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OF PROTON DRIP-LINE NUCLEI**

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FROM ^{20}Mg TO THE ^{100}Sn REGION: EXPERIMENTAL TECHNIQUES FOR DECAY STUDIES OF PROTON DRIP-LINE NUCLEI

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ABSTRACT

The experimental techniques used for decay studies of the very neutron-deficient isotopes such as ^{20}Mg , ^{36}Ca , ^{37}Ca , ^{94}Ag , ^{100}In , ^{101}Sn and ^{114}Ba are discussed. Particular emphasis is put on the discussion of the projectile fragment separator online to the accelerator SIS and the isotope separator online to the accelerator UNILAC.

1 Introduction

During the last few years, improvements in experimental techniques have enabled one to produce and study nuclei very far from the β -stability line. I refer in particular to the investigations of decay properties of neutron-deficient isotopes such as ^{20}Mg , ^{36}Ca , ^{37}Ca and of nuclei around ^{100}Sn . While my contribution to the recent INPC'95 Conference [1] has been focused on the *physics implications* of these measurements, this report is concerned with details of the related *experimental techniques*. The case of the three light (sd-shell) nuclei, studied by using beam-line spectrometers, will be discussed in section 2. In this context, I shall mainly discuss the work performed at the projectile fragment separator (FRS) online to the SIS accelerator of GSI, but shall give also reference to the ^{20}Mg experiment carried out at GANIL. The measurements on nuclei near ^{100}Sn , presented in section 3, have been realized by using the isotope separator online (ISOL) to the UNILAC accelerator of GSI. Section 4 contains a comparison between beam-line spectrometer and ISOL systems.

2 Beta-Decay Studies at the FRS

2.1 General Remarks

The FRS [2], an energy-loss achromat, was used for production and purification of secondary beams of ^{36}Ca and ^{37}Ca [3, 4, 5]. The principle of the separation method of the FRS is displayed in figure 1, while the detector setup positioned at the focus

of the FRS will be described in section 2.2. A 300 MeV/u ^{40}Ca beam impinging on a $1\text{g}/\text{cm}^2$ ^9Be target yielded secondary beam intensities of about 1 atom/4s and 30 atoms/s for the two calcium isotopes, the total numbers of atoms implanted into the detector array being 2.8×10^4 and 2.6×10^6 , respectively. The corresponding number for the ^{20}Mg experiment [6] amounted to 4.5×10^6 .

Figure 1: Sketch of the separation method of the FRS

2.2 Collector and Detector Arrays

The array for the detection of positrons, β -delayed protons (βp) and β -delayed γ -rays ($\beta\gamma$) consisted of a $30\text{ mm} \times 30\text{ mm} \times 500\text{ }\mu\text{m}$ silicon counter (implantation detector) which was positioned between two silicon counters of similar dimensions for detecting β -rays; two large-volume germanium detectors mounted nearby registered γ -rays emitted from the implanted activity. This configuration was similar to that shown in figure 2. The monoenergetic mode of the FRS yielded a very narrow implantation profile in beam direction ($\text{FWHM} \approx 100\text{ }\mu\text{m}$) which was centered around an implantation depth of $250\text{ }\mu\text{m}$. This shape of the profile assured that up to medium proton energies ($\approx 4\text{ MeV}$) all protons were fully stopped in the implantation detector, whereas the energy deposited by high-energy protons was sufficient to separate them as lines in the βp -spectrum. Due to the summation of proton energy and positron energy-loss signals, the energy resolution of the proton spectra measured from deeply implanted radioactive atoms is limited and can only be improved to some extent by demanding coincidences with the β -detectors. Such an improvement can be seen from the ^{20}Mg data [6] displayed in figure 3.

Figure 2: Detector array used for positron, proton and γ spectroscopy of ^{20}Mg [6]: a) foils for degrading the beam energy, b) energy-loss detector, c) implantation detector, d) β -detectors, e) γ -detectors

Figure 3: Proton energy spectra measured for the ^{20}Mg decay, recorded in the six central strips of the implantation detector (a) without any coincidence condition, (b) with a coincidence condition selecting strip positions of the β -detectors, and (c) with an additional coincidence condition on small energy-losses detected in the β -detectors. Lines stemming from the βp -decay of ^{20}Mg are marked by p_1 to p_{11} , lines from the βp -delayed α decay of ^{20}Na by α_1 to α_8 . (See [6] for details.)

The narrow implantation profile mentioned above enables one to trigger the detection of γ -rays, emitted from the implanted activity, with 100% efficiency via the energy-loss of the coincident β -rays registered in the implantation detector. In this way, only γ -rays originating from nuclei decaying *inside* the implantation detector were measured and the room background was suppressed efficiently.

The number of atoms implanted for ^{36}Ca and ^{37}Ca , needed for normalizing the decay rates, was determined by using two independent methods [5]. Firstly, the number of identified ^{36}Ca and ^{37}Ca ions, identified by measuring energy loss and time of flight, was corrected for losses due to secondary reactions in the stopping process; this correction amounted to 11(2)% and 11(1)% for ^{36}Ca and ^{37}Ca , respectively. Secondly, the number of implanted atoms was determined by counting all $^{37,36}\text{Ca}$ β -decay events. The two methods yielded agreement within less than 1%.

Since the energy resolution of the βp -spectrum measured in the implantation detector was rather poor, the βp -energy calibration as well as the βp -decay rates for ^{37}Ca were determined by comparing the βp -spectrum from this work with the high-resolution data [7]. For the βp -energy calibration in the case of ^{36}Ca , α -calibration sources and the βp -spectrum of the ^{37}Ca experiment were used. The latter was based on the fact that the β -decay Q values of ^{36}Ca and ^{37}Ca as well as the proton separation energies in the daughter nuclei ^{36}K and ^{37}K are similar. Therefore, the line shifts due to the summation of the β -ray energy-loss to each proton signal were almost equal [5]. Furthermore, the *difference* of the line shifts due to pulse-height defects of the recoil atoms (^{35}Ar , ^{36}Ar) in ^{36}Ca and ^{37}Ca decay is negligible [8]. Additionally, an improvement in the βp -energy resolution was obtained by applying the above-mentioned β -coincidence technique.

The absolute $\beta\gamma$ -decay rates were determined by using a precise calibration of the γ -efficiency obtained with a calibrated ^{56}Co source, the size of which corresponded to the implantation profile measured in the plane perpendicular to the beam line [5]. The γ -decay rates were corrected for cascade-summing in the ^{56}Co source measurements and for losses in the photopeak intensity from the summing of γ -rays with β -rays or 511 keV annihilation radiation [5].

The decay half-lives were determined from the βp -data accumulated during the 2.5 s beam-off period following each beam pulse, the lengths of these pulses being 0.5 s and 0.2 s for ^{36}Ca and ^{37}Ca , respectively. The resulting βp -energy spectrum was restricted to energies above 2.5 MeV (^{36}Ca) and 3 MeV (^{37}Ca) in the offline analysis. The remaining part of the βp -data, mainly originating from the proton decay of the IAS in the daughter nucleus, are free of background arising from β -ray energy-loss signals of the decay of beam contaminations or daughter nuclei. Furthermore, βp -contributions from such decays is negligible [5]. In the analysis of the time characteristics of the ^{37}Ca decay, a time-dependent dead-time correction was taken into account [5]. The resulting half-life values of 102 ± 2 and 118.1 ± 1.1 ms for ^{36}Ca and ^{37}Ca , respectively, represent indeed improvements over the data obtained in previous measurements.

3 Decay Studies at the ISOL System of GSI

3.1 General Remarks

A sketch of the ISOL of GSI is shown in figure 4. With respect to extraction, acceleration, magnetic deflection, and beam handling as a whole, this facility has essentially remained unchanged since the first online experiments performed almost twenty years ago. The ion source and the collector/detector array, however, have been improved continuously during this period. The development of ion sources will be discussed in section 3.2. The radioactive sources for decay spectroscopy are produced by collecting the mass-separated beam on a moving-tape system or on a thin catcher foil mounted close to a detector array. The decay radiation is registered by using silicon detectors for positrons, protons or α -particles, a mini-orange spectrometer for conversion electrons, germanium, BGO or NaI detectors for γ -rays, or track detectors for heavy ions. The latest developments comprise a large-volume NaI crystal including silicon and germanium detectors for total-absorption measurements [11], and an array of six EUROBALL-CLUSTER germanium detectors for $\beta\gamma$ -measurements [12].

Figure 4: Sketch of the ISOL method used at GSI

Typical values of the UNILAC beam intensity and energy as well as the target thickness, taken from the $^{58}\text{Ni} + ^{50}\text{Cr} \rightarrow ^{101}\text{Sn}$ experiment [9], are 2×10^{11} ions/s, 5.9 MeV/u, and 3 mg/cm², respectively. It is interesting to note that the UNILAC beam intensities used for ISOL experiments at GSI are limited. This is due to the power deposition of the beam in target, heat shields and catcher(s) of the ion source, the maximum power load being of the order of 70 W.

3.2 Ion Source Development

The most important part of any ISOL is the target/ion source system, and there is a continuing effort to increase the release efficiency and to improve the chemical selectivity [10]. An important technique for determining these parameters has been extensively applied at GSI. This method consists in implanting stable-isotope beams from the UNILAC into the catcher positioned inside the ISOL source and measuring the release time profile for this isotope [13]. Figure 5 shows examples of such data.

Figure 5: Half-life dependence of the ISOL separation efficiency calculated by using experimentally derived release parameters. The release data for silver and tin were determined for catchers of graphite and niobium, respectively, inside a FEBIAD-B2 source; the temperature was 1850 K for the enclosure and 2300 K for the catcher [13]. The data for Ba^+ and BaF^+ stem from a thermal ion source with a tantalum catcher at 1700 K and 2400 K, respectively.

The forced electron beam induced arc discharge (FEBIAD) ion source [13] in its normal operation mode is used in cases in which the distribution of fusion-evaporation cross-sections and/or the choice of catcher material guarantees sufficient chemical selectivity:

- The heaviest odd-odd nucleus, ^{95}Ag , was identified by measuring its βp -decay [14]; a prerequisite for the success of this experiment was the high release efficiency of 42% for this short-lived (0.42 s) isotope (see figure 5).
- ^{100}Pd was produced as a mass-separated beam of 10^7 ions/s by using reactions between a 6×10^{12} ions/s, 10 MeV/u ^{12}C beam and a "sandwich" target consisting of foils of ^{94}Mo , ^{93}Nb and ^{92}Mo [15]; ^{100}Pd is of interest as a probe for solid-state investigations of surfaces, interfaces and thin films.
- A high-intensity beam of ^{107}In was realized at Louvain-la-Neuve by using a ^{16}O beam and a sandwich target similar to that mentioned above; this development was instrumental for improving studies of parity violation in β -decay

Improved chemical selectivity can be reached by means of a cold trap that is attached to and removed from the FEBIAD source in regular intervals. This *bunching mode* [13] yielded, for example, a suppression of ^{101}In , which was instrumental for the first observation of ^{101}Sn [9].

In cases where the FEBIAD source in normal or bunching mode does not result in sufficient chemical purity of the mass-separated beams, the thermal ion source [17] offers an alternative for elements of low ionization potential. This solution was chosen, e. g., for identifying ^{100}In , the heaviest odd-odd, $T_{1/2}=1$ nucleus with known decay properties [18].

Figure 6: Schematic view of the laser ion source used for studying short-lived tin isotopes. The dimensions L and ϕ_{in} were varied during the series of test measurements, while ϕ_{hole} was kept constant at a value of 1.2 mm. $^{16}\text{O} + ^{95}\text{Mo}$ reactions were used for producing 10.3 min ^{108}Sn for test purposes [20], whereas the ^{101}Sn experiments [9] were performed with $^{58}\text{Ni} + ^{50}\text{Cr}$ reactions.

Another solution for reducing the isobaric background in ISOL experiments is the laser ion source [19]. Such a source was developed for delivering beams of short-lived tin isotopes GSI (see figure 6). The ionization efficiency for ^{108}Sn has been determined to be 8.5% [20] and is thus approximately six times lower than that obtained for the FEBIAD source (see figure 5). This loss in efficiency, but also the insufficient suppression of indium by the laser ion source (due to the inevitable surface ionization), were the reasons for choosing the FEBIAD source for the ^{101}Sn measurements [9].

Instead of extracting *atomic* ions from the sources described so far, one can also use *molecular* ions. This method was applied to identify ^{114}Ba , the heaviest known $T_z=2$ nucleus, and to measure the decay properties of this and neighbouring barium isotopes [21, 22]. The fluorination source, shown in figure 7, combines high release efficiency (11% for 0.44 s ^{114}Ba) with very efficient suppression of cesium and other contaminants.

Figure 7: Schematic view of the fluorination ion source used for studying short-lived barium isotopes: (1) UNILAC beam, (2) target, (3) reaction products, (4) heat shields, (5) tungsten window, (6) tantalum catcher, (7) CF_4 and test vapour leak, (8) electron bombardment heating, (9) separator beam.

4 Comparison of Separation Methods

It is interesting to compare the properties of beam-line spectrometers and ISOL systems with respect to their use for studying a given exotic nucleus. Results from such a comparison, based on real measurements or gedanken experiments on ^{100}Sn , are compiled in table 1. The production reactions considered are fragmentation of a relativistic ^{124}Xe beam (FRS) [23] and the fusion-evaporation reactions $^{50}\text{Cr} + ^{58}\text{Ni}$ (mass measurement of $A=100$ isobars by means of the GANIL cyclotrons CSS1 and CSS2) [24] or $^{58}\text{Ni} + ^{50}\text{Cr}$ (ISOL). The luminosity and ^{100}Sn intensity obtained by

Table 1: *Comparison of luminosities and secondary beam intensities obtained by using different methods for the production and separation of ^{100}Sn*

Method	Pro- ject- ile	Proj. int., s^{-1}	Target	Target thickness, mg/cm^2	Trans- mission, $\%$	Lumin- osity, $\mu\text{b}^{-1}\text{s}^{-1}$	σ , nb	^{100}Sn int., d^{-1}
FRS	^{124}Xe	3×10^7	^9Be	6000	6	0.8	0.011	1
CSS1- CSS2	^{50}Cr	2×10^{11}	^{58}Ni	1.5	0.01	0.0003	400	10
ISOL	^{58}Ni	2×10^{11}	^{50}Cr	3	5	0.4	400	12000

by means of the beam-line spectrometer SISSI/LISE3 of GANIL [25] are presumably similar to the CSS1-CSS2 data. The ISOL parameters shown in table 1 are taken from the ^{101}Sn experiment [9] except for the production cross-section which represents the CSS1-CSS2 result.

The conclusion from this comparison is that, in principle, an ISOL system based on fusion-evaporation reactions yields higher ^{100}Sn intensities than the FRS or SISSI/LISE3. The serious disadvantage of a potential ISOL experiment on ^{100}Sn is, however, the insufficient chemical separation which leads to a strong contamination of $A=100$ samples by isobars of lower Z .

A wider comparison of beam-line spectrometers and ISOL, which includes parameters such as beam purity and details of the radiation detection, shows that these methods are complementary. On the one hand, the thin point-like sources from ISOL are ideally suited for *high-resolution* βp -spectroscopy. This feature has been impressively demonstrated by ISOLDE measurements of $^{32,33}\text{Ar}$ [26] and ^{37}Ca [7]. On the other hand, the work on ^{20}Mg and $^{36,37}\text{Ca}$, presented in this paper, has shown that beam-line spectrometers allow one to perform β -decay studies of unprecedented accuracy for neutron-deficient isotopes near the proton drip line as well as for other exotic nuclei. The improvement of the decay data for ^{36}Ca compared to the previous work [27] is, I think, an impressive proof of this statement. It is also interesting to note that, due to the record values of source strength and purity realized in FRS experiments, it was possible to use high-resolution germanium detectors, whereas the corresponding ISOLDE experiment [7, 28] was restricted to low-resolution NaI detectors so far. It is thus not surprising that further FRS experiments, e. g. concerning the ^{40}Ti decay [29], are planned.

In summary, it is my impression that the fruitful competition between ISOL and beam-line spectrometers in studying β -decay near the proton-drip line has been and will be very fruitful, and that the quest for improving both methods will thus remain to be a challenge.

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