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Decay properties of N $\simeq$ Z nuclei

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Abstract. This review focusses on recent results obtained by using fusion-evaporation reactions for the production of $N \simeq Z$ nuclei, the on-line mass separator of GSI for the preparation of the radioactive samples, and charged-particle and γ-ray detectors for performing decay spectroscopy. The experimental results on prompt and β-delayed disintegration modes are discussed in comparison with theoretical model predictions.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.40.-s Beta decay; double beta decay; electron and muon capture

1 Introduction

The remarkable progress in experimental and theoretical investigations of $N \simeq Z$ nuclei, achieved in recent years, has been motivated by a multidisciplinary interest. The disciplines involved are i) nuclear-structure physics, in particular effects related to the vicinity of the proton dripline and to the occupation of identical orbits by neutrons and protons (see, *e.g.*, [1,2]), ii) fundamental physics, *e.g.*, tests of the standard model of weak interaction by precision measurements of super-allowed $0^+ \rightarrow 0^+\beta$-decays [3], and iii) astrophysics, concerning, *e.g.*, the electron capture (EC) cooling of supernovae [4,5] or the astrophysical rp-process [6]. The broad scientific interest in these research fields can also be seen from the large number of related contributions to this conference.

In recent years, decays of $N \sim Z$ nuclei have in particular been studied at ISOLDE/CERN, GANIL and GSI. The present report deals with work performed in the latter laboratory, where two major facilities are available for such investigations, *i.e.* the projectile-fragment separator (FRS) and the isotope separator on-line (ISOL). At the FRS, fragmentation reactions induced by relativistic beams from the heavy-ion synchrotron SIS are used. However, only a few experiments $N \simeq Z$ nuclei have been carried out so far (see, *e.g.*, [7]). It is the research programme of ISOL, and in particular the recent decay studies of between the double shell closures at ^{56}Ni and ^{100}Sn, which form the focus of the present overview.

The paper is structured as follows: After a presentation of the techniques used at ISOL, recent experimental results will be discussed for direct charged-particle decay and for β-decay; finally, a summary and an outlook will be given. A detailed discussion of the nuclear-physics aspects of these results, their relation to the corresponding work performed in other laboratories as well as of their relevance to fundamental physics and astrophysics, cannot be given within the scope of this report but can be found in the references cited throughout the text.

2 Experimental techniques

At the ISOL, heavy-ion–induced fusion-evaporation reactions between ^{32}S, ^{36}Ar, ^{40}Ca or ^{58}Ni beams and ^{28}Si, ^{40}Ca, ^{50,52}Cr or ^{58,60}Ni targets were exploited. Chemically selective FEBIAD [8,9] or TIS [10] ion sources were used to produce mass-separated beams of neutron-deficient iron-to-barium isotopes as singly charged atomic or molecular ions. The 55 keV ISOL beams, whose intensities ranged from 5 atoms/min for ^{57}Zn to 1200 atoms/s for ^{60}Ga, were implanted either in a thin carbon foil or in a tape that transported the activity to (or away from) the various detector arrays.

"Direct" (Coulomb-delayed) or β-delayed protons and α-particles are measured by means of ΔE-E telescopes consisting of a thin gas or silicon (Si) ΔE detector and a thick Si E detector. The former records the energy loss of β-delayed charged particles, whereas the latter measures their rest energy. Coulomb-delayed protons or α-particles are stopped in the thin detector, with positrons being recorded in the thick detector to derive an anti-coincidence condition and to thus suppress energy loss events of β-delayed particles.

The *high-resolution* spectroscopy of β-delayed γ-rays emitted from the mass-separated sources is accomplished by using germanium (Ge) detectors, including those of

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the Euroball-cluster and clover type. An exceptionally efficient high-resolution γ-ray detector was available at ISOL in 1996, *i.e.* a cube-like array of 6 Euroball-cluster detectors (cluster cube) which comprised 42 Ge crystals and had an absolute photo-peak efficiency of 10.2(0.5)% for 1.33 MeV γ-rays [11]. Beta-delayed γ-rays emitted from weak sources are measured in coincidence with positrons recorded in a NE102A plastic-scintillation detector.

As a *low-resolution* but high-efficiency alternative to the γ-ray detectors described above, a total-absorption spectrometer (TAS) is used. The TAS [12] consists of a large NaI crystal surrounding the radioactive source, two small Si detectors above and below the source, and one Ge detector placed above the upper Si detector. By demanding coincidence with signals from the Si detectors, the β^+-decay component for the nucleus of interest is selected, whereas a coincidence condition with characteristic $K_{\alpha,\beta}$ X-rays recorded by the Ge detector can be used to select the EC mode. In this way the *complete* distribution of the β strength can be determined for neutron-deficient isotopes, including in particular high-lying levels of the respective daughter nuclei, and the Q_{EC}-value can be deduced from the ratio between β^+ and EC intensities.

Moreover, the TAS enables one to investigate X-rays related to the emission of conversion electrons (from isomeric transitions), with an optional anti-coincidence condition on signals from the Si detectors and the NaI crystal in order to suppress (room) background. Last but not least, the TAS can also be used to measure β-delayed protons, detected in one of the Si detectors (or a telescope of Si detectors) which are operated in coincidence with positrons, X-rays and/or γ-rays. In this way, one can, *e.g.*, distinguish between β^+ and EC transitions preceding proton emission, determine the (Q_{EC}-S_{p}) value for a selected level of the final nucleus populated by proton transitions, deduce information on the lifetime (and ratio between radiative and proton widths) and of the proton-emitting levels by means of the proton X-ray coincidence technique [13], and use proton-γ coincidence data to identify excited states in the final nucleus [14,15].

In studying the β-decay of heavy nuclei, one ought to keep the "Pandemonium" problem in mind. Pandemonium is a fictitious nucleus which has been introduced by Hardy *et al.* [16] in order to demonstrate the difficulty of performing *complete* high-resolution spectroscopy in the cases of high level density in the daughter nucleus and (correspondingly) broad β strength distribution. This topic lead to heated discussions in the late seventies and early eighties, which evidently have cooled off meanwhile, even though the problem concerning the reliability of the determination of *apparent* β intensities from experimental data definitely needs continuing attention. Concerning the β-decay measurements discussed in this paper, one has to take into account that only the low-energy tail of the Gamow-Teller (GT) resonance can be reached for fp-shell nuclei (see, *e.g.*, the recent ^{58}Ni(^{3}He, t) data [17] for an illustration of the question of high-lying *versus* low-lying GT strength) [17]. In contrast, the GT resonance is expected, on the basis of shell model calculations [18], to lie within the Q-value window for the β-decay of nuclei below ^{100}Sn, which makes such studies particularly interesting.

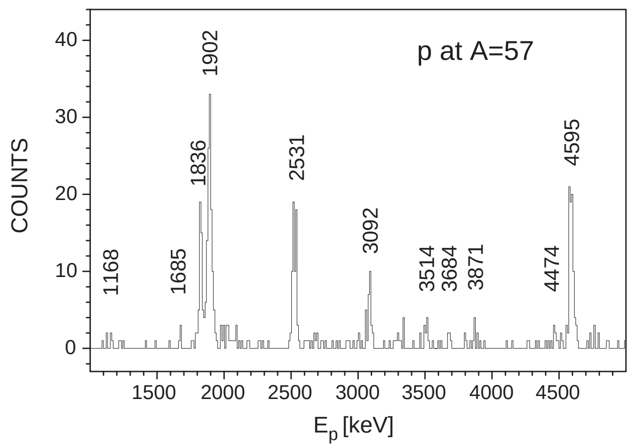

Fig. 1. Energy spectrum of β-delayed protons, measured at mass 57 by operating the E detector of the telescope in coincidence with the related ΔE detector. Intense lines are marked by their proton energies in keV.

3 Results and discussion

3.1 N = Z − 3 ($T_Z = -3/2$) nuclei: ^{57}Zn

By using the ^{28}Si(^{32}S, p2n) reaction and a FEBIAD-E ion source, a mass-separated ^{57}Zn was produced and implanted into the window of the ΔE (gas)-E (Si) telescope. The resulting spectrum of β-delayed protons, accumulated during a measuring time of 42 hours, is displayed in fig. 1 [19]. This result indeed represents an impressive progress, both in energy resolution, counting statistics and background suppression, over the one and only previous measurement of this short-lived ($T_{1/2} = 40(10)$ ms) nucleus [20]. The peaks at 4959 and 1836 keV are assigned to (isospin forbidden) proton emission from the $7/2^-$, $T = 3/2$ isobaric analog state (IAS) of the single-proton nucleus ^{57}Cu to the ground state and 2_1^-, $T = 1/2$ level of ^{56}Ni. The respective intensities might be interpreted within the framework of an isospin-non-conserving interaction. The other proton transitions yield energies of excited ^{57}Cu states and (unfortunately rather inaccurate) apparent β intensities, to be confronted shell model predictions.

3.2 N = Z − 2 ($T_Z = -1$) odd-odd nuclei: ^{56}Cu, ^{60}Ga

A particularly interesting sample of $N \simeq Z$ nuclei is the series of $N = Z-2$ ($T_Z = -1$) odd-odd nuclei in the pf-shell. Within this series, β-decay properties have been studied for ^{40}Sc, ^{44}V, ^{48}Mn, and ^{52}Co, and, more recently, also ^{56}Cu [21,22] and ^{60}Ga [23,24]. ^{60}Ga [25,26] and ^{64}As [25] were observed in fragmentation reactions, which has given evidence that their ground states are probably bound (or weakly unbound) against proton emission, so that β-decay is expected to be the dominant disintegration mode. In the following, the β-delayed proton and γ-ray properties of ^{56}Cu [22] and ^{60}Ga [23] will be presented.

3.2.1 Decay of ^{56}Cu

A recent ISOL experiment [22] succeeded in considerably improving the data from the one and only β-decay measurement of ^{56}Cu [21] available so far. The half-life was determined more accurately to be 93(3) ms, and γ-γ coincidence data were obtained for the first time for this decay. In this way, six new β-delayed γ transitions were observed, and three new ^{56}Ni states identified. The experimental β strengths, determined for five GT transitions, were confronted to large-scale shell model predictions. It was found that the experimental GT strength distribution over ^{56}Ni states from 3.9 to 6.6 MeV qualitatively agrees with these predictions, in particular those performed by using the KBF and KB3G interactions (see [22] for details). This can be considered to be a valuable test of shell model calculations, including their ability to reliably predict the higher-lying GT strength. Furthermore, it was shown that the new experimental data do not imply a revision of the calculated stellar weak-interaction rates of $A = 56$ nuclei.

3.2.2 Decay of ^{60}Ga

By using ^{28}Si(^{36}Ar, 4n) reactions and a FEBIAD-E ion source, it has become possible to measure for the first time the β-delayed proton and γ-ray activity of ^{60}Ga [23]. An intensity of about 20 atoms/min was reached for the mass separated beam of this isotope. In order to confirm the assignment of the decay properties to ^{60}Ga, additional measurements were performed by using a TIS source which yielded a 6 times smaller release efficiency for this isotope but suppressed the isobaric contaminants ^{60}Zn and ^{60}Cu by considerably larger factors. The half-life of ^{60}Ga was measured to be 70(15) ms, in agreement with the result reported in ref. [24]. The preliminary results, obtained from the γ-ray singles and coincidence measurement, are compiled in fig. 2 .

This pilot experiment has yielded several interesting results. First, the excitation energy of the $2^+, T = 1$ IAS in ^{60}Zn has been measured to be 4851.9(5) keV. This result, together with an estimate based on the Coulomb-energy systematics and with the known [27] mass-excess values of ^{59}Zn and ^{60}Zn, yield semi-empirical values of the mass-excess, Q_{EC} and S_{p} data for ^{60}Ga. As the latter value is 40(70) keV and hence compatible with zero, ^{60}Ga can indeed be called a proton dripline nucleus. Second, besides the known 1004 keV 2_1^+ level of ^{60}Zn, a previously unobserved 2559 keV state has been preliminarily assigned to be the 2_2^+ level. As it lies surprisingly high compared to the 2_2^+ state in ^{62}Zn, one may speculate about α-cluster effects above ^{56}Ni. This conclusion is based on the occurrence of a similar discontinuity in $^{20\text{-}22}$Ne, which is the corresponding pair of nuclei above the ^{16}O shell close. Third,

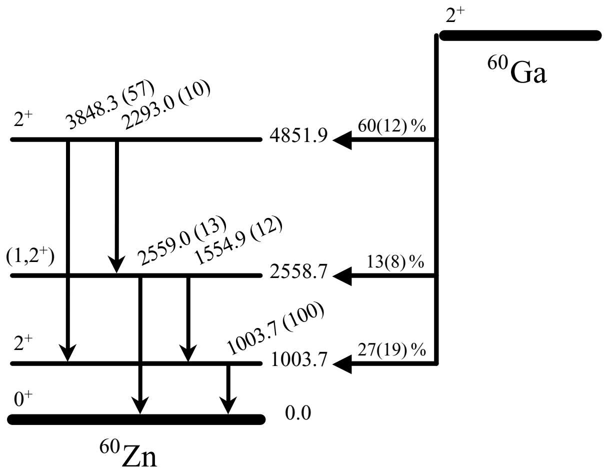

Fig. 2. Beta-decay scheme of ^{60}Ga. The energies (in keV) of the β-delayed γ-rays and of excited ^{60}Zn levels, the intensities of the γ transitions (given within brackets together with the transition energies), and the apparent β intensities (given, together with their experimental uncertainties, in % per decay) are preliminary.

the β intensities, deduced for the ^{60}Ga decay, have large uncertainties (see fig. 2) and can be used for rough tests of GT strengths predictions from shell model calculations, contrary to the quantitative comparison described for the case of ^{56}Cu (see subsubsect. 3.2.1).

3.3 Beta-decay near ^{100}Sn: observation of the Gamow-Teller resonance

As already mentioned in sect. 2, β-decay studies of nuclei below ^{100}Sn offer the chance to observe the entire GT resonance. For this reason, ^{97}Ag [28], a three-proton-hole nucleus with respect to ^{100}Sn, as well as ^{98}Ag [29] and ^{102}In [30] were investigated by using both the TAS and the cluster cube (see sect. 2). The most striking results of these measurements is that the cluster cube, even though being probably the most advanced high-resolution detectors for β-delayed γ-rays available to date, missed a sizeable fraction of the total GT strength detected by the TAS, whereas the TAS is evidently able to “catch” the entire GT resonance and may thus be called a “non-pandemonic instrument” [31]. These observations, which are confirmed for all three nuclei, can be clearly seen from fig. 3 which displays the ^{102}In results. The fact that β intensity was missed by the high-resolution measurement compared to the TAS data follows from the spectra shown in the upper panel of fig. 3. The distribution of the GT strength as a function of the ^{102}Cd excitation energy, deduced from the TAS data, shows a pronounced resonance at an energy around 6 MeV with a width of about 1 MeV. This GT distribution was almost entirely missed by the cluster cube experiment as can be seen from the lower panel of fig. 3. The shape of this GT resonance agrees with that obtained by a shell model calculation which uses the SNB or SNC Hamiltonian [18,28] and a model space consisting of the

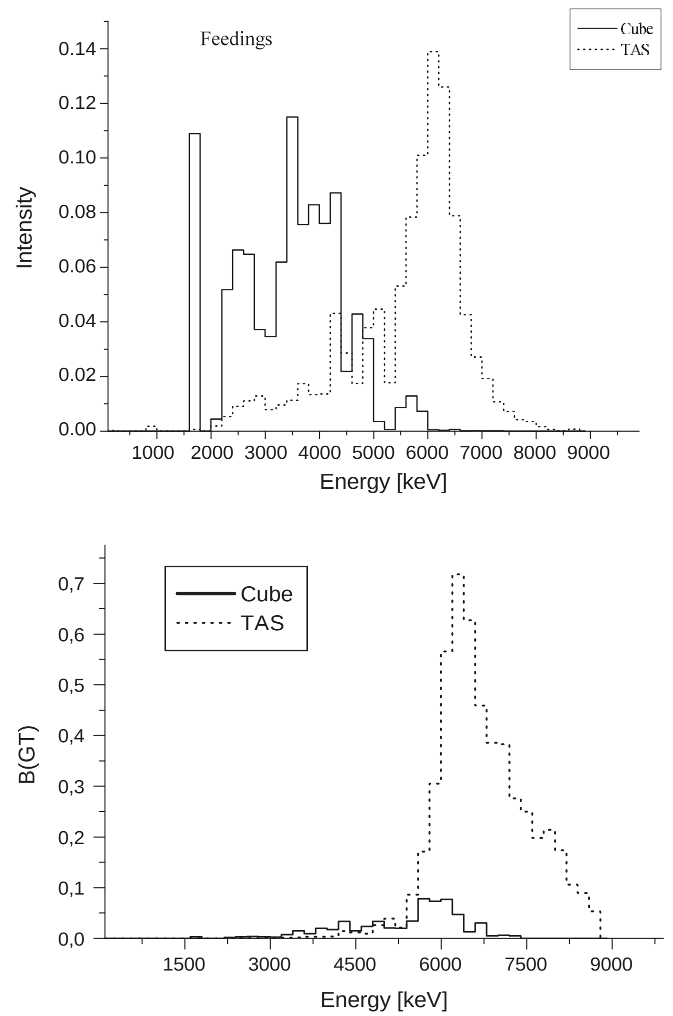

Fig. 3. Beta-decay of ^{102}In. Upper panel: beta-decay intensities as a function of ^{102}Cd excitation energy, as obtained from the TAS (dashed-line histogram) and the cluster cube (solid-line histogram). Lower panel: Gamow-Teller strength as deduced from the TAS data (dashed-line histogram) and from the SNC shell model calculation (solid-line histogram).

active proton orbitals $p_{1/2}$ and $g_{9/2}$ and the active neutron orbitals $g_{7/2}$ and $d_{5/2}$ (larger model spaces have been used for ^{97}Ag and ^{98}Ag). The hindrance factor for the total GT strength, that has to be applied with reference to the shell model value, is qualitatively understood (see [18, 28] for details). Further TAS data have recently been obtained for the chain of indium isotopes from ^{103}In [32] to ^{107}In [33]. These data, together with those for ^{98}Cd [34], ^{97}Ag [28] and ^{98}Ag [29], can now be used to establish for the first time a mass dependence of the GT hindrance factor near ^{100}Sn.

3.3.1 The island of α emission beyond ^{100}Sn

The island of α emission beyond ^{100}Sn was a favorite ISOL topic in the eighties (see, *e.g.*, [35]). More recently, α and cluster emission from ^{114}Ba was searched for, yielding however only upper limits of $3.7 \cdot 10^{-3}$ and $3.4 \cdot 10^{-5}$ for the respective decay branching ratios [36]. (In a related effort, cluster emission from excited states of ^{116}Ba was studied by measuring $^{58}\mathrm{Ni} + {}^{58}\mathrm{Ni}$ reaction cross-sections at ISOL [37].) Recently the decay of ^{114}Ba was re-investigated at the ISOL by implanting the $^{114}\mathrm{Ba}^{19}\mathrm{F}^+$ (mass 133) beam into carbon catchers viewed by detector telescopes. A triplet was observed [38] in the ΔE spectra in coincidence with their related E detectors. The lowest-energy line of the triplet at ~ 3.4 MeV is interpreted as being due to the α-decay of ^{114}Ba, whereas the higher-energy members of the triplet are ascribed to the known [35] α lines of the daughter ^{110}Xe and the grand-daughter ^{106}Te. This result is interesting for the following reasons. First, the increase of the energies along the triple α-chain is a textbook example of experimental evidence for a shell closure. Second, and indeed related to the topic of this conference, by summing the three α-decay Q-values one can deduce, preliminarily again, an experimental Q-value of ~ 19.0 MeV for ^{12}C decay of ^{114}Ba, which is important in order to obtain experimentally relevant predictions from cluster-emission calculations. Third, the analysis of time correlations between ^{114}Ba and ^{110}Xe events will hopefully yield the hitherto unknown half-life of the latter nucleus. This result, together with the previously unknown α-branching ratio of ^{110}Xe, deduced from the intensities of the two lines, can be used to determine the s-wave α width of this nuclide and to thus extend the corresponding systematics towards its low-mass end [39].

4 Summary and outlook

By using heavy-ion induced fusion-evaporation reactions at the ISOL facility of GSI, new and interesting data have been obtained for the β-decays of short-lived $N \sim Z$ nuclei between ^{56}Ni and ^{100}Sn. The results have been interpreted through a comparison with shell model predictions, the topics ranging from B_{GT} values of individual daughter levels, the GT resonance and its quenching all the way to the α-decay chain ^{114}Ba-^{110}Xe-^{106}Te. These investigations are part of an ongoing research programme which includes also the following topics:

– The experimental knowledge on high-spin states in the even-even $N = Z$ nucleus $^{52\mathrm{m}}$Fe [40] is very limited in comparison with neighbouring nuclei. This is due to the occurrence of a 12^+ "yrast-trap" isomer which predominantly decays by positron emission and whose long half-life of 45.9(6) s prevents in-beam measurements from being extended to higher spins. Moreover, the excitation energy of the isomer was poorly known ($E^* = 6820(130)$ keV). In a recent ISOL experiment, the (internal) γ de-excitation of the isomer was observed for the first time, the isomeric energy was measured with higher accuracy ($E^* = 6957.5(4)$ keV), and $B(E4)$ values were determined for the transitions $12^+ \rightarrow 8^+_1$ (597.1(4) keV) and $12^+ \rightarrow 8^+_2$ (465.0(4) keV), which offers a new way of checking shell model (KB3, FPD6 etc.) predictions [41].

– In the first study of the ^{61}Ga decay ($T_{1/2}$ = 140(70) ms) [42], the GT population of four excited ^{61}Zn levels ($I^\pi = 1/2^-$, $3/2^-$ or $5/2^-$) was observed in addition to the dominant Fermi transition to the ^{61}Zn ground state.
– Decay studies of $N = Z - 2$ ($T_Z = 0$) odd-odd nuclei, which are of interest to pave the way to precision experiments of super-allowed $0^+ \to 0^+$ transitions, have been initiated for ^{62}Ga, ^{70}Br [43] and ^{94}Ag [44], including in particular γ-γ coincidence measurements. While the ^{62}Ga [43] data did not allow one to draw definite conclusions concerning non-analog admixtures to the super-allowed decay, preliminary evidence was found for a β-decaying 2.2(3) s isomer in ^{70}Br with a tentative 9^+ assignment [43]. The new ^{94}Ag results [44] confirm the previously found [45] β-decaying high-spin isomer and yield additional information on excited ^{94}Pd levels.
– Beta-delayed γ-rays of the odd-odd nucleus ^{100}In were measured for the first time. The preliminary evaluation [44] of the high-resolution data yielded a half-life of 6.5(2.2) s in agreement with the previous ISOL result of 6.1(9) s, based on β-delayed proton data [46]. The population of the 6_2^+ and 8^+ states in ^{100}Cd, known from in-beam work [47], indicates a tentative spin/parity assignment of 6^+ and/or 7^+ for the β-decaying ^{100}In state(s).

All in all, a wealth of β-decay data has become and will continue to become available for $N \simeq Z$ nuclei between the double closed-shell nuclei ^{56}Ni and ^{100}Sn. Amongst the future ISOL experiments that have been initiated already, there are a TAS β strength measurement of ^{52m}Fe, a precision measurement of the ^{62}Ga half-life, and a search for direct proton decay of ^{105}Sb, to just name a few. It is indeed amazing to see the high data quality that can be obtained for nuclei close to the proton dripline, and it is also encouraging to observe what could be called, at least in the author's judgement, a renaissance in the "interface" between in-beam and decay spectroscopy.

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