NEUTRON-SKIN THICKNESS FROM EXCITATION OF SPIN-DIPOLE RESONANCE*

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A new method, based on the excitation of the giant (spin–dipole) resonances in charge-exchange reactions, for studying the neutron-skin thickness has been tested. For a precise experimental test the (^{3}He,t) reaction on even Sn isotopes has been used. The results obtained are in good agreement with previous neutron-skin thickness values provided by other experimental and theoretical methods.

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1. Introduction

Although the possible presence of a neutron-skin in stable nuclei has been discussed since the mid 1950s [1], there is no consensus in the literature about the definition of neutron-skin. A quantity which is often applied to characterize the spatial extension of the neutron density is the difference between the neutron and proton root-mean square (rms) radii [2]. In heavy neutron rich nuclei there are more neutrons than protons, which implies an excess of neutrons at large distance, *i.e.* the existence of neutron-skin. For instance, the rms radius of the neutron distribution is larger than that of the

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protons by ≈ 0.2 fm in ^{48}Ca [3] and by ≈ 0.15 fm for ^{208}Pb [4]. The first empirical evidence of a thick neutron-skin (≈ 0.9 fm) was presented for ^{6}He and ^{8}He [5].

The correlation between the neutron-skin thickness and the symmetry energy has been recently discussed in theoretical studies of the neutron-rich nuclear matter [6]. An accurate measurement of the neutron-skin thickness may constrain the density dependence of the symmetry energy.

A tool, based on the excitation of the Spin–Dipole Resonance (SDR) in the (^{3}He,t) reaction was developed recently for studying the neutron-skin thickness [7]. In this paper we discuss a critical test of the SDR method by applying it to the tin isotopes.

2. Basic idea of the method

The isovector spin–dipole resonance ($L=1$, $T=1$, $S=1$) can be strongly excited in charge-exchange reactions like (p,n) or (^{3}He,t). This resonance can be interpreted as the superposition of three collective modes with spin parity $J^\pi = 0^-$, 1^-, 2^- mediated by operator $[\sigma\tau r Y_1]$. The total $L = 1$ strength of the SDR is sensitive to the neutron-skin thickness [8, 9]. The following sum rule is valid for the spin–dipole operator involving the difference between the β^- and β^+ strengths:

$$S^-_{\mathrm{SDR}} - S^+_{\mathrm{SDR}} = \frac{9}{2\pi}\Big(N\langle r^2\rangle_n - Z\langle r^2\rangle_p\Big)\,, \tag{1}$$

where $\langle r^2\rangle_n$ and $\langle r^2\rangle_p$ represent the rms radii of the neutron and proton distributions, respectively. The S^-_{SDR} strength, which is proportional to the (^{3}He,t) cross section, can be deduced from the experiment. The difference between the neutron and proton rms radii ($\Delta\mathrm{R_{np}}$) can be derived from Eq. (1)

$$\langle r^2\rangle_n^{1/2} - \langle r^2\rangle_p^{1/2} = \frac{\alpha\sigma_{\mathrm{exp}}(1-B) - (N-Z)\langle r^2\rangle_p}{2N\langle r^2\rangle_p^{1/2}}\,, \tag{2}$$

where $B = S^+_{\mathrm{SDR}}/\mathrm{S}^-_{\mathrm{SDR}}$ is taken from the continuum RPA calculation [10], α is a normalization constant.

3. Experimental method

The experiment was performed at the Kernfysisch Versneller Instituut (KVI), Groningen. The ^{3}He beam was accelerated with the super-conducting cyclotron, AGOR, to an energy of 177 MeV. ^{112}Sn to ^{124}Sn targets isotopically enriched up to 68.3%–99.6% with thickness of 4.75–12.7 mg/cm^2 were used. Tritons resulting from the (^{3}He,t) reaction were detected in the focal plane of the Big Bite magnetic Spectrometer (BBS) [11], which was set at

0° with respect to the beam direction. The spectrometer consists of two quadrupoles ($Q1$ and $Q2$) and a large dipole magnet (D) as shown in Fig. 1. The outgoing particles were detected with the two Vertical Drift Chambers (VDCs) of the Focal Plane Detector System (FPDS) constructed within the EuroSuperNova Collaboration [12]. Measuring the horizontal and the vertical angles of incidence with this detector system made possible to reconstruct precisely the scattering angle of the tritons by ray-tracing techniques.

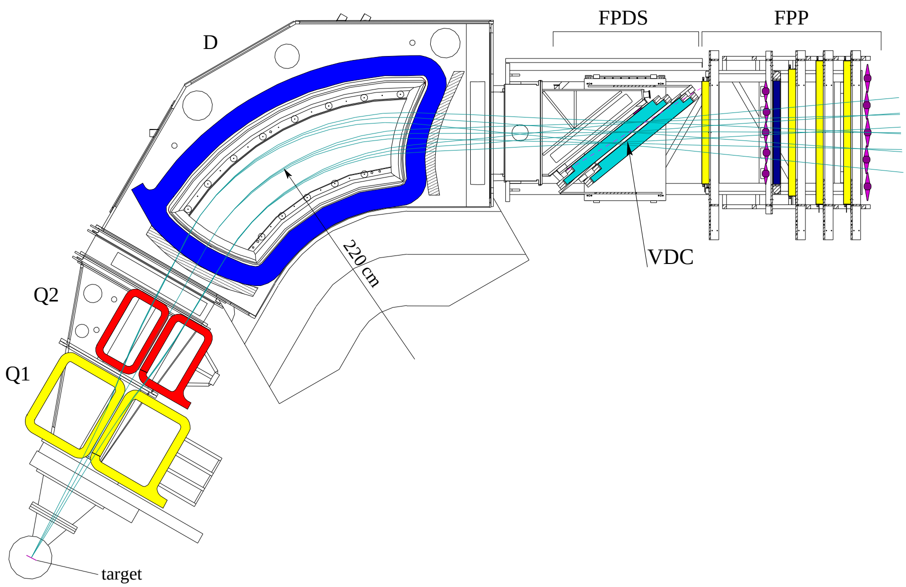

Fig. 1. Schematic view of the Big Bite Spectrometer with the focal-plane detection system.

4. Results

A sample of the resulting triton spectra obtained for ^{124}Sn at different triton scattering angles is shown in Fig. 2(a).

The measured spectra were decomposed into resonant and non-resonant components, as shown in Fig. 2(b). The resonances are described by the Lorentzian shapes for the energy distribution involving three free parameters: the centroid energy, the width and the height. The following relationship is taken for the Quasi-Free Continuum (QFC) background [13]

$$\frac{d^2\sigma_{\mathrm{QF}}}{dEd\Omega} = N_{\mathrm{QF}} \frac{1-\exp\left(\frac{E_t - E_0}{T}\right)}{1+\left(\frac{E_t - E_{\mathrm{QF}}}{W}\right)^2} \,. \tag{3}$$

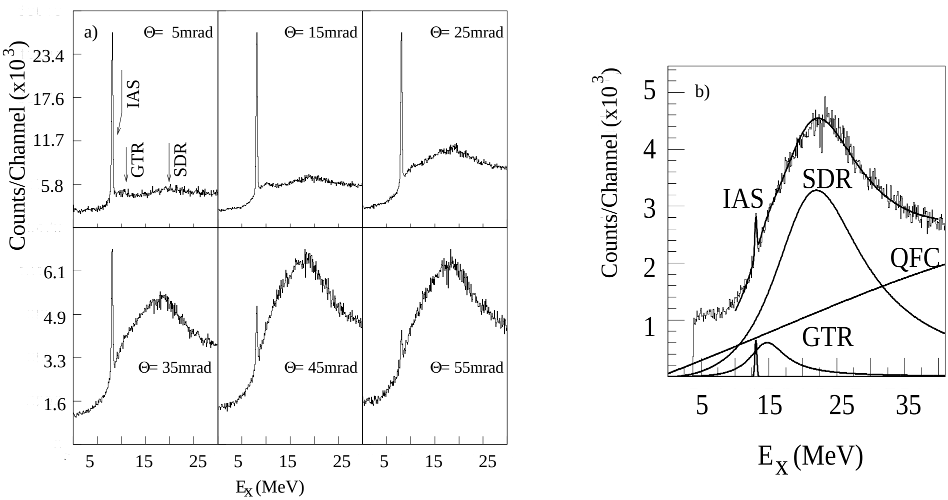

Fig. 2. (a) (^{3}He,t) energy spectra for ^{124}Sn for different triton emission angles (in mrad) as indicated in the figure. (b) The triton energy spectra taken at $\theta_t = 55$ mrad. The solid lines in the spectrum represent the fits of the peaks for the SDR, GTR, IAS and the continuum background due to the QFC process.

Only $N_{\rm QF}$ and $E_{\rm QF}$ are used as free parameters. The other variables were fixed to the recommended values in Ref. [13].

The spectra collected at different angles were fitted simultaneously using the same shape parameters for resonances and for the background and only the amplitudes were considered to be independent.

The relative cross sections of the dipole resonances (dominated by the SDR) compared to that of the isobaric analog state have been determined by analyzing both the excitation energy and the angular distribution of tritons. The following sum rule exists for the β^- and β^+ strengths of the Isobar Analog State (IAS) [8] :

$$S^-_{\rm IAS} - S^+_{\rm IAS} = N - Z \ . \qquad (4)$$

In the case of nuclei with neutron excess, $S^+_{\rm IAS} = 0$ because of Pauli blocking. Thus, the cross section of the IAS is proportional to $N - Z$. Based on the above proportionality, the relative cross sections of the dipole resonances along the whole Sn isotopic chain have been obtained as follows:

$$\sigma_{\rm exp} = (N - Z)\,\frac{I_{\rm SDR}}{I_{\rm IAS}} \ . \qquad (5)$$

The neutron-skin thicknesses were calculated from the cross sections obtained from a fitting procedure according to Eq. (2). The values of

$r_p = \langle r^2 \rangle_p^{1/2}$ were taken from Ref. [14] and the α normalization constant was determined by accepting the theoretical result of Ref. [15] for the difference $\langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$ in ^{118}Sn. The results obtained are compared in Fig. 3 as a function of mass number. Previous experimental results and theoretical values are also displayed in Fig. 3. By the prediction of the different theoretical calculations the mass dependence of the neutron skin thickness is very similar. The relative values of the experimental data reproduce this mass dependence very well, in agreement with the general trend of the theoretical curves.

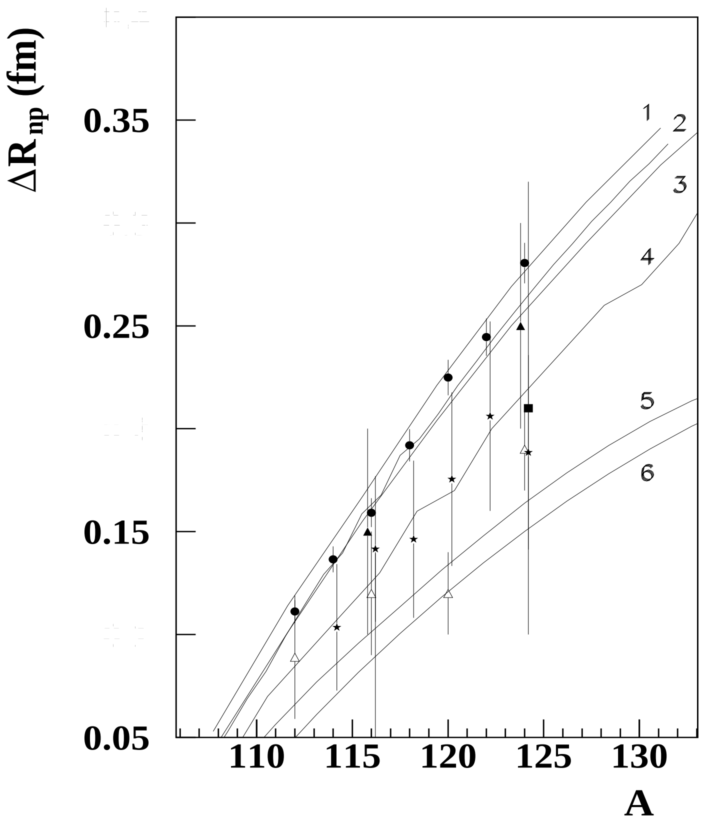

Fig. 3. Neutron-skin thicknesses of the Sn isotopes as a function of the mass number. The experimental values determined by the (p, p) [16], GDR [17] , anti-protonic atoms [18] and SDR (at 450 MeV [7] and at 177 MeV) methods are shown as full triangles, full squares, open triangles full stars and full dots with error bars, respectively. The numbered full lines represent the following theoretical results: (1) RHB/NL3, (3) RHB/NLSH, (5) HFB/SLy4, and (6) HFB/SkP calculations performed by Mizutori *et al.* [2], (2) and (4) calculations performed by Lalazissis *et al.* [15] and Angeli *et al.* [19], respectively.

5. Conclusions

The new method based on the correlation between the $L=1$ cross section measured in (p,n) type charge-exchange reaction and the neutron-skin thickness has been critically tested. Normalizing the results for the rms radius of ^{118}Sn a good agreement could be achieved for the obtained thickness values with all available theoretical predictions and previous experimental data. This method can be used for a wide range of neutron-rich unstable nuclei.

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