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Beta-decay studies using total absorption spectroscopy

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Abstract. Beta-decay experiments are a primary source of information for nuclear-structure studies and at the same time complementary to in-beam investigations of nuclei far from stability. Although both types of experiment are mainly based on γ-ray spectroscopy, they face different experimental problems. The so-called *Pandemonium effect* is a critical problem in β-decay if we are to test theoretically calculated transition probabilities. In this contribution we will present a solution to this problem using total absorption spectroscopy methods. We will also present some examples of experiments carried out with the Total Absorption Spectrometer (TAS) at GSI an describe a new device LUCRECIA recently installed at CERN.

PACS. 23.40.-s Beta decay; double beta decay; electron and muon capture

1 Introduction

The history of the understanding of the β-decay is a long record of fascinating puzzles and discoveries. One of the very first and most "troublesome" questions was related to the continuous nature of the β-decay spectra, in contrast to the discrete nature of α and γ radioactive processes. This feature of the β-decay was considered so odd in the early days of quantum theory, that even the energy conservation law was questioned by the physicists of the time. Even though this particular property of the β-decay is fully understood following the pioneering work of Pauli and Fermi, the continuous nature of the β-decay spectra remains the primary source of experimental difficulties when β-decay is used as a probe to study nuclear structure. Contrary to α and γ spectroscopy, where a measurement of the decay spectra gives direct information about the properties of the nuclear levels involved, this is not possible in β-decay studies. The information on the decay probability in β-decay is usually deduced indirectly from measurements of the intensity balance of gamma rays from the levels populated in the β-decay transitions.

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2 Nuclear structure from β-decay studies

Considering that β-decay is the process that governs the transmutation of most of the nuclear species, the importance of a full understanding of the physics which lies behind is clearly evident. Beta-decay studies can reveal information about the β-decay process itself as well as information on nuclear masses and on the properties of the nuclear states involved.

One particular advantage of these studies is that theoretically the process is governed by a very simple operator, namely the $\sigma\tau$ operator in the case of Gamow-Teller (GT) decay and the τ operator in the case of Fermi (F) decay. Thus, a good and complete description of the ground state of the parent nucleus ($|i\rangle$) and of the states populated in the daughter nucleus ($|f\rangle$) provides, in principle, a good value for the GT strength

$$B_{\rm GT} = g_A^2/g_V^2 |\langle f||\sigma \cdot \tau||i\rangle|^2 ,$$

and of the distribution of the GT strength over the excitation energy range covered by the Q_β window.

The apparent simplicity from the theoretical point of view meets difficulties on the experimental side. The $B_{\rm GT}$ of an individual level populated in the β-decay is determined from the balance of the gamma-feeding and -de-excitation. Common to such investigations is the use of semiconductor detectors to measure the γ-ray intensities. Two main factors contribute to make such measurements difficult: the fragmentation of the gamma intensity and the low detection efficiency for primary γ-rays, usually of high energy. Therefore, much of the β-feeding at high excitation energy is not observed and is then incorrectly assigned to low-lying levels (*Pandemonium effect* [1]). This leads to a large and systematic error in the total $B_{\rm GT}$ and in the $B_{\rm GT}$ distribution which consequently can lead to the misinterpretation of the underlying nuclear structure.

The solution to this experimental problem is to create a device, a Total Absorption Gamma Spectrometer (TAGS), which is sensitive to the β population of the nuclear levels rather than to the individual gamma rays [2]. A TAGS can be constructed using a large NaI(Tl) scintillator which covers 4π in solid angle relative to the source. Such a device will absorb all the energy of the γ-rays produced in the de-excitation of a level fed in β-decay. So, instead of having peaks from the individual γ-rays in the energy spectrum, we will have sum peaks corresponding to the total energy of the γ cascades that follow the β-decay, and this directly gives information on the levels fed in the decay. The high efficiency of the NaI(Tl), as well as the reasonable energy resolution obtained with this kind of scintillator make the TAGS an ideal device for the measurement of the GT strength [3–7].

Even though the application of the TAGS technique dates back to the work of Duke *et al.* [2], the first steps faced several limitations due to the size of the crystals available and to the lack of well-found methods of analysis. The problem arises from the impossibility of building a 100% efficient TAGS. An ideal device would have a response to different gamma cascades which is independent of the gamma decay pattern and therefore the information on the β-feeding can be extracted directly from the measured spectrum (the measured spectrum is proportional to the β-feeding). But a real TAGS will always have an efficiency lower than 100%, producing different responses of the detector to different γ-decay patterns depending on the particular energies of the gamma rays to be summed. Therefore the feeding pattern can only be obtained after applying an unfolding procedure to the measured spectra using the detector response function. This is a complex problem because it is necessary to calculate the response function of the detector to all imaginable cascades and then solve the so-called "inverse problem":

$$\mathbf{d} = \mathbf{R}(\mathbf{B}) \times \mathbf{f} ,$$

where $\mathbf{d}$ represents the measured data, $\mathbf{R}$ is the response matrix of the detector, which depends on the branching ratios ($\mathbf{B}$) of the levels in the daughter nucleus and $\mathbf{f}$ is the feeding distribution we wish to determine. This problem is apparently impossible to solve since detailed information on the level scheme of the daughter nucleus up to high excitation energy (Q_β window) are needed but not always available. However, the high detection efficiency obtained with the large scintillator crystals available strongly reduces the dependence of the results on the level scheme. In addition, algorithms now exist to solve the above-stated inverse problem [4], and we have the computing power necessary to solve them. Putting all of these factors together, the TAGS technique is now a plausible way to obtain reliable experimental information on the $B_{\rm GT}$, as was shown in refs. [4–7].

3 Physics motivations and performed studies

Considering the above-mentioned facts, it is clear that the TAGS technique can be successfully applied to specific problems of physical interest if a proper method of analysis is applied. One problem, well suited to apply this procedure, is the long-standing question of the missing strength in Gamow-Teller decay. In light nuclei there is a great deal of experimental information from both β-decay and charge-exchange reactions, which systematically indicates that $\sim 40\%$ of the strength is missing when experimental results are compared with theoretical predictions [8]. For heavy nuclei, the experimental information is sparser due to the difficulty of accessing nuclei with allowed decays.

Here, as an example of the potential of the method, we present some results obtained in studies of heavy nuclei. In comparison with charge-exchange reactions, results obtained from β-decay studies are reaction model independent and are free from background uncertainties. In addition, they allow to study exotic nuclei far from stability not accessible in charge-exchange reactions. The only difficulty is that, due to selection rules, very few Gamow-Teller decays are allowed above the heaviest $N \sim Z$ particle stable nuclei. This is because the required orbitals for allowed decay lie, in general, outside the Q_β window available to our measurements. In heavy nuclei there are only two regions where the $\sigma\tau$ resonance is accessible in β-decay. In both cases a proton from a high-J orbital decays into its neutron spin-orbit partner with $J-1$, which is, in general, less bound than the J neutron orbital and therefore empty. The nuclei we refer to in particular are the nuclei below ^{100}Sn and above ^{146}Gd. In both cases it should be possible to compare the experimental results with theoretical calculations.

As pointed out earlier, to improve the experimental situation there are two possibilities: 1) the use of a high-efficiency TAGS device, 2) the use of an array of closely packed Ge detectors (CLUSTER CUBE), with greatly enhanced efficiency and high resolution, of the kind developed in recent years for in-beam γ-spectroscopy studies (cluster detectors).

These two alternatives were used in a series of experiments performed at the GSI On-line Mass Separator aimed at studying nuclei in the rare-earth region (^{148}Tb, ^{150}Ho) [4–6] as well as nuclei in the neighborhood of ^{100}Sn (^{97}Ag,^{98}Ag) [7]. In the following we will mainly concentrate on the results obtained for nuclei in the vicinity of ^{146}Gd. The use of the high-resolution detectors in these experiments had a twofold interest. They represent the state-of-the-art for high-resolution γ detection and will give the best results that can be achieved using this technique. Secondly, a more complete knowledge of the level scheme can be used to test the analysis technique for the TAGS data.

The analysis of the CLUSTER CUBE data was performed using the conventional methods of γ-spectroscopy. About 1000 γ-rays where identified from the decay of the 2^- isomer in ^{150}Ho and a ^{150}Dy level scheme with ~ 300 levels was constructed. These numbers show clearly the complexity of the problem we have to solve using high-resolution techniques. They also show the magnitude of the error made in measurements using the conventional techniques (before our measurements only 5 levels were known to be fed in the β-decay of the 2^- isomer). The analysis of the TAGS data was carried out using the methods of analysis established in ref. [4] including the determination of the response function of a large NaI(Tl) crystal and pulse pile-up correction [9]. The response matrix ($\mathbf{R}$) of the detector was calculated using Monte Carlo simulation. For that, the GEANT3 MC library was used [10], because it has a powerful geometry package which allows the description of the apparatus with the required detail. To solve the inverse problem three different algorithms were used [4], which give essentially the same results: Linear Regularization Method [11], Iterative Maximum Entropy Method [12] and Bayesian Iterative Method [13]. In [4] it was also shown that due to the relatively high efficiency of the GSI TAS detector the results of the analysis were not so sensitive to the prior knowledge of the level scheme.

Figure 1 shows the results obtained with both experimental methods in the study of the ^{150}Ho 2^- decay, where a large resonance can be seen. The solid line represents the results obtained with the CLUSTER CUBE and the dotted line the results obtained from the analysis of the TAS data. The comparison of the two results demonstrates the correctness of the analysis method for the TAS data (they show the same shape). However it also shows the limitations of the high-resolution method in the sense that even using the most powerful detectors available, some feeding at high excitation remains undetected. The same facts in numbers: the TAS analysis gives 116% more B_{GT} in total than the data from the CLUSTER CUBE [4].

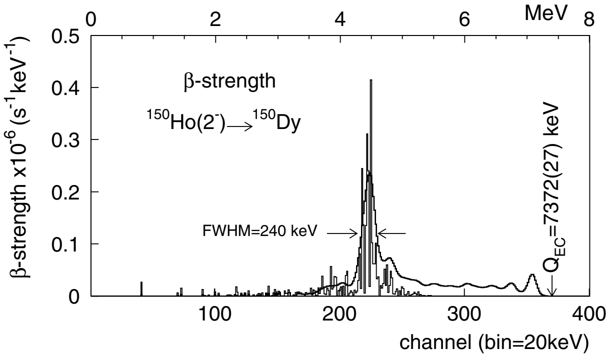

Fig. 1. The TAS (dotted line) and CLUSTER CUBE (solid line) results.

4 Present and future studies

It is not only the "quenching problem" that can be addressed using this method. Other questions that require precise measurements of the β-strength can be studied with this technique. With this in mind a new TAGS, called LUCRECIA, has been recently installed at the PSB ISOLDE Mass Separator (CERN) facility. The crystal, constructed by "St. Gobain Crystals and Detectors", is a large NaI(Tl) crystal of cylindrical shape (38 cm diameter, 38 cm long). The setup allows the study of β-decay processes of more exotic nuclear species (with very short lifetimes), since direct implantation of the radioactive sources in the middle of the crystal is also possible (see fig. 2).

An important question that can be answered using this method is the determination of the ground-state shape of the parent nucleus from the distribution of the measured B_{GT} in the daughter nucleus. Particularly interesting cases are the neutron deficient $N = Z$ nuclei in the mass region $A \sim 70$ which are currently the subject of numerous theoretical and experimental investigations to answer questions about nuclear deformation, shape coexistence, shape transitions, np pairing and isospin mixing. One relevant result in this context is the feature pointed out by I. Hamamoto [14], who showed that, close to the drip lines, the main strength of the Gamow-Teller(GT) resonance might be located below the ground state of the parent nucleus. Further theoretical studies, which take into account deformation and pairing [15,16], show that the GT process is expected to provide valuable information on nuclear deformation, since clear differences appear in the calculated GT strengths depending on the shape of the parent nucleus. Of special interest in this respect are the even-even nuclei in this mass region, where an oblate-to-prolate transition is predicted, and for which various deformation amplitudes have already been inferred from experimental results [17].

This interesting physical problem was already addressed experimentally using a combination of Ge and particle detectors (see, for example, [18]), where it became clear that the TAGS technique is necessary to complement the experimental information. For that reason it was proposed to use the new spectrometer at ISOLDE to study the B_{GT} distributions in the decay of a number of

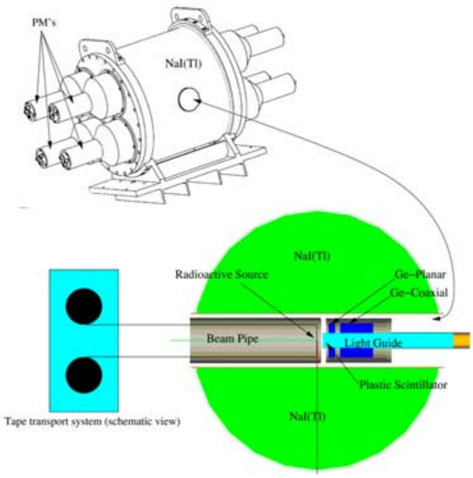

Fig. 2. Schematic picture of the LUCRECIA spectrometer.

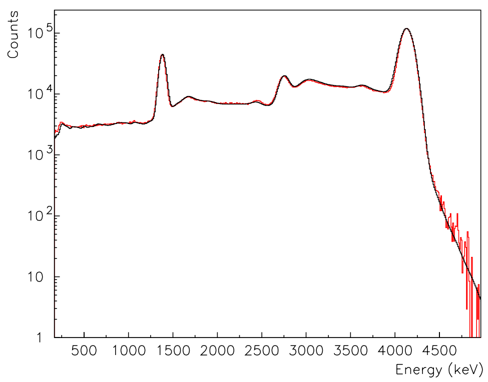

Fig. 3. Comparison of the results of a simulation of the decay of ^{24}Na using GEANT4 with a measurement of the source using the GSI TAS. The results obtained with GEANT4 reproduce better the last part of the spectrum, which is due to the better treatment of the penetration of the β-particles into the crystal.

Kr and Sr isotopes in the $N = Z$ neutron-deficient mass region [19] in order to infer the nuclear deformation of the ground state of the decaying nuclei. Two series of measurements were performed, and the analysis of the decay of ^{74}Kr [20], the first data analyzed, shows the feasibility of the method. The results for the decay of ^{74}Kr show the existence of shape coexistence in the ground state of this nucleus consistent with earlier experimental evidence [21].

We are also working on the improvement of the analysis techniques. From the experience obtained in the work by Cano-Ott *et al.* [4], it was deduced that the GEANT3 code is not able to reproduce accurately the penetration of the β-particles in the crystal. The correct reproduction of this effect may have an important contribution in the precise determination of the strength close to the Q_β value. The new version of the Monte Carlo code, GEANT4 [22], which provides an improved treatment of the low-energy electro-magnetic processes should solve this problem (see fig. 3).

As a conclusion, it is possible to say that the total absorption technique can now be used as a reliable method for the determination of the B_{GT} strength in β-decay studies. The use of this technique will lead to many interesting new results in the near future in the field of nuclear structure.

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