BETA STRENGTH DISTRIBUTION IN THE DECAYS OF NEUTRON–DEFICIENT NUCLEI*

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The results of recent studies of the Gamow–Teller β-decays of nuclei in the ^{100}Sn region are presented. Measurements performed with the use of the total absorption γ-ray spectrometer and the Cluster Cube array of germanium detectors revealed qualitatively new information on the Gamow–Teller strength distribution in the decays of ^{97,98}Ag and $^{103-107}$In. The shape of the measured β-strength distribution and the resulting total B_{GT} values are compared with the results of shell-model calculations.

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1. Introduction

Understanding and reliable description of the β-strength distribution is of crucial importance for the complete characteristics of the nuclear β-decay. The β-strength function determines the gross properties of the decaying nuclei such as half-life or probability of β-delayed particle emission. Predictions and investigations of these basic characteristics of β-unstable nuclei

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are of primary interest in the decay studies far from stability. Data resulting from these studies provide an important nuclear physics input for the understanding of the element synthesis in the universe. The knowledge of the weak interaction rates in stellar matter evolution, in particular rates of the Gamow–Teller (GT) transitions for iron region nuclei, is crucial for the calculations of the electron capture (EC) rates during the presupernova core collapse of the massive stars [1]. High-precision measurements of superallowed $0^+ \rightarrow 0^+$ Fermi β-transitions rates allow one to verify the conserved vector current (CVC) hypothesis, to test the unitarity of the Kobayashi–Maskawa matrix and finally to set limits on extensions to the Standard Model [2]. Very sensitive probes for studying fundamental symmetries of electroweak interaction and properties of neutrino provide studies of double β-decay (2β) [3]. Reliable calculation of nuclear 2β-decay matrix elements is prerequisite for deduction of the neutrino mass from 2β-decay experiments. Matrix elements of the GT transitions are needed for the determination of the neutrino absorption cross-section for (solar) neutrino detectors [4, 5].

In this contribution we restrict our discussion to one of the most intriguing problems related to the β-strength distribution studies which concerns the question of the origin of the quenching observed for the strength of GT transitions. As it is shown by the analysis of the GT β-decays, the experimentally determined strengths appear to be systematically smaller than the calculated GT β-transition rates. Similar regularity was reported for the GT strengths extracted from the forward-angle intermediate-energy charge-exchange reactions [6, 7].

The GT quenching can be quantitatively described in terms of the hindrance factor defined as the ratio of calculated and experimentally determined GT strength. The best description of nuclear wave functions and the GT matrix elements between nuclear states is provided by large-basis shell model calculations. The most complete calculations, based on the diagonalization of the effective Hamiltonian within the full major oscillator shell, are feasible only for relatively light nuclei. Such calculations were used to determine hindrance factors for nuclei with $A \leq 50$. A comparison of the GT decay rates measured and calculated within the full p-shell for $A \leq 18$ nuclei revealed the quenching of the observed B_{GT} values by a factor of 1.49(3) [8]. The systematic analysis of GT strength for $A = 17$–39 nuclei yielded the hindrance factor of 1.68(4) with respect to the complete sd-shell calculations [9]. The recent analysis of the GT decays in the mass range $A = 41$–50 indicated that the agreement between the experimental data and the full fp-shell calculations demands the introduction of the average hindrance factor $h = 1.81(4)$ [10].

Two physically different mechanisms are usually considered to explain the observed quenching of the GT strength. The first one is a higher-order nuclear configuration mixing between nucleons. The second mechanism responsible for the reduction of the observed GT strength is the renormalization of the axial-vector coupling constant g_A in nuclear matter originating from non-nucleonic effects mediated mainly by the admixture of the $\Delta(1232)$-isobar nucleon-hole configurations into the GT states. An estimate given by A. Brown [11] has shown that two thirds of the amplitude of the GT quenching originates from higher-order nuclear configuration mixing and one third from Δ-isobar admixtures. The recent studies of the GT strength of ^{90}Nb based on the multipole decomposition analysis of the $^{90}\mathrm{Zr}(p,n)$ reaction data indicate, however, that one may not need recoursing to Δ-isobar nucleon-hole admixtures for an explanation of the quenching of the GT strength [12, 13].

The question of the "missing" GT strength can be adequately addressed in β-decay studies of nuclei far from stability where the GT strength distribution can be investigated and confronted with theoretical predictions over a broad range of excitation energies. In this respect the ^{100}Sn region is of particular interest: Since the $N = Z = 50$ shell closure occurs far from stability, isotopes in this region, especially non even–even ones, have relatively large Q_β-values. From simple single-particle model considerations one may expect that a substantial part of the total GT-strength resides within the Q_{EC} window and may thus be detected in β-decay measurements conducted with the proper experimental technique. As far as theoretical calculations are concerned, nuclei close to ^{100}Sn can be treated as closed-shell systems with a few valence particles only, which facilitates the model description.

The strength of the GT β-transition to the state at excitation energy E in the daughter nucleus can be derived from the measurements of the β feeding of this state $I(E)$, the decay energy Q_{EC} and the β-decay half-life $T_{1/2}$ according to the relation:

$$B_{\mathrm{GT}}(E) = \frac{D\, I(E)}{(g_A/g_V)^2\, f(Q_{\mathrm{EC}} - E)\, T_{1/2}}\,, \tag{1}$$

where $D = 6147(7)$ s is a constant, $g_A/g_V = -1.262(4)$ is the ratio of axial-vector and vector coupling constants for the free-neutron decay and f is the statistical rate function.

Most frequently, β-feeding distribution has been derived from the detailed decay scheme established in conventional measurements employing standard-size Ge detectors. Such studies can often reveal a wealth of nuclear structure data on all individual levels in simple decay schemes and disclose information about the structure of low-lying states in complex decays. For complex decay schemes with high decay energy, however, such traditional measurements are generally unable, due to the low efficiency of detectors, to record all of the many weak γ transitions and hence to place them in the decay scheme. This is particularly true for energetic γ-rays depopulating states at high excitation energy in the decay product. As a consequence, the classical high-resolution γ-ray spectroscopy studies based on routinely applied Ge detectors usually overestimate the β-feeding intensity to low-lying states. Due to the very strong dependence of the β-decay rate function on the transition energy ($f \sim (Q_{\rm EC} - E)^5$), the distortion of the β-feeding distribution has severe impact on the resulting $B_{\rm GT}$ distribution and causes underestimation of the apparent total GT strength.

A way to overcome the limitations of the standard discrete, high-resolution, low-efficiency γ-ray spectroscopy is a direct measurement of the distribution of β-decay feeding intensity. The ideal tool for this kind of measurements would be a γ-energy calorimeter with 100% full-energy peak efficiency for all γ-ray energies. In such a detector all members of each γ cascade depopulating an excited state would be summed to yield an output signal corresponding to the excitation energy of this state and provide an unambiguous signature for each β-feeding event to the given level.

Today the closest approach to such an ideal spectrometer represents an array of large scintillation detectors in a 4π geometry. The total absorption spectrometer (TAS) installed at the on-line mass separator at GSI consists of a large NaI crystal ($\o$ $14'' \times 14''$) for the detection of γ-rays [14]. A cylindrical well along the crystal's symmetry axis accommodates an assembly of auxiliary detectors. In the standard set-up it contains two Si counters for β particle detection, a high-resolution Ge X-ray detector and a "plug" NaI detector which restores the 4π geometry of the main crystal. The tape transport system is used to position mass separated radioactive sources in the center of the main crystal, between the two Si counters. By demanding coincidence with signals from the Si detectors, the positron component of the β^+/EC decay can be selected, whereas coincidences with characteristic X-rays recorded by the Ge detector can be used to select the EC events. The total γ-ray efficiency of TAS for monoenergetic photons in the energy range of 0.2–4.0 MeV exceeds 88%, and its full-energy peak efficiency is above 56%. The high efficiency values and their weak dependence on photon energy assure the operation of the detector as a satisfactory total absorption spectrometer. However, due to the apparent γ-efficiency loss effects, the determination of the β-feeding distribution from the experimental TAS spectra requires thorough knowledge of the detector response function and application of sophisticated deconvolution procedures. These problems have been elaborated by Karny *et al.* [15] and Cano-Ott *et al.* [16] who pointed to the importance of the high-resolution studies as a source of necessary input data for extracting the β-feeding distribution from the measured TAS spectra.

The genuine requirement for high-quality discrete spectroscopy data triggered the use of state-of-the-art Ge detectors for β-decay studies. In the experiments performed at the GSI on-line mass separator an array of 6 Euroball Cluster Ge detectors arranged to form a cube (Cluster Cube) has been used to complement the TAS measurements. The 42 Ge crystals of this array covered about 65% of the full solid angle with respect to a source positioned at the center of Cluster Cube, and allowed registration of 1.33 MeV γ-rays with a full-energy peak efficiency of about 19% and typical resolution of about 2.8 keV. The sensitivity of the Cluster Cube exceeds by far the sensitivity of any Ge detector set-up used in previous β-decay measurements and makes it indeed an excellent tool for spectroscopy studies of complicated decays. The usefulness of the Cluster Cube detector has been demonstrated in the measurements of ^{97}Ag and ^{150}Ho(2^-) decays performed at GSI on-line mass separator. More than 600 γ transitions (580 new) depopulating 150 levels were placed in the decay scheme of ^{97}Ag [17]. An even more complex decay scheme has been established for ^{150}Ho(2^-) [18]. In both cases, the performance of the Cluster Cube pushed the measurements to the limit of the discrete γ-ray spectroscopy method, *i.e.* up to the excitation energies where deexcitation by statistical γ cascades deexcitation dominates. The comparison of β-feeding distribution for ^{150}Ho(2^-) determined from the Cluster Cube data and from the TAS measurement clearly illustrates the limitations of the discrete γ-ray spectroscopy technique for the investigation of β-strength function in complex decays. In such cases, the high-resolution, discrete spectroscopy should not be considered as an alternative to the total absorption γ-ray studies but rather as a complementary method which, however, is indispensible for the reliable analysis of the TAS spectra and also needed to reveal the fine-structure of the β-strength distribution.

2. GT strength distribution for nuclei in the ^{100}Sn region

The GT decays of nuclei in the vicinity of ^{100}Sn proceeds via transformation of a $g_{9/2}$ proton into a $g_{7/2}$ neutron. In the decays of even–even isotopes the process occurs between the 0^+ ground state and the group of low-lying $1^+(\pi g_{9/2}^{-1}, \nu g_{7/2})$ states in the final nucleus [19]. The dominant role of the even–even core decays should be also apparent in the β-decays of the non even–even isotopes. For odd–odd isotopes one may expect strong population of three-quasiparticle configurations at an excitation energy of 3–4 MeV, whereas in the decays of odd–even nuclei one should observe substantial feeding of four-quasiparticle states at excitation energies of 5–6 MeV in the daughter nucleus. These crude predictions of simple single-quasiparticle model are confirmed by the measured B_{GT} distributions.

Fig. 1 shows the B_{GT} distribution for the decay of ^{97}Ag resulting from the Cluster Cube measurement [17]. The global shape of this distribution is dominated by a resonance structure extending between 3 and 4.5 MeV, in

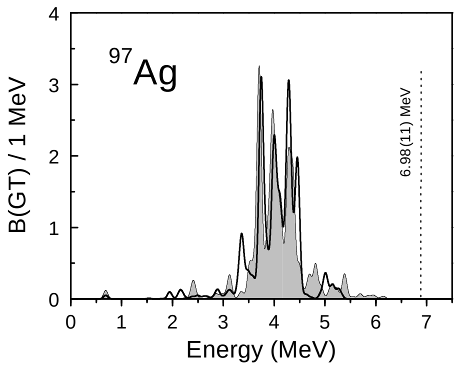

Fig. 1. $B_{\rm GT}$ distribution for the decay of ^{97}Ag deduced from the Cluster Cube measurement (solid line) and obtained from the shell model calculations (shaded area), respectively. Both distributions were smoothed by folding with a Gaussian distribution of 60 keV FWHM. The theoretical data were normalized to the total $B_{\rm GT}$ value derived from the Cluster Cube measurement. The vertical line indicates the $Q_{\rm EC}$ value.

general agreement with the results of the preliminary TAS data analysis [17]. The decay characteristics observed can be interpreted as the GT decay of the even–even core to three-quasiparticle configurations which, due to the residual interactions, are spread over many levels of the final nucleus. As shown in Fig. 2, similar structure of the $B_{\rm GT}$ distribution has been obtained from the TAS measurements for $^{103-107}$In. As expected from the simple single-quasiparticle model, the experimental $B_{\rm GT}$ distribution is concentrated in resonances appearing at an excitation energy of about 3.5 and 5.5 MeV for odd-mass and even-mass indium isotopes, respectively. The full widths at half maximum of the distributions amount to about 1–1.5 MeV.

Within the extreme single-particle shell model the total strength of the $\pi g_{9/2}\!\rightarrow\!\nu g_{7/2}$ GT transition is proportional to the square of the matrix element of the GT operator, to the number of the protons at the $g_{9/2}$ orbital and to the "emptiness" of the neutron $g_{7/2}$ orbit:

$$B_{\rm GT}^{sp} = \frac{16}{9}\, N_{\pi g_{9/2}}\, (1 - N_{\nu g_{7/2}}/8)\,. \tag{2}$$

This simple relation is clearly reflected in a remarkable systematic behavior of the summed experimental $B_{\rm GT}$ strength for nuclei in the ^{100}Sn region [20]. As shown in Fig. 3, the total $B_{\rm GT}$ strength is proportional to the number of protons occupying the $g_{9/2}$ orbital and linearly depends on the number of neutrons filling orbitals above $N = 50$ shell gap.