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# Beta-decay studies using total absorption techniques: some recent results

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Beta-decay experiments are a primary source of information for nuclear structure studies and at the same time complementary to in-beam investigations far from stability. Although both types of experiment are mainly based on $\gamma$-ray spectroscopy, they face different experimental problems. The so called *Pandemonium effect* [1] is a critical problem in $\beta$-decay. 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 spectrometers TAS at GSI and *Lucrecia* recently installed at CERN.

*Keywords:* Beta decay; total absorption technique.

Lejos del valle de la estabilidad, los procesos de desintegración beta constituyen una fuente de información fundamental en estudios de estructura nuclear y al mismo tiempo son complementarios a los estudios "in-beam". A pesar de que ambos tipos de experimentos estan basados en técnicas de la espectroscopía gamma, son diferentes los problemas experimentales a los que ambos tipos de experimentos se enfrentan. El llamado *Efecto Pandemonio* [1] es un problema crítico en estudios de la desintegración beta. En esta contribución presentaremos una solución a este problema, por medio del uso de la técnica de absorción total. Tambien presentaremos algunos ejemplos de experimentos realizados con los espectrómetros TAS en el GSI, y *Lucrecia*, recientemente instalado en el CERN.

*Descriptores:* Desintegración beta; técnica de absorción total.

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## 1. Introduction

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. From a historical point of view the quest for understanding $\beta$ decay is a long record of fascinating puzzles. Most difficulties related to the understanding of this process arise from the continuous nature of the $\beta$-decay spectra, compared to the discrete nature of $\alpha$- and $\gamma$- radioactive processes. Even though this particular property of the $\beta$ decay is fully understood after the pioneering work of Pauli and Fermi, the continuous nature of the $\beta$-decay spectra remains the primary source of experimental difficulties when $\beta$ decay is used as a probe to study nuclear structure. Contrary to $\alpha$ and $\gamma$ 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 $\beta$ decay. The information on the decay probability in $\beta$ decay is usually deduced indirectly from measurements of the intensity balance of $\gamma$ rays that follow the $\beta$-decay transition.

## 2. Nuclear structure from $\beta$-decay studies

Our primary interest is to know the probability of the decay from the ground state (or an isomer state) of the parent nucleus to a particular level in the daughter nucleus. This probability carries information on the spins, parities and wavefunctions of the 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 $\tau$ operator in the case of Fermi (F) decay (the $\tau$ operator is the isospin lowering or rising operator and $\sigma$ is the usual Pauli spin operator). In the particular case of the GT decay for example, 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

$$B(GT) = g_A^2/g_V^2 |\langle f||\sigma\tau||i\rangle|^2, \quad (1)$$

and of the distribution of the GT strength over the excitation energy range of the $Q_\beta$ window.

What is apparently simple becomes a difficult experimental problem in particular situations. Experimentally the relevant quantity is the strength function

$$S_\beta(E) = \frac{I_\beta(E)}{f(Q_\beta - E)T_{1/2}}, \quad (2)$$

where $I_\beta(E)$ is the $\beta$ feeding, $f$ is the Fermi integral, $T_{1/2}$ is the half life of the parent and $E$ is the excitation energy in the daughter. The strength function is related to the $B(GT)$ in the following way

$$S_\beta = \frac{1}{6147_7}\left(\frac{g_A}{g_V}\right)^2 \sum_{E_f \in \Delta E} \frac{1}{\Delta E} B(GT)_{i\rightarrow f}. \quad (3)$$

Since we can not extract information on the fed level in the daughter nucleus directly from the measured $\beta$ spectrum, the probability of the $\beta$ decay to an individual level in the daughter is determined from the balance of the gamma feeding and de-exitation. Common in such investigations is the use of Ge detectors to measure the $\gamma$-ray intensities. There are situations in which such measurements become difficult. These are cases where:

a) there is large fragmentation of the $\gamma$ intensity and
b) the primary $\gamma$ rays that follow the $\beta$ decay are of high energy.

Therefore, much of the feeding at high excitation energy in the daughter nucleus 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 $\beta$ population of the nuclear levels rather than to the individual $\gamma$ rays [2, 3]. A TAGS can be constructed using a large scintillator crystal which covers $4\pi$ in solid angle relative to the source. The sensitivity to the $\beta$ population in such a device is achieved by its high efficiency to detect $\gamma$ cascades that follow the $\beta$ decay. So, instead of detecting peaks of the individual $\gamma$ rays, we will detect sum peaks corresponding to the energy of the $\gamma$ cascades that follow the $\beta$ decay, and this gives direct information on the levels fed in the decay. The high efficiency of the NaI(Tl), as well as its reasonable energy resolution make a TAGS built with this material an ideally suited device for the measurement of the GT strength [4–8] (see Fig. 1 for a schematic view).

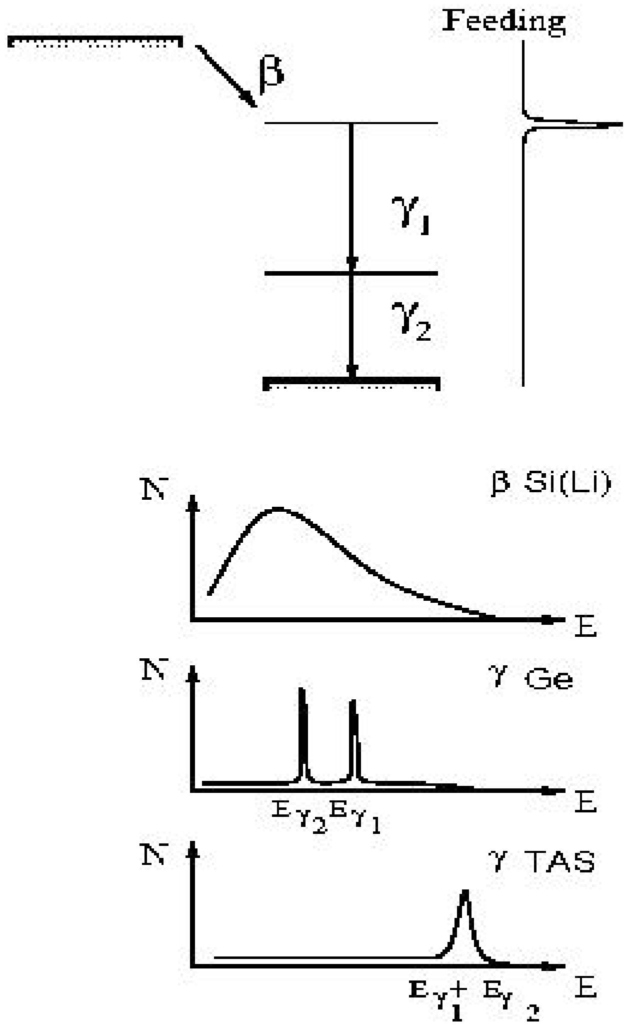


FIGURE 1. Schematic view of a $\beta$-decay process as it is seen by different detectors. A proton(neutron) in the parent nucleus decays into a neutron(proton) leading to a daughter nucleus with a different Z. In the decay process a neutrino(anti-neutrino) and a $\beta$ particle is emitted. The detection of the $\beta$ 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. If the state fed by the $\beta$ decay is an excited state of the daughter nucleus, it will further decay electro-magnetically by the emission of $\gamma$ rays. These $\gamma$ rays can be measured using high resolution gamma detectors (Ge detectors). From the intensity balance of the $\gamma$ rays the $\beta$ feeding can in principle be deduced. In this schematic case $I_{\gamma_1} \sim I_{\gamma_2}$, which shows 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.

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 available sizes of the crystals and to the unavailability of well funded methods of analysis. The problem arises from the impossibility of building 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 $\beta$ feeding can be extracted directly from the measured spectrum (the measured spectrum is proportional to the $\beta$ 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 $\gamma$-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 gamma cascades and after this, it is necessary to solve the so called "inverse problem"

$$d = R(B).f, \tag{4}$$

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 ($Q_\beta$ window) which may not be available. But the larger the crystal, the bigger the efficiency, and less is the dependence of the results of the analysis on the knowledge of 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 reliable way to obtain experimental information on the $B(GT)$, as it was shown in Refs. 4 to 8.

## 3. Physics motivations and some performed studies

As an example of the potential of the method, we first present some results obtained by the GSI TAS collaboration using the TAGS technique in studies of heavy nuclei. Above the heaviest N$\sim$Z particle stable nuclei there are mainly two areas where the $\sigma\tau$ resonance is accessible in $\beta$ decay . This is because the required orbitals for allowed decay lie outside the $Q_\beta$ window in general and our measurements are limited to the energy range covered by the $Q_\beta$ window. In both 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. In particular the nuclei we refer to are the ones below $^{100}$Sn and above $^{146}$Gd. One important remark is that in comparison with charge-exchange reactions, results obtained from $\beta$-decay studies are reaction model independent and are free from background uncertainties. In addition they allow the study of exotic nuclei far from stability presently not accessible in charge exchange reactions.

In the experiments at GSI we have used the total absorption technique explained above and, as an alternative method, an array of closely packed Ge detectors (CLUSTER CUBE) with very good resolution and efficiency (see Fig. 2). These experiments were performed at the GSI On-line Mass-separator. They aimed at study nuclei in the rare earth region ($^{148}$Tb, $^{150}$Ho, $^{152}$Tm) [4–7] as well as nuclei in the neighborhood of $^{100}$Sn (see for instance $^{97}$Ag,$^{98}$Ag ) [8]. 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 the art of the high resolution $\gamma$ 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 of the daughter nucleus to be used lately to test the analysis technique for the TAGS data.

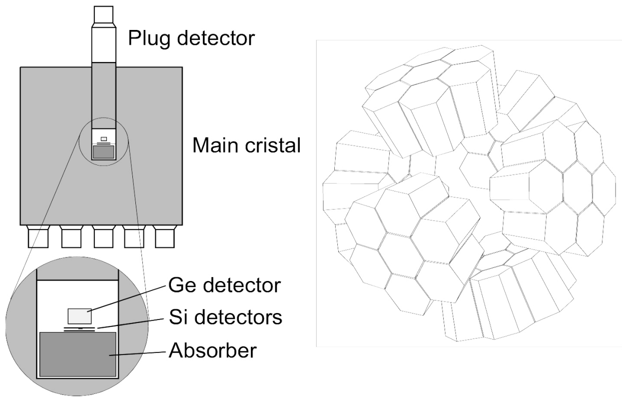


FIGURE 2. The two different experimental setups used in the GSI experiments. Right: cube of 6 cluster detectors (CLUSTER CUBE). Left: schematic view of the GSI Total Absorption Spectrometer and its ancillary detectors.

The analysis of the CLUSTER CUBE data was performed using the conventional methods of $\gamma$ spectroscopy. In the particular case of the $^{150}$Ho $2^-$ decay, 1064 $\gamma$-rays were identified and a level scheme of 295 levels was constructed [9]. 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 traditional techniques (before our measurements only 5 levels were known to be fed in the $\beta$ decay of the $2^-$ isomer based on an experiment using conventional Ge detectors). The analysis of the TAGS experiment was carried out using the methods of analysis established by the Valencia group [4] including the determination of the response function of a large NaI(Tl) crystal and pulse pile-up correction [10]. The response matrix $R$ of the detector was calculated using Monte Carlo simulation. The GEANT3 MC library was used [11] 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 gave essentially the same results:

1) Linear Regularization Method [12]

2) Iterative Maximum Entropy Method [13] and

3) Bayesian Iterative Method [14].

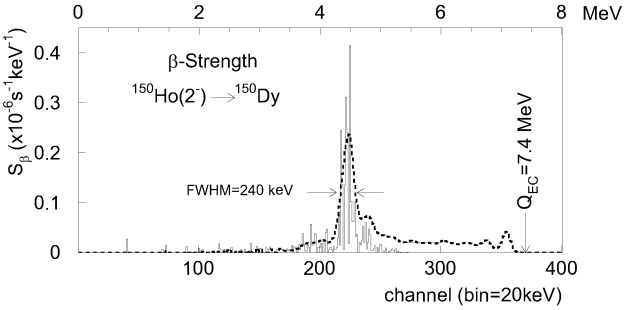


FIGURE 3. The TAS (dashed line) and CLUSTER CUBE (solid line) results [4, 9].

In Ref. 4 it was also shown that due to the relative high efficiency of the GSI TAS detector the results of the analysis were not so sensitive to the prior knowledge of the level scheme of the daughter nucleus.

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 [9] and the dashed line the results obtained from the analysis of the TAGS data [4]. Both methods show the existence of a large GT resonance at $\sim$ 4.4 MeV excitation energy. 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. Even using the most powerful detectors available, $\beta$ feeding at high excitation energy ($>$ 5.9 MeV) in the daughter nucleus remains undetected . The same facts in numbers: the TAGS analysis gives 116% more $B(GT)$ 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 $\beta^+$ Gamow-Teller decay occurs by transformation of one of the protons occupying the $\pi h_{11/2}$ orbital $((\pi h^2_{11/2})_{0^+}\rightarrow(\pi h_{11/2}\nu g_{9/2})_{1^+})$. 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 approximately 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. Since it is not possible to perform full shell model calculations in this region one has to be satisfied with much simpler calculations. Shell model calculations using experimental two-body interactions were performed in a restricted model space. These calculations reproduce the position of the resonance with an accuracy of $\sim$ 75 keV and confirm the interpretation of the resonance as $(\pi d_{3/2}\nu f_{7/2})_{2^-}(\pi h_{11/2}\nu g_{9/2})_{1^+})$ states [9].

## 4. More recent results and future studies

Other questions that require precise measurements of the $\beta$ strength can also be studied with the total absorption technique. Inspired by the results described above and by the possibility of addressing other problems of physical interest (see for example [15]), a new TAS called *Lucrecia* has 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 geometry of this new setup opens the possibility to study $\beta$-decay processes of more exotic nuclear species (with very short lifetimes) since it is possible to collect the radioactive sources directly in the centre of the crystal.

An important question that can be addressed 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 N$\sim$Z nuclei in the mass region A$\sim$70 which have been the subject of numerous theoretical and experimental investigations to answer questions about nuclear deformation, shape coexistence, shape transitions, np pairing and isospin mixing. I. Hamamoto showed, that close to the drip lines, the main strength of the GT resonance might be located below the ground state of the parent nucleus [16]. Other theoretical studies, which take into account deformation and pairing [17], 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 [18]. In the same mass region, extensive calculations have been carried out by P. Sarriguren and collaborators, using the self consistent Hartree-Fock (HF) plus

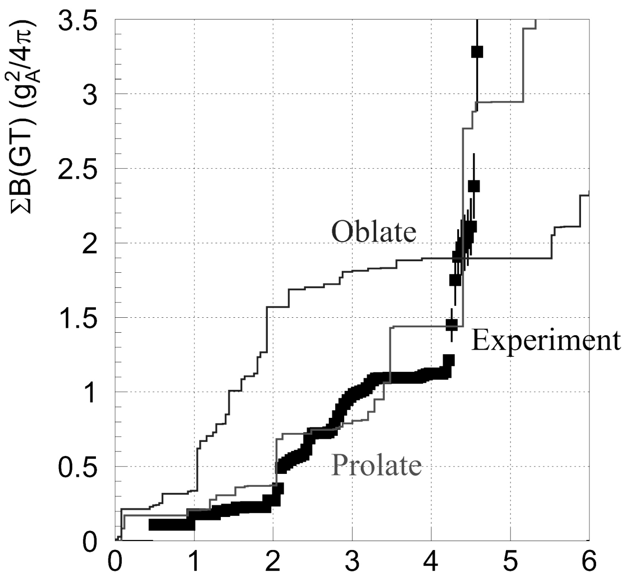


FIGURE 4. Accumulated Gamow-Teller strength as a function of excitation energy in the daughter nucleus ($^{76}$Rb). The experimental results are compared with theoretical calculations [19] (Hartree-Fock - BCS - QRPA with density dependent Skyrme force) assuming prolate and oblate shapes for the parent $^{76}$Sr ground state [23].

Random Phase Approximation (RPA) method with different types of Skyrme interaction, stressing the effect of deformation, residual interactions, pairing and RPA correlations on the GT strength distributions [19].

Considering the particular interest from the theoretical point of view and the limitations encountered on the experimental side with the use of conventional techniques, high priority was given to obtain reliable GT strengths in this mass region. For that reason it was 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 [20] and a series of experiments were performed using the new TAGS *Lucrecia* at the PSB ISOLDE Mass Separator (CERN) facility. The analysis of two cases have been recently finished ($^{74}$Kr and $^{76}$Sr decays). In the $^{74}$Kr case the results of the analysis show that the accumulated $B(GT)$ distribution is inconsistent with either the prolate or with the oblate theoretical results [21] confirming the earlier experimental evidence of shape coexistence [22]. The results of the accumulated $B(GT)$ distribution for $^{76}$Sr are presented in Fig. 4 [23]. In this case the analysis confirms earlier indication of strong deformation in the ground state of $^{76}$Sr [24]. This validate the application of this novel method to infer the ground state deformation of a parent nucleus from the distribution of the beta strength in the daughter, since the $^{76}$Sr ground state is a very clean case, free of shape admixtures.

Up to now we have discussed only $\beta^+$ decays, but of course there are also cases of interest in the $\beta^-$ side that can be studied using the TAGS technique. Nuclei of astrophysical interest can be measured with this method. Another problem well suited to be studied with this technique is the measurement of $\beta$-decay processes of nuclei important for the safe operation of nuclear reactors. It is well known that approximately 13% of the released energy in neutron induced fission comes from the beta decay of the fission products. This source of energy continues and becomes the dominant component after the reactor shutdown. The evaluation of this component is commonly known as reactor heat calculations. The decay heat varies as a function of cooling time, and can be determined from known nuclear data. If the nuclear data available is not properly measured, the estimation of the reactor heat is not correct. We plan to perform some experiments using the TAGS technique to measure neutron rich nuclei of interest in this framework.

Some improvements have been also obtained recently in the analysis techniques. From the experience obtained in the work of Cano-Ott *et al.* [4], it was deduced that the GEANT3 code is not able to reproduce accurately the penetration of the $\beta$ 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 $Q_\beta$ value. The new versions of the Monte Carlo code, GEANT4 [25] has been tested with encouraging results. This code has an improved treatment of the low energy electro-magnetic processes which may be relevant to handle 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 $\beta$-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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1. J.C. Hardy, L.C. Carraz, B. Jonson, and P.G. Hansen, *Phys. Letts B* **71** (1977) 307.
2. C.L. Duke *et al.*, *Nucl. Phys. A* **151** (1970) 609.
3. M. Karny *et al.*, *Nucl. Inst. Meth. B* **126** (1997) 411, and references therein.
4. D. Cano-Ott, PhD Thesis (University of Valencia 2000); J.L. Tain and D. Cano-Ott unpublished.
5. J. Agramunt *et al.*, *Int. Symp. on New Facets of Spin Giant Resonances in Nuclei* (World Scientific, 1998) p. 150; M. Karny *et al.*, *Nucl. Phys. A* **640** (1998) 3; M. Karny *et al.*, *Nucl. Phys.* in print.
6. A. Algora *et al.*, *Nucl. Phys. A* **654** (1999) 727c.
7. B. Rubio, *Proceedings of the Int. Symp. on Frontiers of Collective Motions (CM2002)* (World Scientific, 2003) p. 102.
8. Z. Hu *et al.*, *Phys. Rev. C* **60** (1999) 4315; Z. Hu *et al.*, *Phys. Rev. C* **62** (2000) 6431.
9. A. Algora *et al.*, *Phys. Rev. C* **68** (2003) 034301.
10. D. Cano-Ott *et al.*, *Nucl. Instr. and Meth. A* **430** (1999) 488; D. Cano-Ott *et al.*, *Nucl. Instr. and Meth. A* **430** (1999) 333.
11. R. Brun *et al.*, *GEANT 3 User's Guide (CERN DD/EE/84-1)*, and ref. therein.
12. A.N. Tykhonov and V.Y. Arsenin, *Solutions to Ill-Posed Problems* (Willey, New York, 1977).
13. D.M. Collins, *Nature* **298** (1982) 49.
14. G. D'Agostini, *Nucl. Inst. Meth. A* **362** (1995) 487.
15. Ch. Miehé *et al.*, *Proc. of the 2nd Int. Conf. on Exotic Nuclei and Atomic Masses* (Shanty Creek Resort, Bellaire, Michigan, USA, 23-27 June 1998)
16. I. Hamamoto and H. Sagawa, *Phys. Rev. C* **48** (1993) 2960.

17. I. Hamamoto and X.Z. Zhang, *Z. Phys. A* **353** (1995) 145; F. Frisk *et al.*, *Phys. Rev. C* **52** (1995) 2468.

18. W. Gelletly, *et al.*, *Phys. Lett. B* **253** (1991) 287; P. Lievens *et al.*, Cern report CERN-PPE/95-160.

19. P. Sarriguren *et al.*, *Nucl. Phys. A* **635** (1998) 55; P. Sarriguren *et al.*, *Nucl. Phys. A* **658** (1999) 13; P. Sarriguren, private communication.

20. ISOLDE Proposals IS370, IS377 (spokesperson: P. Dessagne and B. Rubio).

21. E. Poirier, PhD thesis (Strasbourg, 2003); E. Poirier *et al.*, *Phys. Rev.* **69** (2004) 034307.

22. C. Chandler *et al.*, *Phys. Rev. C* **56** (1997) R2924; F. Becker *et al.*, *Eur. Phys J. A* **4** (1999) 103; F. Becker *et al.*, *Phys. Scr. T* **88** (2000) 17.

23. E. Nácher, PhD thesis (Valencia); E. Nácher *et al. Phys. Rev. Lett.* **92** (2004) 232501

24. C.J. Lister *et al.*, *Phys. Rev. C* **42** (1990) R1191.

25. GEANT4 User's Guide, GEANT4 Collaboration.