Beta-decay Studies Using Total Absorption Techniques

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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 the one related to the continuous nature of the β-decay spectra, compared to the discrete nature of α and γ radioactive processes. This feature of the β-decay was so odd in the early days of quantum theory, that even the energy conservation law was questioned by well known physicists of that time. Even though this particular property of the β-decay is fully understood after 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 can give more or less 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 that follow the β-decay transition.

Nuclear structure from β-decay studies. Considering that β-decay is the process that governs the transmutation of most of the nuclear species, it is clear the importance of a full understanding of the physics which lies underneath. Beta decay studies can reveal information about the beta-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 from the theoretical point of view 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. Therefore, a good and complete description of the ground state of the parent nucleus ($|i>$) and of the states populated in the daughter nucleus ($|f>$) provide, in principle, a good value for the GT strength

$$B_{GT} = g_A^2/g_V^2 \ |<f||\sigma.\tau||i>|^2 ,$$

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

The apparent simplicity from the theoretical point of view meets difficulties on the experimental side. The B_{GT} of an individual level is determined from the balance of the gamma feeding and de-exiting the level. Common in such investigations is the use of semiconductor detectors to measure the gamma-ray intensities. Two main factors contribute to make such measurements difficult : a) fragmentation of gamma intensity and b) the primary gamma-rays are usually of high energy. Therefore, much of the GT feeding at high excitation energy is not observed and then it is incorrectly assigned to low-lying levels. This leads to a large and systematic error in the total B_{GT} and in the B_{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 [1, 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 of the individual γ-rays, we will have sum peaks corresponding to the energy of the γ cascades that follow the β-decay, and this gives direct 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 material make the TAGS an ideally suited device for the measurement of the GT strength [3, 4, 5, 6] (see Fig. 1 for an schematic view).

Even though the application of the TAGS technique dates back to the work of Duke *et al.* [1], the first steps faced several limitations due to the available sizes of the crystals and to the unavailability of well funded methods of analysis. The problem arises from the impossibility of building (or having) a 100% efficient TAGS. An ideal device will 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 spectra (the measured spectra is proportional to the β-feeding). But a real TAGS will always have an efficiency less than 100%, and this means that we can have 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 in first place, it is necessary to calculate the response function of the detector to all imaginable cascades and after this, it is necessary to solve the so called "inverse problem":

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

Where **d** represents the measured data, **R** is the response matrix of the detector, which depends on the branching ratios (**B**) of the levels in the daughter nucleus and **f** is the feeding distribution we wish to determine. This problem is apparently impossible to solve. To find a solution one may need information on the level scheme of the daughter nucleus up to high excitation energy (Q_β window) which may not be available. But the larger the crystal, (and today is possible to build larger crystals than 30 years ago), the bigger the efficiency, and less is the dependence of the results on the level scheme. Another point is that nowadays, algorithms to solve the above stated inverse problem exist, and we have the computing power necessary to solve them. Putting all this factors together, nowadays the TAGS technique is a plausible way to obtain reliable experimental information on the B_{GT}, as it was shown in refs. [3, 4, 5, 6].

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 particularly suited to study with 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 [7]. For heavy nuclei, the experimental information is more sparse due to the difficulty of accessing nuclei with allowed decays.

Here, as an example of the potentiality of the method, we present some results obtained by our group using the TAGS technique 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 the study of 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 outside the beta-window in general and our measurements are limited to the energy range covered by the Q_β window. There are only two areas where the $\sigma\tau$ resonance is accessible in β-decay. In both of these areas a proton in a high J orbital decays into its spin-orbit partner neutron orbital with J-1, which is in general less bound than the J neutron orbital and therefore empty. The nuclei we refer 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 it was pointed out, 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 to study nuclei in the rare earth region (^{148}Tb, ^{150}Ho) [3, 4, 5] as well as nuclei in the neighborhood of ^{100}Sn (^{97}Ag,^{98}Ag) [6] (see Fig. 2). In the following we will mainly concentrate in 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. First, representing the state of art of the high resolution γ detection, it will give the best results that can be achieved using this technique. Secondly, it will give a more complete knowledge of the level scheme to be used lately 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. In the particular case of the ^{150}Ho 2^- decay ~ 900 γ-rays where identified and a level scheme of ~ 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 by the Valencia group [3] including the determination of the response function of a large NaI(Tl) crystal and pulse pile-up correction [8]. The response matrix (**R**) of the detector was calculated using Monte Carlo simulation. For that, the GEANT3 MC library was used [9], because it has a powerful geometry package which allows the implementation of the apparatus with the required detail. To solve the inverse problem three different algorithms were used, which give essentially the same results: 1)Linear Regularization Method [10] 2)Iterative Maximum Entropy Method [11] and 3)Bayesian Iterative Method [12]. In [3] it was also shown that due to the relative high efficiency of the GSI TAGS detector the results of the analysis were not so sensitive to the prior knowledge of the level scheme.

Figure 3. shows the results obtained with both experimental methods in the study of the ^{150}Ho 2^- decay. The solid line represents the results obtained with the CLUSTER CUBE and the dashed line the results obtained from the analysis of the TAGS data. *They show for the very first time the observation of a large GT resonance in β-decay studies, hidden until now by experimental limitations.* The comparison of the two results demonstrate the correctness of the analysis method for the TAGS 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 TAGS analysis gives 70% more strength than the data from the CLUSTER CUBE.

In a very simple picture, the ^{150}Ho 2^- isomer can be interpreted as a $(\pi d_{3/2}\nu f_{7/2})_{2^-}(\pi^2)_{0^+}$ state. Thus, the only allowed Gamow-Teller decay occurs when the pair of protons occupy the $\pi h_{11/2}$ orbital $((\pi h_{11/2})_{0^+} \rightarrow (\pi h_{11/2}\nu g_{9/2})_{1^+})$. The resulting decay will populate 4 quasiparticle states ($(\pi d_{3/2}\nu f_{7/2})_{2^-}(\pi h_{11/2}\nu g_{9/2})_{1^+}$) at approx. 4 times the pairing gap (4-5 MeV excitation). This extremely simple interpretation gives a qualitative picture of the decay, but is not able to quantitatively reproduce the value of the strength. The experimental value correspond to a transition which is six times slower than an hypothetical case when there are two protons in the $\pi h_{11/2}$ orbital and the $\nu g_{9/2}$ orbital is empty. Since it is not possible to perform full shell model calculations in this region one has to be satisfied with less. First order corrections to this extreme single particle picture were performed by Towner [13]. The results of the comparison are presented in Fig. 4. In this figure results of the analysis of the TAGS technique are presented for the ^{150}Ho 2^-, 9^+ decay [3], and the recently obtained data on ^{148}Tb 9^+.

Figure 4. shows that even with the corrections of Towner the discrepancy between theory and experiment remains. We believe that the experimental results obtained using the TAGS technique are more reliable that the ones obtained in the past, so an appeal is made to study this problem more deeply from the theoretical side.

Present and future studies. It will be interesting to check if the trend of the experimental points in Fig. 4 follow the pattern of the Towner predictions. This may show that an overall scaling factor is necessary to interpret the experimental results. We expect to answer this question soon. We have an accepted experiment, to be performed in the 2001 summer at the GSI, aimed to study this problem [14].

But not only the "quenching problem" can be addressed using this method. Other questions that require precise measurements of the β strength can be studied with this technique. With this hope in mind a new TAGS have been recently installed at the PSB ISOLDE Mass Separator (CERN) facility. The crystal, constructed by "St. Gobain Crystals and Detectors", is one of the largest NaI(Tl) crystals ever built. The setup will allow the study of β-decay processes of more exotic nuclear species (with very short lifetimes).

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 [15], 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 mother nucleus. Further theoretical studies, which take into account deformation and pairing [16], show that the GT process is expected to bring in 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].

In the same mass region, extensive calculations are currently being carried out by P. Sarriguren and collaborators, using the self consistent HF plus RPA method with different types of Skyrme interaction, stressing the effect of deformation, residual interactions, pairing and RPA correlations on the GT strength distributions [18]. From these studies it is clear that the strength is clearly shifted to higher excitation energy when small mixing of multiparticle-multihole excitations are taken into account. This effect should be amenable to experimental confirmation.

Taking into account the importance of the theoretical investigations and the limitations encountered on the experimental side with the use of conventional techniques , it is of the highest interest to obtain reliable GT strengths in this mass region. For that reason it has been proposed to use the TAGS technique to study the B_{GT} distributions in the decay of a number of Kr and Sr isotopes in the N=Z neutron deficient mass region [19].

We are also working on the improvement of the analysis techniques. From the experience obtained in the work of Cano-Ott *et al.* [3], 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. We are now testing the possibility of using a new version of the Monte Carlo code, GEANT4 [20], which have an improved treatment of the low energy electro-magnetic processes (see Fig. 5) in order to solve this problem.

As a conclusion it is possible to say that nowadays the total absorption technique can be used as a reliable method for the determination of the B_{GT} 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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Fig. 1. Schematic view of a β-decay process as it is seen by different detectors. A proton(neutron) in the parent nucleus decays into a neutron(proton) leading to a daughter nucleus with a different Z. In the decay process a neutrino(anti-neutrino) and a β particle is emitted. The detection of the β particles using a particle detector (Si(Li)) results in a continuous spectra which is very difficult to interpret in case than more than one final state is possible. In case that the state fed by the β-decay is an excited state of the daughter nucleus, it will further decay electro-magnetically by the emission of γ-rays. These γ-rays can be measured using a high resolution gamma detector (Ge detector). From the intensity balance of the γ-rays the energy of the excited state can be deduced. In this particular case $I_{\gamma_1} \sim I_{\gamma_2}$, showing that the decay occurs at a level situated at an excitation of $E_{\gamma_1} + E_{\gamma_2}$. The lowest spectra shows the same decay as it is seen by an ideal TAGS detector.

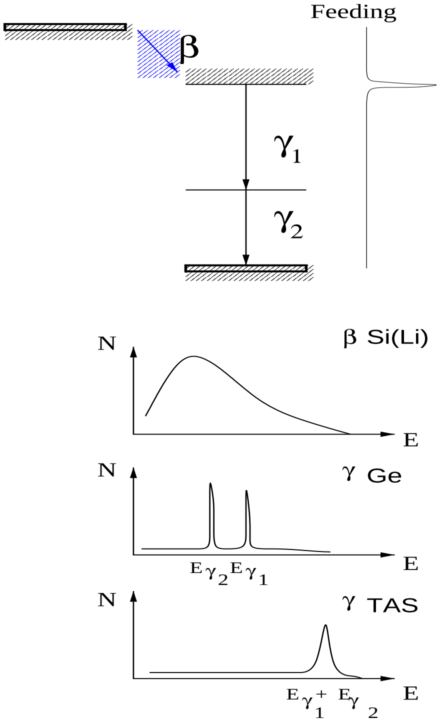


Fig. 2. The two different experimental setups used in the GSI experiments. Right: cube of 6 Cluster detectors. Left: Total Absorption Spectrometer and its ancillary detectors.

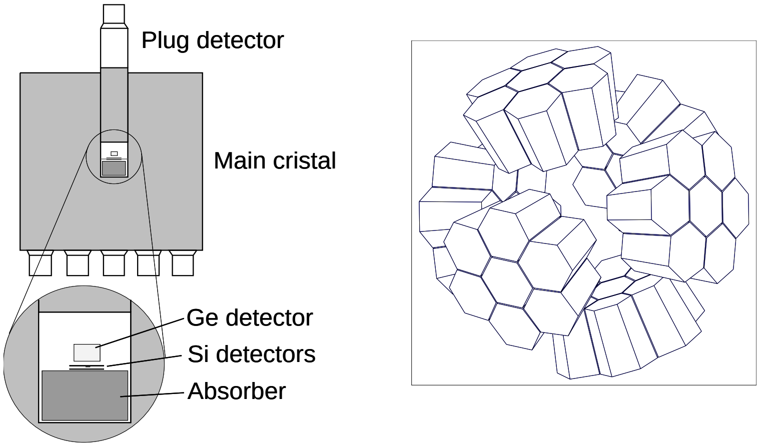
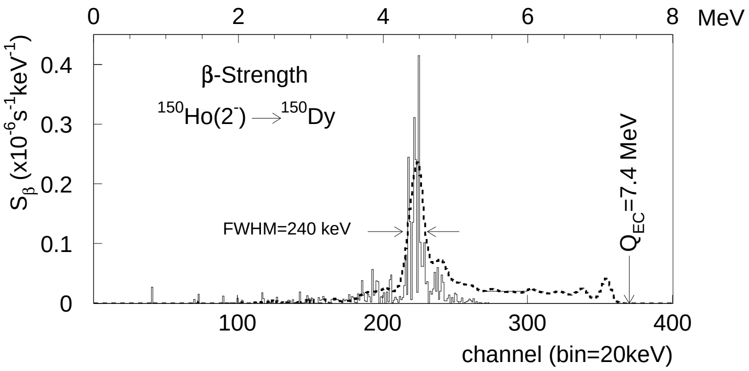


Fig. 3. The TAS (dashed line) and CLUSTER CUBE (solid line) results.



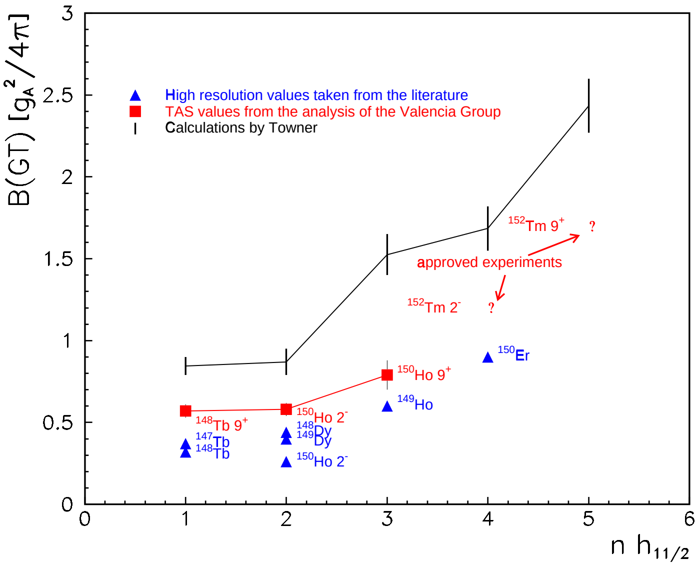


Fig. 4. Comparison of the B_{GT} as a function of the number of protons in the $h_{11/2}$ orbital. The theoretical values (horizontal lines) are taken from the work of Towner [13]. They include correction factors (hindrance) in the extreme single particle approximation due to pairing, core-polarization and high order effects. Triangles represent values coming from various high resolution experiments (see [3] for details). Squares represent the data obtained from the analysis of the TAGS data.

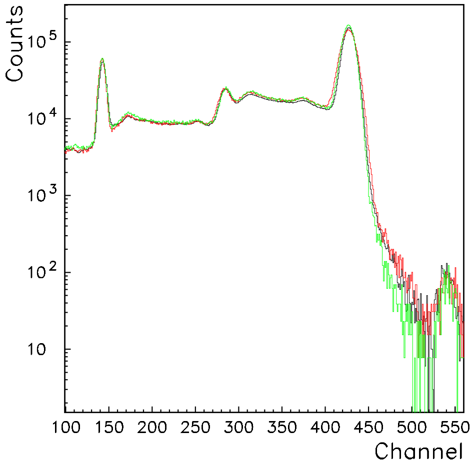


Fig. 5. Comparison of the results of a simulation of the decay of ^{24}Na using GEANT3 (green), GEANT4 (red) with a measurement of the source (black) using the GSI TAGS. The results obtained with GEANT4 reproduces better the last part of the spectra, which is due to the better treatment of the penetration of the β particles in the crystal