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REVIEWING THIRTY YEARS OF RESEARCH AT THE GSI ONLINE MASS SEPARATOR*

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Seven years ago, the GSI Online Mass Separator was decommissioned after 30 years of operation. The Golden Age of Jan Żylicz, celebrated at this Conference, is an adequate occasion to review the research performed at this facility. Its programme reached from nuclear-structure studies based on decay spectroscopy — the focus of this contribution — to investigations of nuclear shapes by means of laser spectroscopy all the way to experiments of astrophysical and fundamental-physics relevance. Reviewing this work I shall present my personal view on, firstly, examples of technical and scientific highlights and, secondly, the "humanistic" aspect of collaborating with many colleagues from abroad, including in particular Jan Żylicz and his associates from the University of Warsaw.

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1. Introduction

It is, indeed, a pleasure and honour for me to participate in this Conference's session devoted to celebrating Jan Żylicz's Golden Age. However, I feel a little uneasy here as I, being in the tantalum age, might be considered to be too young to contribute anything valuable at this occasion. In spite of these doubts, I shall try to review 30 years of research on the structure of exotic nuclei that has been performed at the GSI Online Mass Separator jointly with Jan Żylicz and the "Żyliczians", *i.e.* his students, scholars and collaborators from the Spectroscopy Group of the University of Warsaw.

In contrast to the "great history" related to the legacies of Maria Skłodowska-Curie and Ernest Rutherford, which part of this Conference is devoted to, there is the "small, individual history" of all of us. As an example of the merge of these two topics I would like to make a very personal remark. What is shown in Fig. 1 is — no, it is *not* young Jan Żylicz

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dressed up for carnival but — the Polish hero Andrzej Tadeusz Bonawentura Kościuszko (1746–1817). Every Pole knows and admires him. He visited the pre-revolutionary France, fought on the side of George Washington during the War of Independence and on the side of Józef Poniatowski during the Russian–Polish War of 1792 and the Uprising of 1794. The reason for showing this picture here is that it forms part of my family heritage. It used to hang at the wall in my grandparents' and parents' home. My Polish great-grandmother, Marie-Emilie Gutleben, née Poll von Pollenburg (1843–1926), apparently brought it along when she emigrated from Poland to Germany: It may thus be my Polish genes that make me a good candidate for collaborating with Poles!

Fig. 1. Picture of Tadeusz Bonaventura Kościuszko.

This contribution is structured as follows. After a description of the Separator, experimental results on α, proton and β radioactivity will be presented, followed by concluding remarks.

2. The GSI Online Mass Separator

The GSI Online Mass Separator served to study isotopes far from stability. They were produced by using heavy-ion beams from the UNILAC Accelerator to induce fusion-evaporation or multinucleon-transfer reactions. The reaction products were stopped in a catcher inside an ion source, from where they were extracted as singly charged (atomic or molecular) ions and re-accelerated to 60 keV. These beams were implanted, yielding thin, point-like sources for, *e.g.*, decay spectroscopy.

The heart of such a facility is the system of target and ion source. The demands for the release and ionisation processes, *i.e.* chemical selectivity, short release time, high efficiency and long operation period, are easy to list but difficult to realize. Reinhard Kirchner's successful work of developing ion sources for the GSI Online Mass Separator (see, *e.g.*, Ref. [1]) may be illustrated by the following examples:

— A high-purity beam of the isomeric states of ^{94}Ag, whose half-lives are of the order of 0.4 s, was obtained at an intensity of about 2 atoms/s, corresponding to a separation efficiency of 30%, the partial production cross section for two-proton emission corresponding to about 350 pb (see Sec. 4).

— Molecular ions, such as ^{102}Sn^{32}S^{+} and of ^{114}Ba^{19}F^{+}, were used to study the decay of ^{102}Sn (see Sec. 5) and ^{114}Ba (see Sec. 3), respectively, a fusion-evaporation cross section of the order of nb being reached in the latter case.

3. Alpha radioactivity

The α-decay chain ^{110}Xe–^{106}Te–^{102}Sn was studied, including the new isotopes ^{110}Xe and ^{106}Te ($T_{1/2} = 60\ \mu$s) [2]. Alpha-decay energies probe the slope of the mass-energy surface, and the observation that the α-decay energy of ^{106}Te is larger than that of ^{110}Xe (see Fig. 2) clearly indicates the increased binding of the double shell closure occurring at ^{102}Sn. By using α–α time correlations the half-life of ^{106}Te was determined to be $60^{+30}_{-10}\ \mu$s (see Fig. 2). This measurement performed 30 years ago represents an early example for a method which has meanwhile become commonplace, *e.g.* in heavy-element research.

More recently the above-mentioned α-decay chain ending in ^{102}Sn has been extended to the next high-Z member, ^{114}Ba [3], confirming the above-mentioned increase of α-decay energy with decreasing Z (see Fig. 3). Another piece of evidence for the special structure of ^{100}Sn can be deduced from the systematics of the reduced α-transition probabilities, displayed in Fig. 3 for isotopes near this shell closure and that of ^{208}Pb. These data reveal a weak indication for an increase of this parameter for ^{106}Te which is apparently related to an enhanced "preformation probability" when approaching configurations of the parent nucleus that correspond to a ^{100}Sn core plus an α-particle [4].

An island of cluster radioactivity is expected to occur beyond ^{100}Sn, in analogy with the corresponding phenomenon observed beyond ^{208}Pb. The known α-decay energies of ^{114}Ba, ^{110}Xe and ^{106}Te yield already an experimental value for the energy of ^{12}C decay of ^{114}Ba. However, a search for the latter disintegration mode remained unsuccessful, corresponding to an upper branching-ratio limit of 3.4×10^{-5} [5].

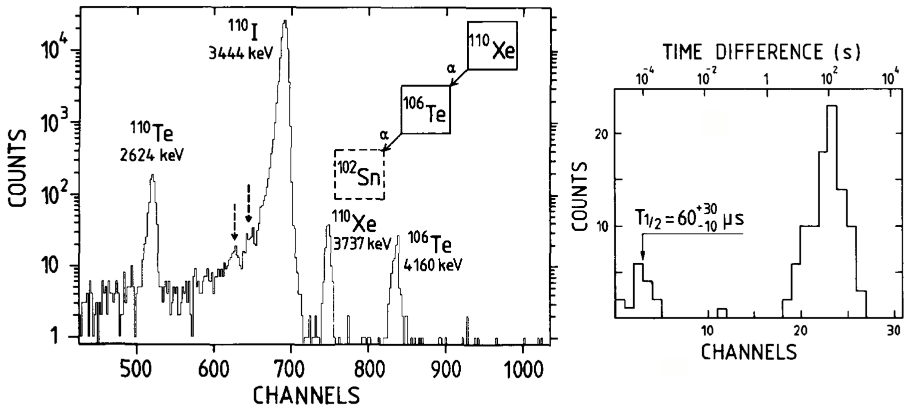

Fig. 2. Alpha-decay energies of mass-110 isotopes and the daughter of the ^{110}Xe decay, ^{106}Te, (left panel) and result obtained by studying time correlations between ^{110}Xe and ^{106}Te decays [2] (right panel).

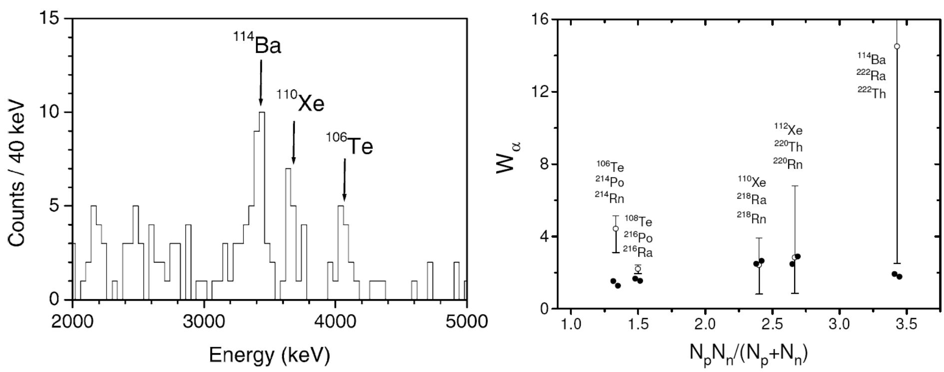

Fig. 3. Alpha-decay energies for ^{114}Ba, ^{110}Xe and ^{106}Te [3] (left panel), and reduced α-transition probabilities near ^{100}Sn [4] (right panel).

4. Proton radioactivity

Proton radioactivity was first observed for an isomeric state, namely ^{53m}Co [6], whereas proton disintegration from a ground-state was co-discovered in experiments performed at the Velocity Filter SHIP [7] and at the GSI Online Mass Separator [8]. Later on, two-proton radioactivity was discovered [9, 10], presumably occurring from the ground state. The one and only case, where a state decays by one-proton [11] and two-proton [12] emission is ^{94m}Ag (21^+), recently observed at the GSI Online Mass Separator. The assignment of the proton and two-proton radioactivity was achieved by demanding coincidence with known γ-rays de-exciting high-spin states in the daughter nuclei ^{93}Pd [13] and ^{92}Rh [14], respectively. These results, in particular the conclusion on a large deformation of ^{94m}Ag (21^+), have led to considerable controversy. The present state of affairs can be described as follows:

— The in-beam spectroscopy of ^{92}Rh was repeated [15], even though I personally have the impression that a substantial improvement of the data obtained previously [14] is still to come (see below).

— Improved mass measurements were performed for ^{92}Rh and ^{93}Pd at Jyväskylä [16]. The results make the ^{94m}Ag (21^+) case even more puzzling as they suggest that the one-proton and two-proton decay stem from two different isomeric states (see Fig. 4).

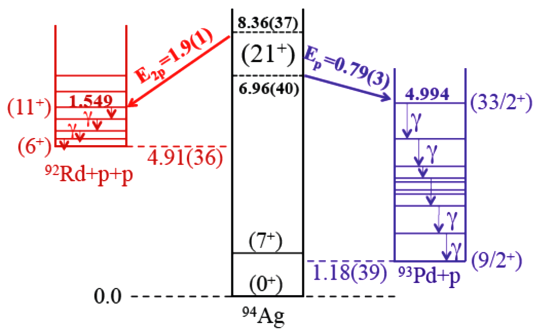

Fig. 4. Preliminary interpretation of the one-proton and two-proton decay of ^{94m}Ag (21^+), combining the proton data obtained in Refs. [11, 12] with the mass results presented in Ref. [14].

— In a helium-jet experiment without mass separation, one of the one-proton line of ^{94m}Ag was confirmed whereas the two-proton radioactivity was not observed [17].

— Critical remarks on the two-proton data were published which, however, are not based on any new experimental results [18].

In view of this situation I draw the following conclusions:

— There is a clear need for re-measuring the ^{94m}Ag (21^+) decay by using high-intensity, high-purity sources and thus improving the data obtained at the GSI Online Mass Separator in 2005 [11] and 2006 [12], respectively.

— Improving the data is not an easy task as the work presented in Refs. [11, 12], firstly, used a high-intensity and high-purity beam of mass-separate ^{94m}Ag and, secondly, investigated a large number of approximately 5×10^4 of (21^+) decays.

— A very important prerequisite for future experiments on ^{94m}Ag (21^+) is to improve the experimental data on excited (high-spin) levels of ^{93}Pd and ^{92}Rh, and thus clarify the properties of the states populated in the one-proton and two-proton decay of ^{94m}Ag (21^+), respectively. It seems to me that the data obtained recently on ^{92}Pd [19] might well be used for this purpose: While the $2n$-evaporation channel has allowed the authors of Ref. [19] to produce ^{92}Pd through the $2n$ channel of ^{36}Ar + ^{58}Ni reactions, I presume that the same experimental data may allow them to improve the results on ^{93}Pd [13] and ^{92}Rh [14] by studying the $1n$ and pn channels, respectively.

5. Beta activity

Most of the β-decay work performed at the GSI Online Separator was devoted to studies of the Gamow–Teller (GT) decay of nuclei in the ^{100}Sn and ^{146}Gd region, with particular emphasis being put on the determination of β strengths, Q values and masses. Before discussing this topic, I would like to mention a different one, namely the measurement of the 0^+ to 0^+ Fermi decay of ^{62}Ga. The half-life of this nuclide was determined to a precision of 3 parts in 10^4 [20], aiming at a test of the CVC hypothesis [21].

Returning to GT decay, I would like to recall the pandemonium problem [22]. It occurs when trying to measure reliable β-decay branching ratios far from stability, where the density of excited levels in the daughter nucleus is generally high and thus the measurement of the numerous and partly weak β-delayed γ-rays is difficult. At the GSI Online Mass Separator, the "non-pandemonic" Total Absorption Spectrometer [23] was used to investigate the β^+/EC decay of neutron-deficient isotopes:

— As an example of the decay studies performed in the ^{100}Sn region, the data obtained for ^{102}Sn are displayed in Fig. 5. The total GT strength was measured to be 4.2(8) for ^{102}Sn [24] and extrapolated to be 5.21(60) for ^{100}Sn [25]. The latter result serves as reference value for the recent study of the ^{100}Sn decay [26] and for future endeavours of this type, which hopefully apply high-resolution and total-absorption spectroscopy.

— The proton X-ray coincidence technique [27] was used to measure lifetimes in the range 10^{-15} to 10^{-17} s for excited states of ^{113}Xe, populated in the β-decay ^{113}I [28].

— By presenting accurate branching ratio for its EC decay, ^{152}Yb was shown to be a suitable candidate for a monoenergetic neutrino facility [29].

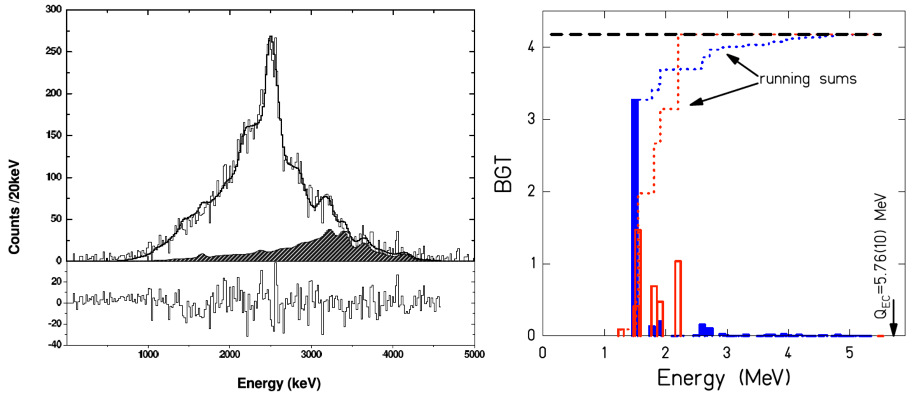

Fig. 5. Experimental data obtained for the ^{102}Sn decay by total-absorption spectroscopy (left panel), and the GT strength deduced by combining the latter data with those from high-resolution measurements and compared to a theoretical prediction (right panel) [24].

6. Concluding remarks

The above-mentioned Ref. [29] appeared past week, and there are apparently even more publications from work performed at the GSI Online Mass Separator still to come. This together with the follow-up studies, described in Sec. 4 for the case of ^{94m}Ag (21^+), indicate that the results obtained at this good, old facility are still of current interest and, at least partly, still present challenges to experiments today.

Fig. 6. Jan on the way to his Golden Age.

When considering the collaborative aspect involved in the experiments presented here, a particular word has be addressed to the many essential contributions achieved by Jan Żylicz and the Żyliczians: my cordial thanks to all of you — without your competent, creative and amicable engagement we would not have been able to achieve what we did.

In all my modesty, I would claim that we have realized a shining example of a smooth and successful Polish–German collaboration, which hopefully motivates further Polish–German collaborations to follow.

Last not least, looking back to 30 years of joint work (see Fig. 6): All the best to you, Jan, at your Golden Age and beyond!

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