CACTUS setup are placed relatively close (22 cm) to the target and this way the time-of-flight method cannot be used to discriminate safely against neutrons produced in the ^{208}Pb(p,n) reaction and also in the decay of the giant resonances, so we took their effects into account.

According to the previous experimental studies [15, 16] the angular distribution of the ejected neutrons in the ^{208}Pb(p,n) reaction is strongly forward peaked. The cross section of the reaction drops by one order of magnitude beyond 30 degrees. Since the smallest angle of the NaI detectors of the CACTUS setup was 39° with respect to the beam direction, the ejected neutrons did not disturb the γ-spectrum considerably.

The giant resonances including the AGDR, are mostly decaying also by neutrons, which are detected by CACTUS with high efficiency. However, such neutron emission goes to low lying states of ^{207}Bi in our case, and therefore such neutrons are not in coincidence with the proton-decay of the IAS in ^{208}Bi, which decays by protons to ^{207}Pb. Such neutrons may contribute to the random coincidences only, which are subtracted.

As the CACTUS random-coincidence spectrum around 7 MeV is dominated by the neutrons, the real coincidence events caused also by neutrons are eliminated by subtracting the random coincidence spectrum with slightly larger factor, than the ratio of the time windows. In this way we can safely state that the peak observed in the CACTUS $p - \gamma$ coincidence spectrum around 7 MeV contains only γ-rays from the AGDR $\rightarrow$ IAS transition.

The energy distribution of the γ-rays was fitted by a Gaussian curve and a second-order polynomial background as shown in Figure 3. The obtained energy and width of the transition are $E_\gamma = 8.090 \pm 0.013$ MeV and $\Gamma = 2.2$ MeV. However, the energy calibration of the spectrometer has been performed with photopeaks, and now we are dealing with a broad giant resonance. In order to make a correct energy determination for the resonance, GEANT Monte-Carlo simulations were performed and convoluted with a Gaussian function with the width of the resonance. This convolution caused about 10% lowering of the position of the peak, which was taken into account by correcting the final energy of the transition. The obtained energy of the transition is $E_\gamma = 8.900 \pm 0.020$ MeV including only the statistical error.

The contribution of the systematical error coming from the uncertainty of the energy calibration is estimated to be 1.0%, so the final transition energy is: $E_{\text{AGDR}} - E_{\text{IAS}} = 8.90 \pm 0.09$ MeV. The energy and width of the transition agree well width previously measured values [15, 16], but they are more precise.

4 Theoretical Analysis

The theoretical analysis employed in this work was carried out with the fully self-consistent relativistic proton-neutron quasiparticle random-phase approximation (pn-RQRPA) based on the Relativistic Hartree-Bogoliubov model (RHB) [26]. The RQRPA was formulated in the canonical single-nucleon basis of the RHB model in Ref. [27] and extended to the description of charge-exchange excitations (pn-RQRPA) in Ref. [28]. The RHB + pn-RQRPA model is fully self-consistent: in the particle-hole channel, effective Lagrangians with density-dependent meson-nucleon couplings are employed, and pairing correlations are described by the pairing part of the finite-range Gogny interaction [29].

For the purpose of the present study, we employ a family of density-dependent meson-exchange (DD-ME) interactions, for which the constraint on the symmetry energy at saturation density has been systematically varied, $a_4 = 30$, 32, 34,

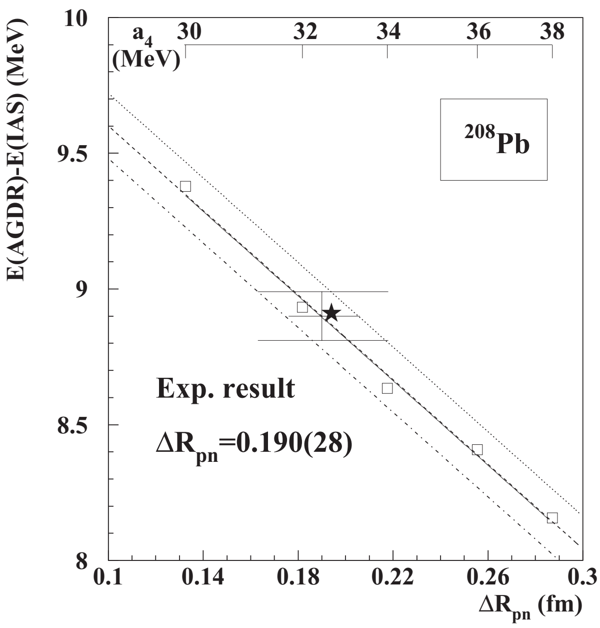

Figure 4. The difference in the excitation energy of the AGDR and the IAS for the target nucleus ^{208}Pb, calculated with the pn-RQRPA using five relativistic effective interactions characterized by the symmetry energy at saturation a_4 = 30, 32, 34, 36 and 38 MeV (squares), and the interaction DD-ME2 (a_4 = 32.3 MeV) (star). The theoretical values $E(\text{AGDR}) - E(\text{IAS})$ are plotted as a function of the corresponding g.s. neutron-skin thickness ΔR_{pn}, and compared to the experimental value $E(\text{AGDR}) - E(\text{IAS}) = 8.90 \pm 0.09$ MeV.

36 and 38 MeV, and the model parameters are adjusted to accurately reproduce nuclear-matter properties (the saturation density, the compression modulus) and the binding energies and charge radii of a standard set of spherical nuclei [30]. These effective interactions were used to provide a microscopic estimate of the nuclear-matter compressibility and symmetry energy in relativistic mean-field models [30] and in Ref. [37] to study a possible correlation between the observed pygmy dipole strength (PDS) in ^{130,132}Sn and the corresponding values for the neutron-skin thickness. In addition to the set of effective interactions with $K_{nm} = 250$ MeV (this value reproduces the excitation energies of giant monopole resonances), and a_4 = 30, 32, 34, 36 and 38 MeV, the relativistic functional DD-ME2 [31] will be used here to calculate the excitation energies of the AGDR with respect to the IAS, as a function of the neutron skin. Important for the present analysis is the fact that the relativistic RPA with the DD-ME2 effective interaction predicts the dipole polarizability

$$\alpha_D = \frac{8\pi}{9} e^2 \, m_{-1} \tag{1}$$

(directly proportional to the inverse energy-weighted moment m_{-1}) for ^{208}Pb, α_D=20.8 fm^3, in very good agreement with the recently measured value: $\alpha_D = (20.1 \pm 0.6)$ fm^3 [4].

The results of the calculations for ^{208}Pb are shown in Figure 4. The difference in the excitation energy of the AGDR and the IAS, calculated with the pn-RQRPA based on the RHB self-consistent solution for the g.s. of the target nucleus, is plotted as a function of the corresponding RHB prediction for the neutron-skin thickness. For the excitation energy of the AGDR we take the centroid of the theoretical strength distribution, calculated in the energy interval above the IAS that corresponds to the measured spectrum of γ-ray energies: 6 to 14.8 MeV (cf. Figure 3). A single peak is calculated for the IAS. For effective interactions with increasing value of the symmetry energy at saturation a_4 = 30, 32, 34, 36 and 38 MeV (and correspondingly the slope of the symmetry energy at saturation [32]), we find an almost perfect linear decrease of $E(\text{AGDR}) - E(\text{IAS})$ with the increase of the neutron skin ΔR_{pn}. The value calculated with DD-ME2 ($a_4 = 32.3$ MeV) is denoted by the star symbol.

The uncertainty of the theoretical predictions for the neutron-skin thicknesses is estimated to be 10%. Such an uncertainty was used earlier for the differences between the neutron and proton radii for the nuclei ^{116}Sn, ^{124}Sn, and ^{208}Pb in adjusting the parameters of the effective interactions [30,31]. These effective interactions were also used to calculate the electric dipole polarizability and neutron-skin thickness of ^{208}Pb, ^{132}Sn and ^{48}Ca, in comparison to the predictions of more than 40 non-relativistic and relativistic mean-field effective interactions [2]. From the results presented in that work one can also assess the accuracy of the present calculations.

In comparison to the experimental result for $E(\text{AGDR})-E(\text{IAS})$ we deduce the value of the neutron-skin thickness in ^{208}Pb: $\Delta R_{np} = 0.190 \pm 0.028$ fm (including the 10% theoretical uncertainty). In Table 1, this value is compared to previous results obtained with a variety of experimental methods. Very good

Table 1. Neutron-skin thicknesses of ^{208}Pb determined in the present work compared to previously measured values.

Method	Ref.	Date	ΔR_{pn} (fm)
(p,p) 0.8 GeV	[33]	1980	0.14 $\pm$ 0.04
(p,p) 0.65 GeV	[34]	1994	0.20 $\pm$ 0.04
($\alpha, \alpha\prime$) IVGDR 120 MeV	[13]	1994	0.19 $\pm$ 0.09
antiproton absorption	[35]	2001	0.18 $\pm$ 0.03
($\alpha, \alpha\prime$) IVGDR 200 MeV	[36]	2003	0.12 $\pm$ 0.07
pygmy res.	[37]	2007	0.180 $\pm$ 0.035
pygmy res.	[38]	2010	0.194 $\pm$ 0.024
($\vec{p}$,$\vec{p}\prime$)	[4]	2011	0.156 $\pm$ 0.025
parity viol. (e,e)	[1]	2012	0.33 $\pm$ 0.17
AGDR	pres. res.	2012	0.190 $\pm$ 0.028

agreement has been obtained with the previous data, which supports the reliability of our method.

5 Conclusion

In conclusion, we have investigated the γ-decay of the AGDR to the IAS excited in the ^{208}Pb(p,n$\gamma\bar{p}$) ^{207}Pb reaction. Using the experimental results obtained for the energy difference of the AGDR and the IAS, and the RHB+pn-RQRPA model, we deduce the following value of the neutron skin thickness: $\Delta R_{pn} = 0.190 \pm 0.028$ fm in ^{208}Pb. The agreement between the ΔR_{pn} determined using measurements of the energy difference of AGDR-IAS and previous methods is very good. In particular, the present study supports the results from very recent high-resolution study of electric dipole polarizability α_D in ^{208}Pb [4], respective correlation analysis of α_D and ΔR_{pn} [2], as well as the Pb Radius Experiment (PREX) using parity-violating elastic electron scattering at JLAB [1].

Acknowledgments

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