

EE

# GSI

GSI-Preprint-96-63  
Dezember 1996



**RECENT DEVELOPMENTS  
AT THE GSI ON-LINE MASS SEPARATOR**

K. Burkard, R. Collatz, M. Hellström, Z. Hu, W. Hüller, O. Klepper,  
R. Kirchner, E. Roeckl, K. Schmidt, M. Shibata, A. Weber

**COUPLING A TOTAL ABSORPTION SPECTROMETER  
TO THE GSI ON-LINE MASS SEPARATOR**

M. Karny, J.M. Nitschke, L.F. Archambault, K. Burkard, D. Cano-Ott,  
M. Hellström, W. Hüller, R. Kirchner, S. Lewandowski, E. Roeckl, A. Sulik

**RELEASE STUDIES OF ELEMENTARY AND METAL-FLUORIDE IONS  
AT THE GSI ON-LINE MASS SEPARATOR**

R. Kirchner

Contributions to 13th Int. Conf. on Electromagnetic Isotope Separators and  
Techniques Related to their Applications (EMIS-13), Bad Dürkheim, 22-27 September 1996,

(to be published in Nuclear Instruments and Methods in Physics Research, Section B)

Sur 9728

Gesellschaft für Schwerionenforschung mbH  
Planckstraße 1 • D-64291 Darmstadt • Germany  
Postfach 11 05 52 • D-64220 Darmstadt • Germany

# RECENT DEVELOPMENTS AT THE GSI ON-LINE MASS SEPARATOR

K. BURKARD, R. COLLATZ, M. HELLSTRÖM, Z. HU, W. HÜLLER, O.  
KLEPPER, R. KIRCHNER, E. ROECKL, K. SCHMIDT, M. SHIBATA, A.  
WEBER

*Gesellschaft für Schwerionenforschung, Planckstr. 1, D-64291 Darmstadt,  
Germany*

## ABSTRACT

The experimental techniques used at the GSI on-line mass separator for decay studies of nuclei far from stability are described. Particular emphasis is put on recent developments made for investigating nuclei near  $^{100}\text{Sn}$ . The methods applied for identifying and studying the new isotopes  $^{94}\text{Ag}$ ,  $^{100}\text{In}$ ,  $^{101}\text{Sn}$  and  $^{114}\text{Ba}$  are used as examples.

## 1 Introduction

During the last few years, improvements in experimental techniques have enabled the production and study of nuclei very far from the  $\beta$ -stability line. Particularly impressive progress has been made, for example, in the investigation of decay properties of neutron-deficient isotopes such as  $^{20}\text{Mg}$ ,  $^{36}\text{Ca}$ ,  $^{37}\text{Ca}$  and of nuclei around the double shell-closures at  $^{100}\text{Sn}$  and  $^{146}\text{Gd}$  [1]. This is almost entirely due to experiments performed by means of magnetic spectrometers such as those available at GANIL, Caen, MSU-NSCL, East Lansing, RIKEN, Saitama, and GSI, Darmstadt, or by using on-line mass separators. This report deals with an instrument of the latter kind, which has been in operation at the heavy-ion accelerator UNILAC of GSI since 1976. A first description of the GSI on-line mass separator has been given in a contribution to the EMIS-9 Conference [2]. Today, after 20 years of operation, this separator still allows for front-line experiments on exotic nuclei. It is the *recent technical development* of this facility which is surveyed in this paper, whereas the related *physics implications* can be seen from the references cited in the text or from a recent review [1].

With respect to extraction, acceleration, magnetic deflection, and beam handling to the focal-plane chamber, the GSI on-line mass separator has essentially remained unchanged since the first on-line experiments performed twenty years ago. The ion source and the collector/detector array, however, have been improved continuously during this period. The development of target/ion-source systems will be discussed in section 2, while the collector/detector arrays are presented in section

3. Section 4 contains examples of recent experiments. Summary and outlook as well as a comparison between magnetic spectrometer and on-line mass separators will be given in section 5.

## 2 Target/Ion-Source Development

At the GSI on-line separator, a continuing effort has been made to improve the target/ion-source system and, in particular, to increase chemical selectivity and release efficiency of the ion source. An important technique for determining the latter quantity has been extensively applied at GSI. This method consists in implanting stable-isotope beams from the UNILAC into the catcher positioned inside the ion source and measuring the release time profile for this isotope [3]. The heavy-ion induced fusion-evaporation or multinucleon transfer reactions, used at the GSI on-line mass separator, imply a limitation of the thickness of target (and catcher) to values of the order of  $\text{mg}/\text{cm}^2$ . The target is generally mounted *outside* of the ion source. However, for the case of light-ion induced or multinucleon transfer reactions, target (and catcher) foils can be mounted in a “sandwich” array *inside* the source. Some of the recent developments will be reviewed in this section, with Table 1 compiling examples of separation efficiencies for short-lived isotopes, determined by this method.

Table 1: *Compilation of separation efficiencies for short-lived isotopes, obtained at the GSI on-line mass separator. The efficiencies measured for stable-isotope beams [3] have been corrected for incomplete collection of reaction products and limited separator into transmission*

Isotope	$^{94}\text{Ag}$	$^{101}\text{Sn}$	$^{103}\text{Sn}$	$^{105}\text{Sb}$	$^{114}\text{Ba}$	$^{205}\text{Au}$
Half-life	0.42 s [4]	3 s [5]	7 s [6]	1.12 s [7]	0.43 s [8]	31 s [9]
Ion source	FEBIAD-B2	FEBIAD-E2	Laser	FEBIAD-E4	Fluorination	FEBIAD-E2
Separation efficiency (%)	30	15	3.5	1.5	10	40

The forced electron beam induced arc discharge (FEBIAD) ion source [10, 11] *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.

Improved chemical selectivity can be reached by means of a cold trap that is heated or cooled in *bunching mode* [11]. This method was instrumental, for example, to produce isotopically pure beams of  $^{98}\text{Ag}$  [12] and  $^{103-107}\text{In}$  [13], whereas an

*antibunching mode* was used for the case of  $^{98}\text{Cd}$  [12]. The cold trap can also be operated at a constant (high or low) temperature in order to suppress contaminants. This *suppression mode* or *DC mode* was used, e. g., to decrease the admixture of  $^{94,95}\text{Pd}$  to  $^{94,95}\text{Ag}$  beams [4] and of  $^{101}\text{Sn}$  to  $^{101}\text{In}$  beams [5].

In cases where the FEBIAD source in normal, bunching or suppression mode does not result in sufficient chemical purity of the mass-separated beams, the thermal ion source [14] offers an alternative for elements of low ionization potential. This solution was chosen, e. g., for studying the  $\beta$ -decay of  $^{102}\text{In}$  [15]. In this case, the higher beam purity achieved by the thermal ion source was accompanied by a 9 times lower beam intensity compared to the FEBIAD source. It is this intensity argument that lead to the choice of the FEBIAD source for the study of light indium isotopes [15].

A drawback of the thermal ion source is that its release efficiency generally decreases as a function of operation time, the characteristic half-time being approximately 6 hours. The reason for this time-dependent loss is essentially due to degradation of entrance window and ionizer foils.

Another solution for reducing the isobaric background in the mass-separated beams is the *laser ion source* [16]. Such a source was developed at GSI for delivering beams of short-lived tin isotopes (see Fig. 1). The ionization efficiency for  $^{108}\text{Sn}$  has been determined to be 8.5% [17] and is thus approximately six times lower than that obtained for the FEBIAD source. 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  $^{101}\text{Sn}$  measurements [5].

Instead of extracting *atomic* ions from the sources described so far, one can also use *molecular* ions. The *fluorination source* [3] combines high release efficiency (10% for 0.44 s  $^{114}\text{Ba}$ ) with very efficient suppression of cesium and other contaminants. This method was applied to measure the decay properties of  $^{114-118}\text{Ba}$  [8, 18].

In concluding this section, we would like to briefly discuss the limits on the target/ion source system imposed due to power density and radioactivity. 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 [5], are  $2 \times 10^{11}$  ions/s, 5.9 MeV/u, and 3 mg/cm<sup>2</sup>, respectively. On the one hand, the maximum UNILAC beam intensities, that can be used for experiments at the GSI on-line separator, are dictated by the power deposition of the projectile beam in target, window and catcher(s) of the ion source. The corresponding maximum power load, which is of the order of 70 W, represents the limit for light-ion induced reactions such as  $^{16}\text{O} + \text{Mo}$ , whereas for heavier ions such as  $^{58}\text{Ni}$  the projectile beam intensities are restricted, due to target heating, at even lower power values (15 W for the reaction parameters mentioned above). This situation could be somewhat improved if the duty cycle of the macrostructure of the UNILAC, which is presently about 30% for  $^{58}\text{Ni}$  beams, would be increased. On the other hand, the  $\gamma$ -radiation level at the target/ion-source system is low enough, even after a few days' irradiation with high-intensity UNILAC

beams, to allow for immediate ion source maintenance and exchange which is done manually, i. e. without involving robot operation.

### 3 Collector and Detector Setup

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  $\alpha$ -particles, a mini-orange spectrometer for conversion electrons, germanium, BGO or NaI detectors for  $\gamma$ -rays, or track detectors for heavy ions. The latest developments comprise

- a summation-free  $\beta^+$ -endpoint spectrometer consisting of a Si(Li) and a germanium detector in a segmented BGO ring [19],
- a large-volume NaI crystal including silicon and germanium detectors for total-absorption measurements [13],
- an array of six EUROBALL-CLUSTER germanium detectors [20] (see Fig. 2) for the measurement of  $\beta$ -delayed  $\gamma$ -rays.

### 4 Examples of Recent Experiments

The region near  $^{100}\text{Sn}$  plays a special role among exotic nuclei with respect to the double shell-closure at  $N=Z=50$ , the isospin symmetry ( $N\cong Z$ ), the close neighbourhood to the proton drip line, the dominance of fast  $\pi g_{9/2} \rightarrow \nu g_{7/2}$  (or  $\pi g_{9/2} \rightarrow \nu g_{9/2}$ ) GT  $\beta$ -decay, the termination of the  $rp$  process, and the occurrence of an island of charged-particle emission. In this section, we want to discuss recent research highlights from experiments on neutron-deficient isotopes in the  $^{100}\text{Sn}$  region:

- Concerning direct (in contrast to  $\beta$ -delayed) charged-particle radioactivity, two search experiments were carried out. First, an attempt to measure direct proton radioactivity of  $^{105}\text{Sb}$  [21] has given tentative agreement with results obtained by Tighe et al. [22]. Second, a lower limit of 1100 s has been determined for the half-life of  $^{114}\text{Ba}$  against spontaneous  $^{12}\text{C}$  emission; the half-life of this isotope, the heaviest known  $T_z=2$  nucleus, was measured by both  $\beta^+$  and  $\beta$ -delayed proton ( $\beta p$ ) counting [8].
- The heaviest known odd-odd  $N=Z$  nucleus,  $^{94}\text{Ag}$ , was identified by measuring its  $\beta$ -delayed proton ( $\beta p$ ) decay [4]. The observed 0.42 s activity has been assigned to the decay of a  $9^+$  isomer of  $^{94}\text{Ag}$  whereas the predicted  $0^+$  groundstate remained unobserved so far [4].  $\beta p$  detection was also used for the identification of the new isotopes  $^{101}\text{Sn}$  [5],  $^{100}\text{In}$  [15],  $^{103,105}\text{Sn}$  [23] and  $^{114-116}\text{Ba}$  [18].  $^{100}\text{In}$  [15] is the heaviest odd-odd  $T_z=1$  nucleus with known decay properties. By comparing the measured  $\beta p$  spectra to those predicted by shell-model calculations, this model can be tested. Another interesting aspect is the role of

$\beta$ p branching ratios of nuclei such as  $^{96,98}\text{Ag}$  and  $^{98}\text{Cd}$  in the astrophysical  $rp$ -process [12].

- In order to perform more stringent tests of nuclear models, it is desirable to perform a “complete spectroscopy” which, for the case of  $\beta$ -decay, means the measurement of the complete  $\beta$ -intensity distribution. By applying *high-resolution* gamma spectroscopy with single germanium detectors, the decays of  $^{95-98}\text{Ag}$  [24],  $^{102-104}\text{In}$ , [15, 23],  $^{105}\text{Sn}$  [25], and  $^{117,118}\text{Ba}$  [18] were studied. However, the resulting level schemes are usually far from being complete and often yield hints of missing  $\beta$  strength. Two alternative ways were chosen to improve this situation. One is the approach to a high-resolution total absorption spectrometer consisting of six EUROBALL CLUSTER detectors (see Fig. 2). This array was recently (August/September 1996) used to study the decays of  $^{97,98}\text{Ag}$  and  $^{102}\text{In}$ . For the latter case, the on-line analysis indicates high-energy  $\gamma$ -rays beyond those identified previously [15] and thus a substantial  $\beta$ -feeding of high-lying states in  $^{102}\text{Cd}$ . The second attempt, based on the *low-resolution* total absorption spectrometer, was used for a pilot experiment on the decay of  $^{100}\text{Ag}$  [26], which yielded evidence for a resonance-like concentration of the Gamow-Teller strength at a  $^{100}\text{Cd}$  excitation energy of 5.6 MeV. This observation is interpreted as being due to four-quasiparticle excitations. The new total absorption spectrometer (see section 3) was recently (April 1996) used for a systematical investigation of  $^{103-107}\text{In}$ .
- Sandwich targets of the type mentioned in section 2 have been instrumental for obtaining high-intensity (up to  $3 \times 10^7$  ions/s) beams of neutron-deficient isotopes of indium, tin, thallium and lead from  $^{16}\text{O}$ -induced reactions [10]. This method was recently applied to produce  $^{100}\text{Pd}$  as a mass-separated beam of  $2 \times 10^7$  ions/s by using reactions between a  $3 \times 10^{12}$  ions/s, 10 MeV/u  $^{12}\text{C}$  beam and a sandwich target consisting of foils of  $^{94}\text{Mo}$ ,  $^{93}\text{Nb}$  and  $^{92}\text{Mo}$ ;  $^{100}\text{Pd}$  is of interest as a probe for solid-state investigations of surfaces, interfaces and thin films.

## 5 Summary and Conclusion

We presented recent developments of the target/ion-source system and of the collector/detector array used at the GSI on-line mass separator, and described decay studies of nuclei near  $^{100}\text{Sn}$ . It would have exceeded the scope of this report to cover the full research programme presently realized at this facility. Therefore, we did not discuss investigations on neutron-deficient isotopes near  $^{146}\text{Gd}$  [27, 28, 29, 30] and of neutron-rich isotopes in the mass range 180–205 [9, 31, 32].

It is interesting to compare the properties of magnetic spectrometers and on-line mass separators with respect to their use for studying a given exotic nucleus. Results from such a comparison, based on real measurements or gedanken experiments on  $^{100}\text{Sn}$ , are compiled in Table 1. The production reactions considered are fragmentation of a relativistic  $^{124}\text{Xe}$  beam (FRS) [33] 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 [34]) or  $^{58}\text{Ni} + ^{50}\text{Cr}$  (ISOL). The luminosity and  $^{100}\text{Sn}$  intensity obtained by means of the magnetic spectrometer SISSI/LISE3 of GANIL [35] are presumably similar to the CSS1–CSS2 data. The parameters shown in Table 1 for the GSI on–line mass separator are taken from the successful  $^{101}\text{Sn}$  measurement [5] except for the production cross–section which stems from the CSS1–CSS2 experiment (It is interesting to note that the latter value is a factor of 4 higher than that expected on the basis of the  $^{101}\text{Sn}$  data).

Table 2: Comparison of luminosities and secondary beam intensities obtained by using different methods for the production and separation of  $^{100}\text{Sn}$

Method	Pro- ject- ile	Proj. int., $\text{s}^{-1}$	Target	Target thickness, $\text{mg}/\text{cm}^2$	Trans- mission, %	Lumin- osity, $\mu\text{b}^{-1}\text{s}^{-1}$	$\sigma$ , nb	$^{100}\text{Sn}$ int., $\text{d}^{-1}$
FRS	$^{124}\text{Xe}$	$3 \times 10^7$	$^9\text{Be}$	6000	6	0.8	0.011	1
CSS1– CSS2	$^{50}\text{Cr}$	$2 \times 10^{11}$	$^{58}\text{Ni}$	1.5	0.1	0.003	40	10
On–line mass sep.	$^{58}\text{Ni}$	$2 \times 10^{11}$	$^{50}\text{Cr}$	3	5	0.4	40	1200

The conclusion from this comparison is that, in principle, an ion-source based separation of fusion–evaporation reactions yields higher  $^{100}\text{Sn}$  intensities than the FRS or SISSI/LISE3 todate. The serious disadvantage of a potential  $^{100}\text{Sn}$  experiment at the GSI on–line mass separator is, however, the insufficient chemical discrimination within the isobarically separated beams, which leads to a strong contamination of  $A=100$  samples by isobars of lower  $Z$ . This is the reason why a search for  $^{100}\text{Sn}$  has not been attempted at the GSI on–line mass separator so far. In this context, the results obtained by using a laser ion source for tin isotopes do not seem to offer a solution of the problem. The situation may in principle be improved by high–resolution devices that would be able to sufficiently separate  $^{100}\text{Sn}$  from its isobaric contaminants. Such solutions, in particular the injection of radioactive ion beams from the recoil separator SHIP or the GSI on–line mass separator into an Penning trap, are under investigation.

A more detailed comparison of these separation methods, which includes parameters such as beam purity and details of the radiation detection, shows that they are complementary. On the one hand, the thin point–like sources from ion–source based separators are ideally suited for *high–resolution*  $\beta p$ –spectroscopy. This feature has been impressively demonstrated by ISOLDE measurements of  $^{32,33}\text{Ar}$  [36] and  $^{37}\text{Ca}$  [37]. On the other hand,  $\beta$ –decay studies of  $^{20}\text{Mg}$  [40] and  $^{36,37}\text{Ca}$  [38, 39],

performed by means of magnetic spectrometers, have yielded unprecedented accuracy for *half-lives and absolute branching ratios* of neutron-deficient isotopes near the proton drip line. 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 experiments [37, 41] were restricted to low-resolution NaI detectors so far.

In summary, it appears that the competition between on-line mass separators and magnetic spectrometers has been and will be very fruitful. Therefore the quest for improving both methods may well continue to be an experimental challenge in the near future.

### Acknowledgement

The authors would like to acknowledge valuable contributions made from participants of the GSI Experiments U65, U83, U84, U85, U86, U129, U134 and U151. One of us (MH) would like to acknowledge support from the Alexander von Humboldt Foundation. This work was supported by the European Community under Contracts. No. ERBCIPDCT940091 and ERBFMGECT950083.

### References

- [1] E. Roeckl, in Proc. Int. Nuclear Physics Conf. 1995 (INPC'95), World Scientific, Singapore, 1996, p. 526.
- [2] K. Burkard *et al.*, Nucl. Instr. and Meth. **139** (1976) 275.
- [3] R. Kirchner, contribution to this conference.
- [4] K. Schmidt *et al.*, Z. Phys. **A350** (1994) 99.
- [5] Z. Janas *et al.*, Phys. Scr. **T56** (1995) 262.
- [6] P. Tidemand-Petersson *et al.*, Z. Phys. **A302** (1994) 343.
- [7] J. Friese *et al.*, in Proc. Int. Workshop XXIV on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, 1996, H. Feldmeier, J. Knoll and W. Nörenberg (eds.), GSI Report ISSN 0720-8715, p. 123.
- [8] A. Guglielmetti *et al.*, Phys. Rev. **C52** (1995) 740.
- [9] C. Wennemann *et al.*, Z. Phys. **A347** (1994) 185.
- [10] R. Kirchner *et al.*, Nucl. Instr. and Meth. in Phys. Res. **A234** (1985) 224.
- [11] R. Kirchner *et al.*, Nucl. Instr. and Meth. in Phys. Res. **B26** (1987) 204.
- [12] M. Hellström *et al.*, Z. Phys., in press.
- [13] M. Karny *et al.*, contribution to this conference.
- [14] R. Kirchner, Nucl. Instr. and Meth. in Phys. Res. **A292** (1990) 203.
- [15] J. Szerypo *et al.*, Nucl. Phys. **A584** (1995) 221.
- [16] V. I. Mishin *et al.*, Nucl. Instr. and Meth. in Phys. Res. **B73** (1993) 550.
- [17] V. N. Fedoseyev *et al.*, in Proc. 7th Int. Symposium on Resonance Ionization Spectroscopy, Bernkastel-Kues, 1994, AIP Conf. Proc. **132** (1995) 465.
- [18] Z. Janas *et al.*, to be published.
- [19] H. Keller *et al.*, Nucl. Instr. and Meth. in Phys. Res. **A300** (1991) 67.



- [20] J. Eberth, in Proc. Conf. on Physics from Large  $\gamma$ -Ray Detector Arrays, Berkeley, 1994, Report LBL-35687 (1994), p. 160.
- [21] M. Shibata *et al.*, submitted to Phys. Rev. **C**.
- [22] R. J. Tighe *et al.*, Phys. Rev. **C49** (1994) R2871.
- [23] J. Szerypo *et al.*, to be published.
- [24] K. Schmidt *et al.*, to be published.
- [25] M. Pfützner *et al.*, Nucl. Phys. **A581** (1995) 205.
- [26] L. Batist *et al.*, Z. Phys. **A351** (1995) 149.
- [27] H. Keller *et al.*, Z. Phys., **A352** (1995) 1.
- [28] A. Gadea *et al.*, Z. Phys., **A355** (1996) 253.
- [29] R. Collatz *et al.*, submitted to Z. Phys.
- [30] R. Collatz *et al.*, to be published.
- [31] K. Krumbholz *et al.*, Z. Phys. **A351** (1995) 11.
- [32] F. Meissner *et al.*, Phys. Phys. **C51** (1995) 1558.
- [33] R. Schneider *et al.*, Z. Phys. **A348** (1994) 241.
- [34] M. Chartier *et al.*, Phys. Rev. Lett. **77** (1996) 2400.
- [35] M. Lewitowitz *et al.*, Phys. Lett. **B332** (1994) 20.
- [36] D. Schardt and K. Riisager, Z. Phys. **A345** (1993) 265.
- [37] A. Garcia *et al.*, Phys. Rev. Lett. **67** (1991) 3654; A. Garcia, Ph.D. thesis, University of Washington, 1991.
- [38] W. Trinder *et al.*, Phys. Lett. **B348** (1995) 331.
- [39] W. Trinder *et al.*, Phys. Lett. **B349** (1995) 267.
- [40] A. Piechaczek *et al.*, Nucl. Phys. **A584** (1995) 509.
- [41] A. Garcia *et al.*, Phys. Rev. **C51** (1995) R439.

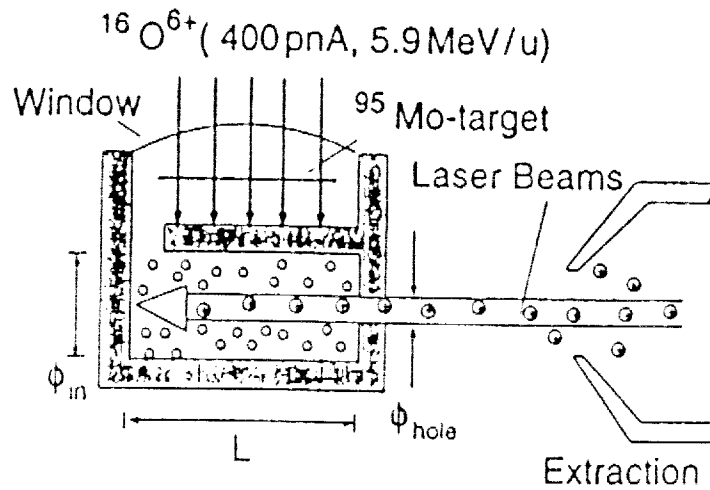


Figure 1: Schematic view of the laser ion source used for studying short lived tin isotopes. The dimensions  $L$  and  $\phi_{in}$  were varied during the series of test measurements, while  $\phi_{hole}$  was kept constant at a value of 1.2 mm.  $^{16}\text{O} + ^{95}\text{Mo}$  reactions were used for producing  $10.3 \text{ min } ^{108}\text{Sn}$  for test purposes [17] whereas the  $^{101}\text{Sn}$  experiments [5] were performed with  $^{58}\text{Ni} + ^{50}\text{Cr}$  reactions.

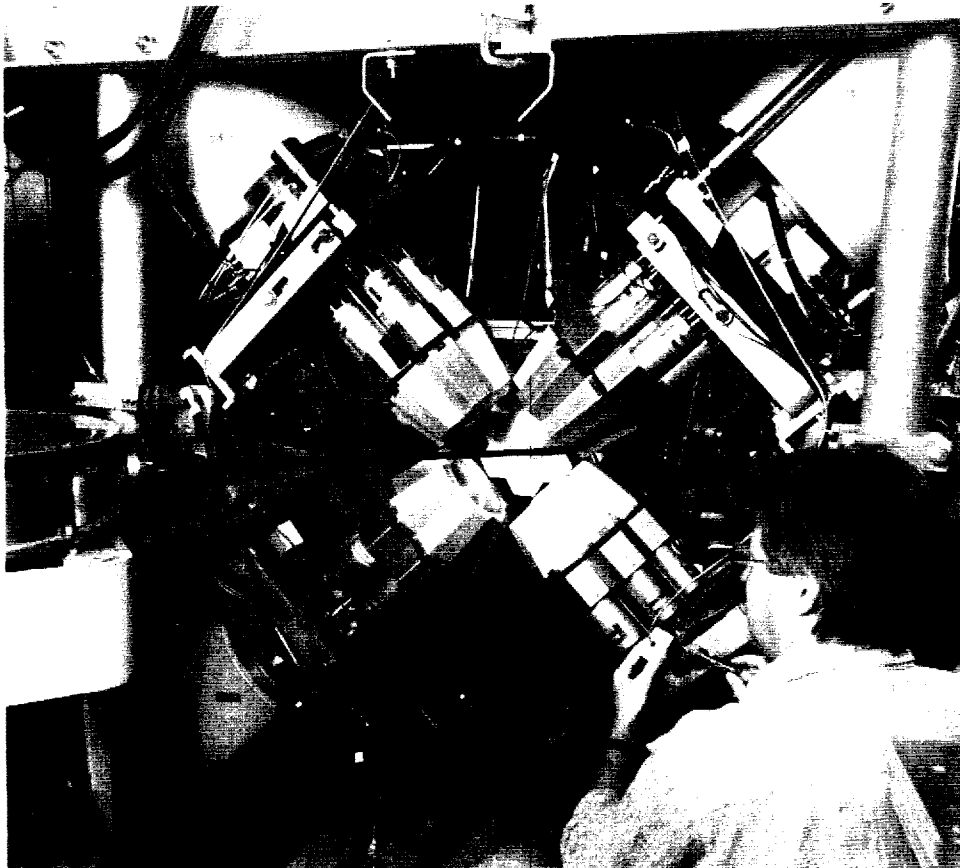


Figure 2: View on five of the six EUROBALL CLUSTER detectors mounted at the GSI on-line mass separator. Since the sixth detector has been removed the transport tape is clearly visible. (Photo: A. Zschau, GSI)

