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SPIN–ISOSPIN GIANT RESONANCES: REVIEW AND FUTURE PERSPECTIVES*

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Gamow–Teller (spin-flip, isospin-flip) transitions have played an important role in nuclear physics. Basic understanding of the processes requires reliable knowledge of the GT strength distribution at large excitation energy range as well as in nuclei far from the stability line. Spin-flip and isospin-flip transitions with higher multipolarities are also important. There is a predictable correlation between the cross section of the spin dipole resonance and the neutron-skin thickness of nuclei, which quantity is important for constraining the symmetry energy of the nuclear interaction. These investigations can be extended to unstable nuclei using (p,n) reactions with radioactive nuclear beams in inverse kinematics. Relativistic heavy-ion beams and especially rare-isotope beams open up a new avenue for studying spin–isospin giant resonances. Kinematically complete experiments can be performed in inverse kinematics and a large part of the physical background can be reduced in this way. After a review of the present status of the spin-flip and isospin-flip giant resonances I am going to discuss the future perspectives for studying such interesting giant resonances.

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1. Introduction

Understanding the nature of giant resonances began with the publication of the Goldhaber–Teller model [1]. Edward Teller was Hungarian and died last year. I want to use this opportunity also to remember his work.

They imagined the first observed giant resonance as a collective oscillation of the protons against neutrons [1]. It was an isovector and dipole oscillation of the two-component liquid drop model. By this model other

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oscillations were also predicted: not only isovector, when protons oscillate against neutrons, but also isoscalar ones when they oscillate in phase with different multipolarities.

There is a complete harmony of collective nuclear excitations. The discovery of these new giant resonances happened 20–30 years after finding the giant dipole resonance. It occurred when high energy isoscalar alpha particle beams became available. Small angle scattering including 0 degree, using magnetic spectrographs was the other ingredient of the discoveries.

A nice overview of such electric giant resonances can be found in the recently published book of Harakeh and van der Woude [2].

For an experimental physicist, these giant resonances are not sharp peaks, but wide bumps as a function of excitation energy. Their spectrum is similar to a mountain, like the Tatra mountain here. Beautiful and fascinating.

Edward Teller took part also in the understanding of the β-decay process. According to the Fermi theory, the spin of the nucleon does not change during the β-decay process. However, in reality one can observe also strong transitions when the spin changes by $1\hbar$ unit, like in the case of the ^{6}He decay process. Gamow and Teller were able to describe such a decay process with spin-flip isospin-flip transitions.

We can generalize the two-component liquid drop model of the giant resonances by introducing the spin and isospin degrees of freedom. We can introduce vibrations in the spin and isospin space and then we get the spin–isospin giant resonances.

2. Spin–isospin giant resonances

It was known already from the beginning that the β-decay process in N>Z nuclei is much slower than theoretically predicted. For the missing Fermi strength a sharp state was predicted at high energy, outside of the energy window of the β-decay process.

(p,n) reaction, which transforms a neutron to a proton like in the case of the β-decay was used to discover the isobaric analogue state (IAS). The IAS contains the missing strength and introduced as an isospin-flip giant resonance by Ikeda in 1963 [3]. He predicted also a Gamow–Teller giant resonance close to the IAS, which was discovered by Doering *et al.*, in 1975 [4].

We have introduced spin- and isospin-flip transitions in β-decay. It turned out, however, that the giant resonances associated with them are lying at higher energy and can be accessed using strong interaction, like the (p,n) reaction. The central part of the strong nucleon–nucleon interaction contains the scalar, the spin dependent, the isospin dependent, and the spin–isospin dependent parts of the interaction [5]. The scalar part dominates the interaction especially at low energy. The next term is the isospin dependent term. That is the reason that the IAS have been discovered already at low bombarding energy.

If we want to study spin and isospin-flip giant resonances we should go up to the 100–400 MeV energy region, where the spin–isospin term is relatively the largest [6].

3. Gamow–Teller giant resonance

The GT resonance was discovered at MSU using (p,n) reaction on ^{90}Zr. The bombarding energy was 45 MeV [4]. The energy of the neutrons was measured by the TOF method.

(p,n)-reaction studies have been performed extensively at 200 MeV at IUCF and also at RCNP. At higher beam energies the TOF method requires very long flight distances, which makes this method very difficult.

An alternative method is the (^{3}He,t) reaction. In Fig. 1. you can see the excitation energy spectra of ^{90}Zr and ^{208}Pb.

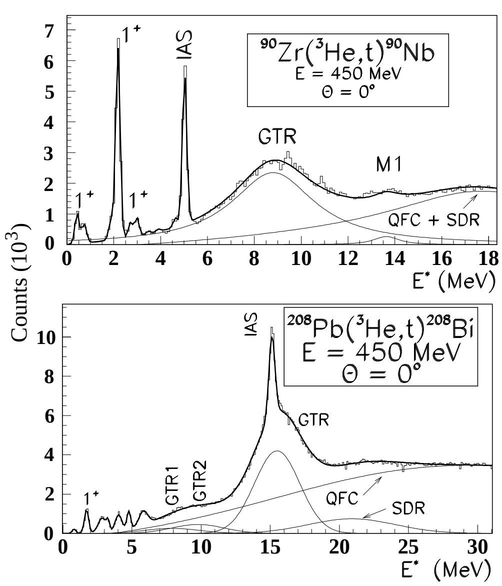

Fig. 1. Zero-degree (^{3}He, t) energy spectra for ^{90}Zr and ^{208}Pb isotopes. The positions of the 1^+ states, isobaric analog states (IAS), the Gamow–Teller resonances (GT) and spin-flip dipole resonances (SDR) are indicated together with the Quasi-Free Continuum (QFC) background. The solid lines through the data are results of fits with Lorentzian line shapes for ^{90}Nb and Gaussian line shapes for ^{208}Bi.

Although the bombarding energy was much higher (450 MeV), the energy resolution was much better compared to the previous (p,n) results. One can nicely recognize the sharp IAS and the broad GTR. The energy of the tritons was measured with the Grand Raiden magnetic spectrograph [7] (shown schematically in Fig. 2.) in Osaka. In this energy region they could reach the best energy resolution in the world. I was also using that spectrograph for studying the GT and SDR resonances [8,9]. Similar setups exist at MSU and also at KVI, but for lower energies [10,11].

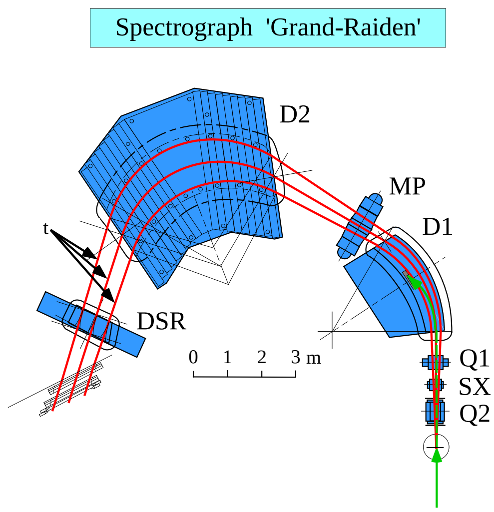

Fig. 2. Schematic layout of the Grand Raiden magnetic spectrograph with dipole (D1, D2), quadrupole (Q1, Q2) and higher order correction coils.

3.1. Quenching of the Gamow–Teller strength

If we assume only nuclear excitations in the structure of the giant resonances, then very simple sum rules can be derived for their strengths, which are proportional to the number of excess neutrons [12].

$$S^{-}_{\rm IAS} - S^{+}_{\rm IAS} = (N - Z)\,. \quad (1)$$

$$S^{-}_{\rm GTR} - S^{+}_{\rm GTR} = 3(N - Z)\,. \quad (2)$$

The S^{-} strength means the β^{-} strength, while the S^{+} is the β^{+} one. Moreover, for a heavy neutron rich nucleus the S^{+} strength is close to zero, because of the Pauli principle.

As the cross section of a (p,n)-type reaction measured at zero degree is proportional to S^-, the sum rule can easily be controlled. It turned out that the IAS exhausts the full 100 % strengths, while the GTR only 50 %.

Theorists suggested that the missing strength may be the consequence of the excitation of the nucleons, so some sub-nucleonic degrees of freedom may also play a role. They seriously considered the excitation of the Δ-resonance lying at about 300 MeV excitation energy [5].

As the question was interesting, the experimental data was also reconsidered. The broad GT resonance usually sits on a high background, the origin of which is not completely clear and makes the determination of the GT strength distribution very difficult. Some authors considered it as a consequence of the quasi-free charge exchange process between the bombarding proton and one of the target nucleon.

The quasi-free charge exchange background was carefully investigated in case of ^{48}Ca [12]. They used ^{40}Ca target also in the same experiment to estimate the background in the ^{48}Ca spectra. In the case of ^{40}Ca, the strengths of the GT is zero as $Z = N$ so only the quasi-free charge exchange background play a role. That background could be described using DWIA and scaled up for ^{48}Ca according to DWIA. Then the remaining spectrum was analyzed with the multipole decomposition method and the strengths of the GTR turned out to be about 50 % of the sum rule.

As the question was very important, new experiments were performed starting at 1997 in Osaka [13]. Polarized proton bean was used and the polarization transfer was also measured. The whole spectrum was analyzed with the multipole decomposition method without assuming any background from the quasi-free charge exchange process. They obtained about 100 % sum rule strengths in this way [13].

The question is still interesting. It would be worthwhile to identify the heavy reaction product also to avoid the contributing backgrounds.

3.2. Fragmentation of the Gamow–Teller strength

We have also investigated the strengths distribution of the GTR using (^{3}He, t) reaction on a few targets at RCNP [9]. We were mostly interested in the fragmentation of the resonance into low-energy components, which are important for nuclear astrophysics and for constructing new type of neutrino detectors. We were trying to describe the fragmentation with QRPA, but I belive more experimental data is still needed to tune the parameters of the description properly [9].

Up till now I was speaking only about the investigation of β^- strengths with GT$^-$ probes. Especially for lighter nuclei, the β^+ strength distribution is also important. That is the reason why physicists started using (n,p)

reaction at TRIUMF (Canada) already in the early 90's to study the GT^+ strength distribution. As another approach, the EuroSupernova collaboration at KVI Groningen has been employing (d, ^{2}He) reaction since 2000 [11].

The main motivation of the experiments came from nuclear astrophysics. But (d, ^{2}He) is not an easy reaction. One has to detect both protons from the decay of ^{2}He, with high efficiency and high resolution. That was one of the reason that people at Michigan started using also the (t, ^{3}He) reaction. The disadvantage of this reaction is that triton beams are allowed to make nowadays only as secondary beams, with different reactions.

Recently, Hagemann and coauthors [14] at KVI obtained very nice energy resolution which was orders of magnitude better compared to the energy resolution of (n, p). Moreover the background was also smaller.

4. Spin–dipole resonance and the neutron-skin of nuclei

After the $L = 0$ GT component of the strength distribution, the next component is the $L = 1$ one, which is called spin–dipole resonance (SDR).

I would like to draw your attention to the difference in spin transfer, and as a consequence the difference in the final spin, which is a mixture of the 0^-, 1^- and 2^- states in the case of the SDR. As a consequence of the different operators, the sum rules are also completely different. In the case of the GDR it is the well known TRK sum rule [2], which in the case of the SDR depends also on the difference of the neutron and proton density distribution, namely on the neutron-skin. The following sum rule is valid for the spin–dipole operator involving the difference between the β^- and β^+ strengths [6, 15],

$$S^-_{\mathrm{SDR}} - S^+_{\mathrm{SDR}} = \frac{9}{2\pi}\left(N\langle r^2\rangle_n - Z\langle r^2\rangle_p\right), \tag{3}$$

where $\langle r^2\rangle_n$ and $\langle r^2\rangle_p$ represent the rms radii of the neutron and proton distributions, respectively. One can obtain a similar expression also for the charge-exchange non-spin-flip modes [16].

The experimental cross section of the $L = 1$ transitions measured in (p, n)-type reactions allows one to deduce the S^- only, therefore a theoretical estimate of the S^+ is needed. In this work, instead of using a simple model for the energy-weighted sum rule as we did previously [8], we took more precise S^+/S^- ratios from continuum RPA calculations [17]. The model parameters were taken from Ref. [18] and the effects of neutron pairing correlations have been neglected.

Using the calculated $B = S^+/S^-$ ratios the neutron-skin thicknesses can be deduced from Eq. (3):

$$\langle r^2\rangle_n^{1/2} - \langle r^2\rangle_p^{1/2} = \frac{\alpha\sigma_{\rm exp}(1-B) - (N-Z)\langle r^2\rangle_p}{2N\langle r^2\rangle_p^{1/2}}\,, \tag{4}$$

where $\sigma_{\rm exp}$ is the experimental cross section of the SDR strengths and α is a normalization constant.

In order to measure the cross section of the SDR in the Sn isotopes we have performed an experiment first at RCNP using (^{3}He, t) reaction and the Grand Riden spectrometer [8]. In order to get better statistics, the experiment was repeated also at KVI Groningen using again (^{3}He, t) reaction. The triton spectrum was measured with the BBS [10]. You can see an example in Fig. 3. The scattering angle was 3.2 degree, which was optimal for the SDR.

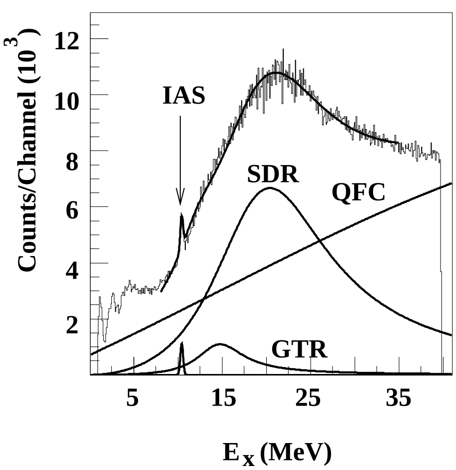

Fig. 3. (^{3}He, t) energy spectrum for ^{118}Sn taken at $\theta_t = 3.2°$. The solid lines in the spectrum represent the fits of the peaks for the SDR, GTR, IAS and the background due to the QFC process.

The differential cross section of the IAS and the SDR was derived from the data and compared with the calculated ones. The agreement was nice, and this confirmed the normalization of the background caused mainly by the quasifree charge exchange process.

The difference of the neutron–proton rms radii was calculated by using Eq. (4). The values of $r_p = \langle r^2\rangle_p^{1/2}$ are taken from Ref. [19] and the α normalization constant is determined by accepting the experimental result of Ref. [20] for the difference $\langle r^2\rangle_n^{1/2} - \langle r^2\rangle_p^{1/2}$ in ^{116}Sn.

The results obtained are compared in Fig. 4 as a function of mass number. The results of the previous measurements and theoretical values are also presented in Fig. 4.

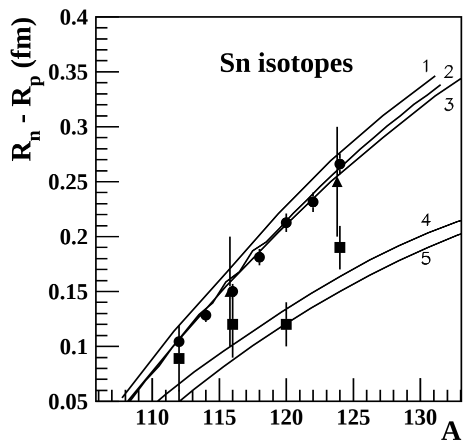

Fig. 4. The full dots with error bars show the neutron-skin thicknesses of the Sn isotopes determined in the present work as a function of the mass number. The experimental values determined by the (p,p) [21], and the antiprotonic methods are shown as full triangles and full squares with error bars, respectively. The numbered full lines represent the following theoretical results: (1) RHB/NL3, (3) RHB/NLSH, (4) HFB/SLy4, and (5) HFB/SkP are calculations performed by Mizutori *et al.* [22]. The line (2) is the calculation performed by Lalazissis *et al.* [23].

You can see also the results of a few different calculations as full curves. The upper curves show the results of the Relativistic Hartree–Fock calculations, while the lower curves were obtained with nonrelativistic Hartree–Fock calculations. I want to draw your attention to the very large, factor of 2, difference between them.

It turned out very recently [25] that this big difference is caused mainly by one of the parameters of the mean field, namely the symmetry energy. The calculations have been performed with different models and different parameterizations, but the correlation remained.

Using that correlation curve and the experimental neutron-skin thicknesses one can constrain the symmetry energy parameter of the mean field, which is very important in describing the neutron rich nuclei. That is the physics of radioactive beams.

5. Neutron-skins in neutron rich rare isotope beams

One of the main challenges of our contemporary nuclear structure physics is studying nuclei far from the stability line.

There exists a large part in the nuclear chart between the known neutron-rich isotopes and the neutron drip line, which has been denoted TERRA INCOGNITA. Because of limited knowledge about the properties of such neutron-rich nuclear matter we can not determine even the border of the Terra Incognita, *i.e.* neutron drip line, with a precision better than 10 mass units around $Z = 50$. A number of questions arises: Could we determine the neutron drip line more precisely? What do we know about the equation of state of neutron-rich nuclear matter? How does the nuclear force depend on isospin?

By studying giant resonances in radioactive beams one can obtain both macroscopic and microscopic information. For example, important macroscopic informations are the compressibility and symmetry energy of nuclear matter. Neutron skin will be a central issue, which can be studied by measuring the SDR sum rule, and also with another method published recently by Vretenar *et al.* It is based on the measurement and calculation of the energy difference of the GTR and IAS [24].

Neutron-skin is already a kind of neutron-rich matter, which can be studied even in stable isotopes. Therefore, an intriguing question is: can we learn something about the equation of state (EOS) of neutron-rich matter by measuring the thickness of the neutron-skin? Furnstahl answered this question in his recent work [25]. He calculated the neutron-skin thickness in various models with different parameterizations, and investigated their sensitivity. One of the surprising results he found was that a well-defined correlation exists between the symmetry-energy term of the nucleus-energy function and the neutron-skin thickness. This correlation remained about the same in all the relativistic and non-relativistic models. According to this correlation, one can constrain the symmetry-energy term of the EOS by measuring the thickness of the neutron-skin.

The strength distribution of the GT resonance is also important for nuclear astrophysics in the neutrino induced reactions.

These spin-flip isospin-flip transitions can be excited in (p, n) reactions using inverse kinematics. The cross sections are reasonably high and we can detect both the heavy and light reaction products. In this complete kinematics we can significantly reduce the background. The energy of the neutrons is low and suitable for TOF. We can use thick targets. The neutrons do not lose energy in the target.

If we are aiming at an energy resolution of 1 MeV in excitation energy, than we should have good granularity of the detector. We should measure the scattering angle with a precision of 1 degree. The energy resolution required for neutrons is not so strict. It can be achieved with a flight distance of 1 m already, which enables the construction of a nearly 4π TOF spectrometer.

In an R3B (Reactions with Relativistic Radioactive Beams) [26] and in an EXL (EXotic nuclei studied with Light hadronic probes) [27] collaboration based on the present and future accelerators at GSI we started to build such a neutron spectrometer for studying the GT strength distribution, the spin–dipole resonance and neutron skins in Radioactive Nuclear Beams. Let me mention that detecting such low-energy neutrons with high efficiency is a real challenge of the development.

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