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Abstract

The new neutron-deficient nuclei ^{103}Sb,^{104}Sb,^{98}In, ^{91}Pd,^{89}Rh and ^{87}Ru have been identified among the quasifragmentation products of a ^{112}Sn beam (63 MeV/nucleon). The fragment identification based on energy-loss, total kinetic energy and time-of-flight measurements has been independently confirmed via observation of γ-radiation following the decay of known short-lived isomers. The region of known isotopes is extended to the predicted proton drip-line for indium and silver, and beyond it for antimony and rhodium. Tentative evidence for the existence of ^{105}Te, ^{99}Sn and ^{93}Ag is also presented.

25.70.Mn,25.70-z,21.10.Dr,21.10.Tg,27.60.+j

Typeset using REVTEX

The identification and study of exotic nuclei in the vicinity of the doubly-magic nucleus ^{100}Sn has been an experimental challenge of great interest over the last years resulting recently in the observation of ^{100}Sn [1,2] as well as of several other new isotopes in this region [3–6].

Many experimental and theoretical efforts have been undertaken due to the unique attractive features characterizing the nuclei close to ^{100}Sn. The double-shell closure far from the line of β-stability provides test for the nuclear structure models over a wide range of excitation energy. This is particularly important for the studies of the β-decay governed by the selective $\pi g_{9/2} - \nu g_{7/2}$ Gamow-Teller transformation [7,8] - one of the main motivations for the present experimental program as well as for the decay spectroscopy experiments performed at on-line mass separators. With the latter technique the decay properties of some of the closest neighbours of ^{100}Sn namely ^{101}Sn [6], ^{100}In [9] and ^{101}In [10], have been determined.

The influence of the Z=50 and N=50 shell-closures on the nuclear binding energies can be investigated by means of the identification of the proton drip-line nuclei (presented below) as well as by the observation of exotic disintegration modes such as ground-state proton decay [11] or heavy cluster emission [12]. Mapping the exact location of the proton drip-line represents a stringent test for the predictive power of different mass models far from stability.

The residual interaction of protons and neutrons occupying the same l=4 orbitals is one of the main interests of 'in-beam' experiments performed with multidetector arrays in the region of ^{100}Sn [13,14]. Here another motivation for the studies becomes apparent as this region forms the heaviest 'corner' in the chart of nuclides where self-conjugated (N=Z) nuclei are still proton-bound. The recently reported clear observation of the decays of μs-isomeric states in nuclei implanted at the final focus of LISE3 [15,16] provides an opportunity to complement the in-beam studies with spectroscopy of yrast traps at the projectile-fragment separators.

Investigations in the region of ^{100}Sn region also have an astrophysical context related to the nucleosynthesis path in the rapid proton capture process [17,18,5].

The main objective of the presented studies was to explore the possibility of using the ^{112}Sn projectiles at intermediate energies to produce neutron-deficient nuclei in the region of ^{100}Sn and to examine the detector arrays necessary to study these nuclei separated in-flight. The set-up presented here incorporates features of the three experimental techniques mentioned above and makes it, in principle, possible to perform not only identification measurements, but also in-beam (μs-isomers) and decay spectroscopy.

Two experiments with the LISE3 spectrometer at GANIL using a ^{112}Sn have been carried out. Encouraging results were obtained in the first one with a 58 MeV/nucleon beam and a ^{nat}Ni (78 mg/cm^2) target, where the neutron-deficient tin isotopes out to ^{101}Sn, including the new isotope ^{102}Sn, were observed [3]. At the final focus of the LISE3 spectrometer, four large-volume Ge detectors were used to detect the emitted gamma-rays. By correlating the heavy-ion implantation signals via slow (about 10 μs) coincidences with gamma-rays characteristic for the decay of known, short-lived (100 ns - 100 μs) isomeric states, it was possible to independently verify the isotope identification. An example is given in Fig.1a. Forty known isomers have been observed. These findings, together with the details of this novel method and the measured intensities of isomeric beams, will be discussed in a forthcoming paper [16]. The yields for the very neutron-deficient nuclei were increased by about an order of magnitude in the second experiment with a ^{112}Sn beam at 63 MeV/nucleon, in which ^{100}Sn was identified [2].

In the following we present the results of the full evaluation of the data (mass, A, and atomic number, Z) for the exotic quasi-fragmentation products in the ^{100}Sn region obtained in the second experiment. The experimental set-up has been described previously [2], as well as the method of determining the A and Z of the fragments using the energy loss (ΔE), total kinetic energy (TKE), and time-of-flight (TOF) measurements [2,19]. Briefly recapitulating, a beam of the isotopically rare isotope ^{112}Sn delivered by the GANIL cyclotron complex at an energy of 63 MeV/nucleon and average intensity of 2.4 pnA impinged on a ^{nat}Ni target (144 mg/cm^2) placed between the two superconducting solenoids of the SISSI device [20]. The total beam dose during the final measurement was 2.4×10^{15} particles. Reaction products were transported over a 118 m long flight path with a time-of-flight of $\approx$1.5 μs and separated by means of the Alpha [21] and LISE3 [22] spectrometers set to a magnetic rigidity (Bρ) of 1.876 Tm. A thin mylar foil placed between the two sections of the LISE3 spectrometer was used to change the charge states of the ions. An asymmetric magnetic rigidity settings of the two sections allowed a reduction of the rate of the unwanted light fragments at the final detector position. The Wien filter [22] at the exit of the spectrometer provided a further selection of the reaction products.

At the final focus of LISE3, the fragments were implanted in a telescope consisting of four silicon detectors : the first pair of detectors (300μm, 300μm) provided information on the energy loss (ΔE) and the total kinetic energy (TKE) of the heavy ions, while the last pair (300μm, 500μm) was used in a veto mode in order to reject the lighter ions. The time of flight (TOF) was measured using a start signal from the first Si detector and a delayed stop signal derived from the radiofrequency of the second cyclotron. The Ge detector array surrounding the implantation telescope used in the first experiment was replaced by a segmented BGO ring [23]. An increase in efficiency (from 6.4% to 50% for the 511 keV photopeak) was preferred here to the higher resolution of the Ge array as priority was the detection of annihilation radiation (the 511-511 keV pairs in opposite segments) in correlation with the heavy-ions, in order to obtain half-life information. However, even with the poor resolution of the BGO ring, nine known decays of the short-lived isomeric states (from ^{43m}Sc to ^{96m}Pd) were clearly observed. This confirmed unambiguously the standard ΔE-TKE-TOF isotope identification procedure, which was based on the calibrations with ^{112}Sn charge states. An example of the recorded spectra is given in Fig.1b. For further details see reference [16].

In the first experiment with the ^{112}Sn^{+43} beam (58 MeV/nucleon) the intensity distribution of the tin fragments versus the charge state Q after the target (78 mg/cm^2 of ^{nat}Ni with a 9.5 mg/cm^2 carbon foil backing) was dominated by the Q=+48 and Q=+49 charge states (about 90% of all ions), see refs. [3,15]. In the second experiment (^{112}Sn^{+44} at 63 MeV/nucleon and 144 mg/cm^2 ^{nat}Ni target without backing), most of the very neutron-deficient tin isotopes were observed in the Q=+48 and +47 charge states. The primary charge and momentum distributions after the target were modified for each individual fragment according to the Bρ of the beam line and the Wien filter setting.

The events attributed to the same fragment but produced in the different charge states after the production target have been summed together. For the even-mass nuclei the charge states corresponding to A-2Q=4 (e.g. ^{100}Sn^{+48}) and A-2Q=6 (e.g. ^{100}Sn^{+47}) have been taken into account, while for the odd-masses A-2Q=3 (e.g. ^{101}Sn^{+49}) and A-2Q=5 (e.g. ^{101}Sn^{+48}) have been included. The resulting mass distributions for odd-A and even-A nuclei are presented in Fig.2 - following the separation of odd- and even-mass isotopes at the two-dimensional Z versus A/Q plot, see [2]. In these mass-spectra the respective neighbouring nuclei (with ΔA=2) are clearly separated. In addition to the eleven ^{100}Sn^{+48} events reported in [2], thirteen more events have been identified as ^{100}Sn^{+47} ions, giving a total of 24 ^{100}Sn events identified in this experiment.

The obtained data have allowed also for the identification of six other new nuclei, namely ^{103}Sb, ^{104}Sb, ^{98}In, ^{91}Pd, ^{89}Rh and ^{87}Ru, which are clearly isolated from the neighbouring heavier isotopes in the mass spectra of Fig.2. A comparison with the mass formula predictions compiled in [26] shows that the expected proton drip-line in the ^{100}Sn region has been reached for odd-Z elements of indium and silver, and even crossed for antimony and rhodium. Three antimony isotopes observed in this study, the newly identified ^{103}Sb and ^{104}Sb and the reported ground-state proton emitter ^{105}Sb [11], are already beyond the predicted proton drip-line [26]. However, for ^{104}Sb and ^{105}Sb, the calculated β-decay probabilities are much larger than the direct proton-decay channel [27,11]. The resulting half-lives are predicted to be 1.5 s [27] and 0.5 s [11], respectively. These large values are mainly due to the relatively small energies of the emitted protons, estimated to be 460 keV for ^{104}Sb [27] and measured to be 478±15 keV for ^{105}Sb [11].

The new isotopes ^{103}Sb and ^{89}Rh are expected to be proton unbound by $S_p \approx 1$ MeV when the measured $S_p(^{105}\mathrm{Sb})$, and the differences $\Delta S_p(^{103}\mathrm{Sb},^{105}\mathrm{Sb})$ and $\Delta S_p(^{89}\mathrm{Rh},^{105}\mathrm{Sb})$ according to Masson-Janecke (MJ) and Janecke-Mason (JM) mass models, are taken. The MJ and JM models, among eleven given in [26], predict the S_p value for ^{105}Sb closest to the experimental one [11]. Direct proton emission should therefore be the dominant decay mode. Predictions of the proton half-life $T^p_{1/2}$ for their ground state decay depend very strongly on the proton energy as well as on the assumption of the shell model orbital occupied by the emitted proton. Therefore, $T^p_{1/2}$ estimations vary by five orders of magnitude, from a few picoseconds to microseconds [11,28]. Since ^{103}Sb and ^{89}Rh were observed after a time-of-flight of about 1.5 μs, this suggests that the energies of the emitted protons are below 1 MeV. However, the possible presence of comparably long-lived ($\approx \mu$s) spin-gap isomers in these nuclei might also account for the observation of such ions. This remains to be verified experimentally.

Seventeen events have been assigned to ^{106}Te corresponding to the two-proton pick-up and eight-neutron stripping reaction channel for ^{112}Sn projectiles. Such a reaction channel with a ^{106}Cd beam corresponds to the production of ^{100}Sn. A simple extrapolation of the result obtained for ^{106}Te suggests that a production rate similar to that achieved here for ^{100}Sn might also be expected with a ^{106}Cd beam at intermediate energy and an intensity at the 10^{10} pps level, compare [5].

Some events have been observed which may correspond to the even more exotic nuclei like ^{105}Te, ^{99}Sn (see Fig.2a) and ^{93}Ag (see Fig.2b), the latter one also being expected to be proton unbound by about 1 MeV [26]. As there are still a few background counts present, we can interpret these events as only tentative evidence for the existence of these nuclei. In a future experiment with yields increased by at least a factor of five we aim to make an unambiguous identification. The expected improvements are mainly related to an increase in the primary beam intensity sustainable by the rotating target of SISSI as well as an increase in the momentum acceptance of the Alpha spectrometer.

The correlation between heavy fragments implanted in the Si-telescope, and the 511-511 keV annihilation quanta could not be used in the present data to extract decay properties as the implantation rate, mainly of lighter ions, was still too high (a few hundred per second). As noted earlier,to strongly reduce the number of light ions, a combination of a thin, charge-changing foil with an asymmetric setting of LISE3 may be used. In future however, this will be done with a lower magnetic rigidity in the spectrometer section behind the foil. This method should preserve a good transmission for heavy products while simultaneously reducing the counting rate of the fully stripped lighter fragments. The expected reduction of contaminants should allow for correlation measurements between incoming ions and β-delayed radiation (positrons, photons) to be made. Thus it should prove possible to measure the half-life of ^{100}Sn and of neighbouring exotic nuclei. Simultaneously, the search for new isomeric states in the proton-drip line nuclei with a high-resolution gamma detection set-up at the final focus of the spectrometer may be undertaken.

REFERENCES

* On leave of absence from IFD, Warsaw University, 00681 Warsaw, Poland

[1] R. Schneider *et al.*, Z. Phys. **A348** (1994) 241

[2] M. Lewitowicz *et al.*, Phys. Lett. **B332** (1994) 20

[3] M. Lewitowicz *et al.*, Nouvelles du Ganil **48** (1993) 7

[4] K. Schmidt *et al.*, Z. Phys. **A**, in print

[5] M. Hencheck *et al.*, submitted to Phys. Rev. **C** as Brief Report

[6] Z. Janas *et al.*, contribution to the Int. Symposium 'New Nuclear Structure Phenomena in the Vicinity of Closed Shells', 30th Aug.-3rd Sept. 1994, Stockholm-Uppsala, Sweden, to be published in Phys. Scripta

[7] K. Rykaczewski, Proc. of 6th Int. Conf. on Nuclei far from Stability and 9th Int. Conf. on Atomic Masses and Fundamental Constants, Bernkastel-Kues 1992, R. Neugarth, A. Wöhr (eds), IOP Conf. Ser. **132** (1993) 517

[8] B. A. Brown and K. Rykaczewski, Phys. Rev. **C**, Rapid Communication, in print

[9] J. Szerypo *et al.*, Nucl. Phys. **A**, in print

[10] M. Huyse *et al.*, Z.Phys. **A330** (1988) 121

[11] R. J. Tighe *et al.*, Phys. Rev. **C49** R2871 (1994)

[12] A. Guglielmetti *et al.*, Proc. of the Fifth Int. Conf. on Nucleus-Nucleus Collisions, Taormina, Italy, 30 May-4 June, 1994, Nucl. Phys. **A**, in print

[13] A. Johnson *et al.*, Nucl. Phys. **A557** (1993) 401c

[14] D. Seweryniak *et al.*, Z.Phys. **A345** (1993) 243

[15] M. Lewitowicz *et al.*, contribution to the Int. Conf. on Nuclear Shapes and Nuclear

Structure at Low Excitation Energies, Antibes, France, 20-25 June 1994, to be published

[16] R. Grzywacz *et al.*, 'Identification of μs-Isomers produced in the Quasifragmentation of a ^{112}Sn beam', to be submitted

[17] R.K. Wallace and S.E. Woosley, Astrophys. J. Suppl. **45** (1981) 389

[18] A.E. Champagne and M. Wiescher, Ann. Rev. of Nucl. and Part. Sci. **42** (1992) 39

[19] D. Bazin *et al.*, Nucl. Phys. **A515** (1990) 349

[20] A.Joubert *et al.*, Proc. of the Second Conf. of the IEEE Particle Accelerator, San Francisco, May 1991, p.594 and Nuclear Physics News, Vol.1, N°2, 1990, p.30

[21] R. Rebmeister *et al.*, Report CRN/PN 1983-16, 1983

[22] R. Anne and A.C.Mueller, Nucl. Instr. and Meth. **B70** (1992) 276

[23] H. Keller *et al.*, Z.Phys. **A340** (1991) 363

[24] P.M. Endt, Nucl. Phys. **A521** (1990) 1

[25] C.M. Baglin, Nucl. Data. Sheets **70** (1993) 1

[26] P.E. Haustein (ed.), At. Data Nucl. Data Tables **39** (1988) 185

[27] R.D. Page *et al.*, Phys. Rev. Lett. **72** (1994) 1798

[28] S.Hofmann, private comunication 1994

FIGURE CAPTIONS

1 Gamma spectra recorded in a slow time correlation with the ions identified as ^{43}Sc and ^{93}Ru by means of the ΔE-TKE-TOF measurements (a) with high-resolution Ge detectors in the experiment with the ^{112}Sn beam at 58 MeV/nucleon, and (b) with a low-resolution but high-efficiency BGO ring in the experiment with the ^{112}Sn beam at 63 MeV/nucleon The known characteristic gamma transitions deexciting isomeric states in ^{43m}Sc (E*=3123.2 keV, $T_{1/2}$=468 ns, ref. [24]) and ^{93m}Ru (E*=2082.5 keV, $T_{1/2}$=2.15 μs, ref. [25]) are clearly observed in both measurements, despite the low energy resolution of the BGO crystal. For further examples, see [16].

2 Mass distributions separated into odd-A (left column) and even-A (right column) quasi-fragmentation products observed in the experiment with the ^{112}Sn beam at 63 MeV/nucleon: (a) for Z from 52 to 48, and (b) for Z from 47 to 44. Nuclei identified for the first time in this study are indicated by solid arrows, while the events assigned to ^{100}Sn and ^{106}Te (discussed in the text) are marked by dashed arrows. The data correspond to 2.4×10^{15} particles incident on the ^{nat}Ni (144 mg/cm^2) target.

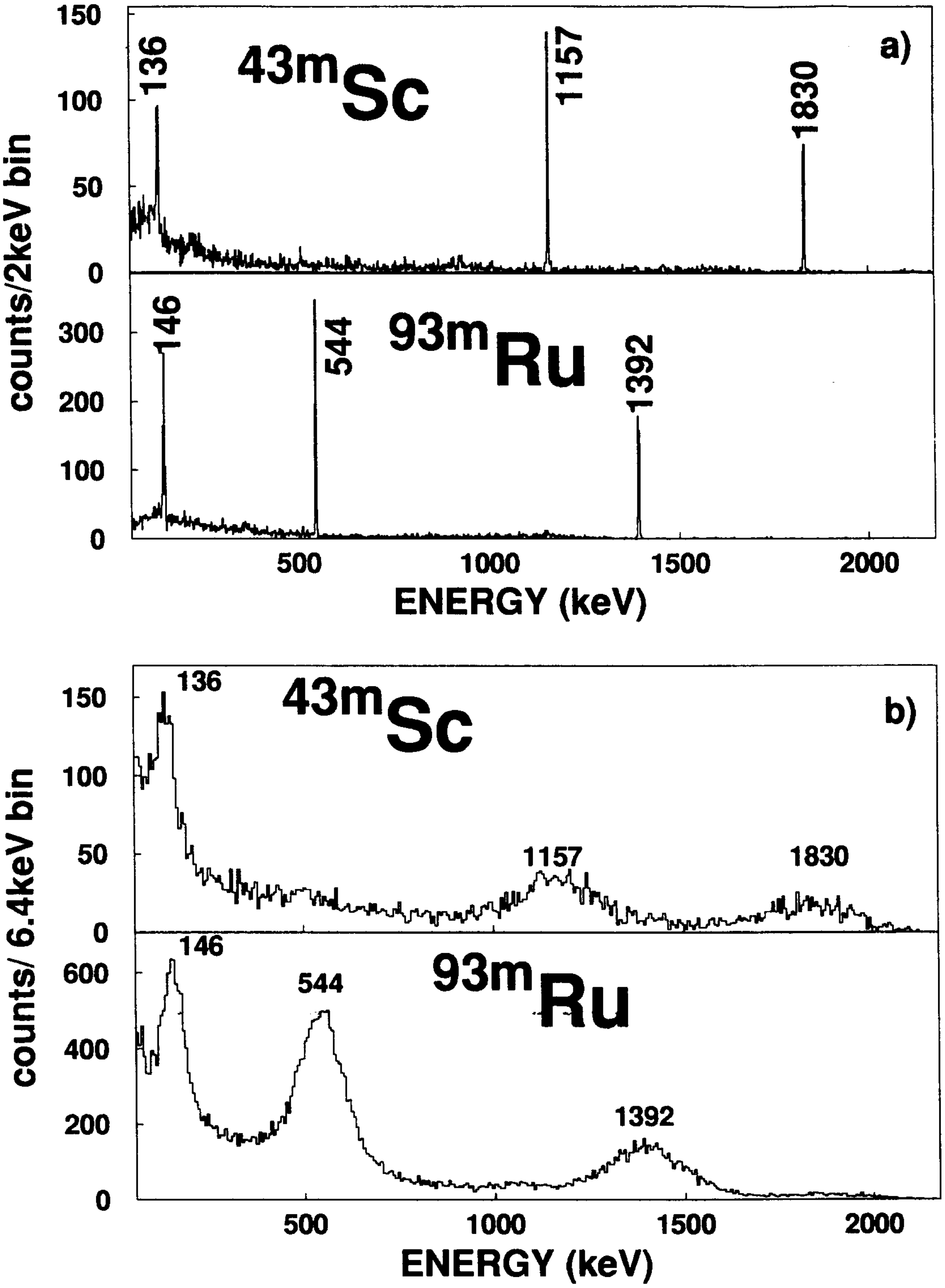
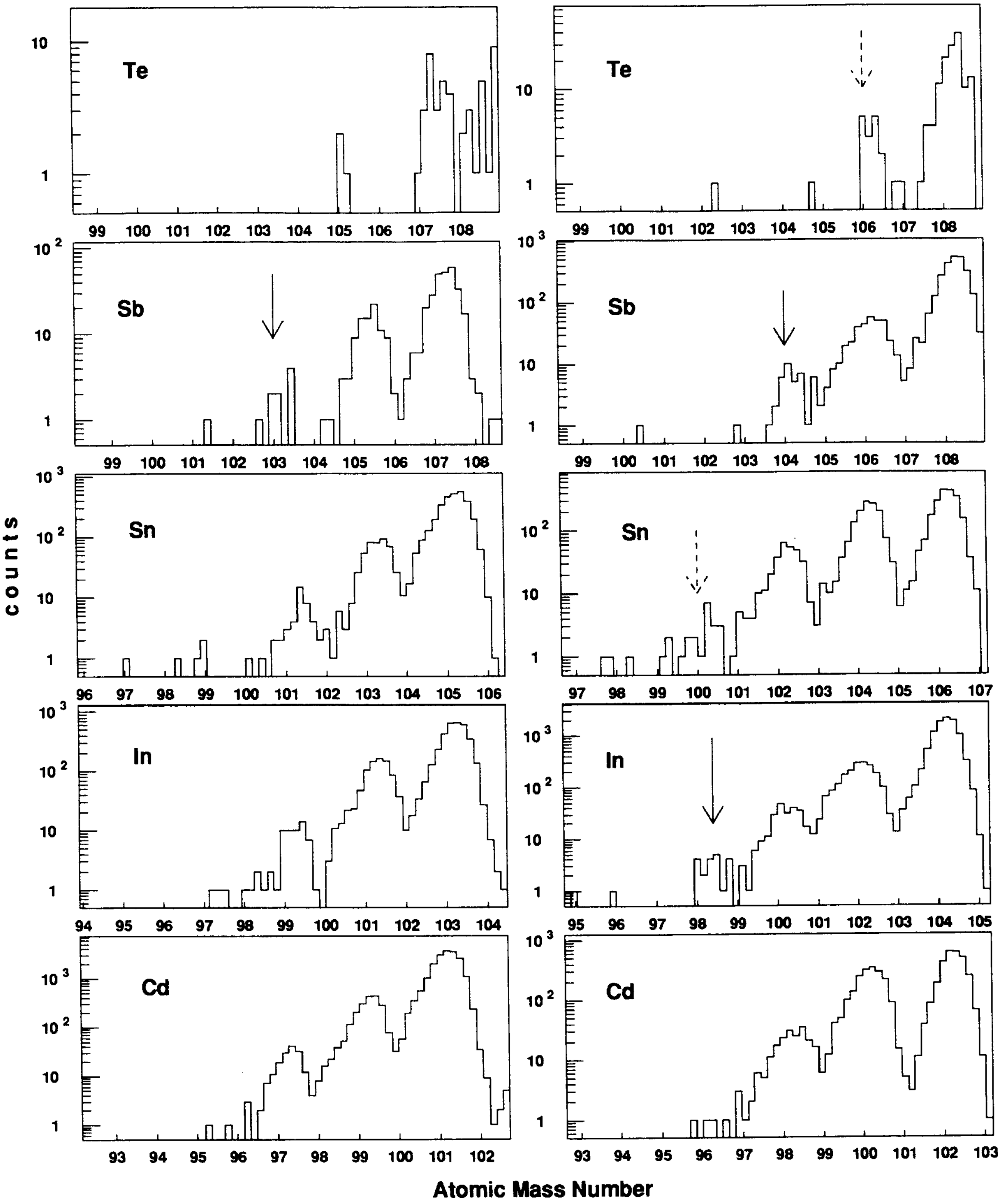

a)
^{43m}Sc
136
1157
1830
^{93m}Ru
146
544
1392
counts/2keV bin
150
100
50
0
300
200
100
0
500
1000
1500
2000
ENERGY (keV)
b)
^{43m}Sc
136
1157
1830
^{93m}Ru
146
544
1392
counts/ 6.4keV bin
150
100
50
0
600
400
200
0
500
1000
1500
2000
ENERGY (keV)

Fig. 1



counts
Te
Te
Sb
Sb
Sn
Sn
In
In
Cd
Cd
10
1
10
1
10 2
10
1
10 3
10 2
10
1
10 3
10 2
10
1
10 3
10 2
10
1
10 3
10 2
10
1
10 3
10 2
10
1
10 3
10 2
10
1
99 100 101 102 103 104 105 106 107 108
96 97 98 99 100 101 102 103 104 105 106
97 98 99 100 101 102 103 104 105 106 107
94 95 96 97 98 99 100 101 102 103 104
95 96 97 98 99 100 101 102 103 104 105
93 94 95 96 97 98 99 100 101 102
93 94 95 96 97 98 99 100 101 102 103
Atomic Mass Number

Fig. 2a

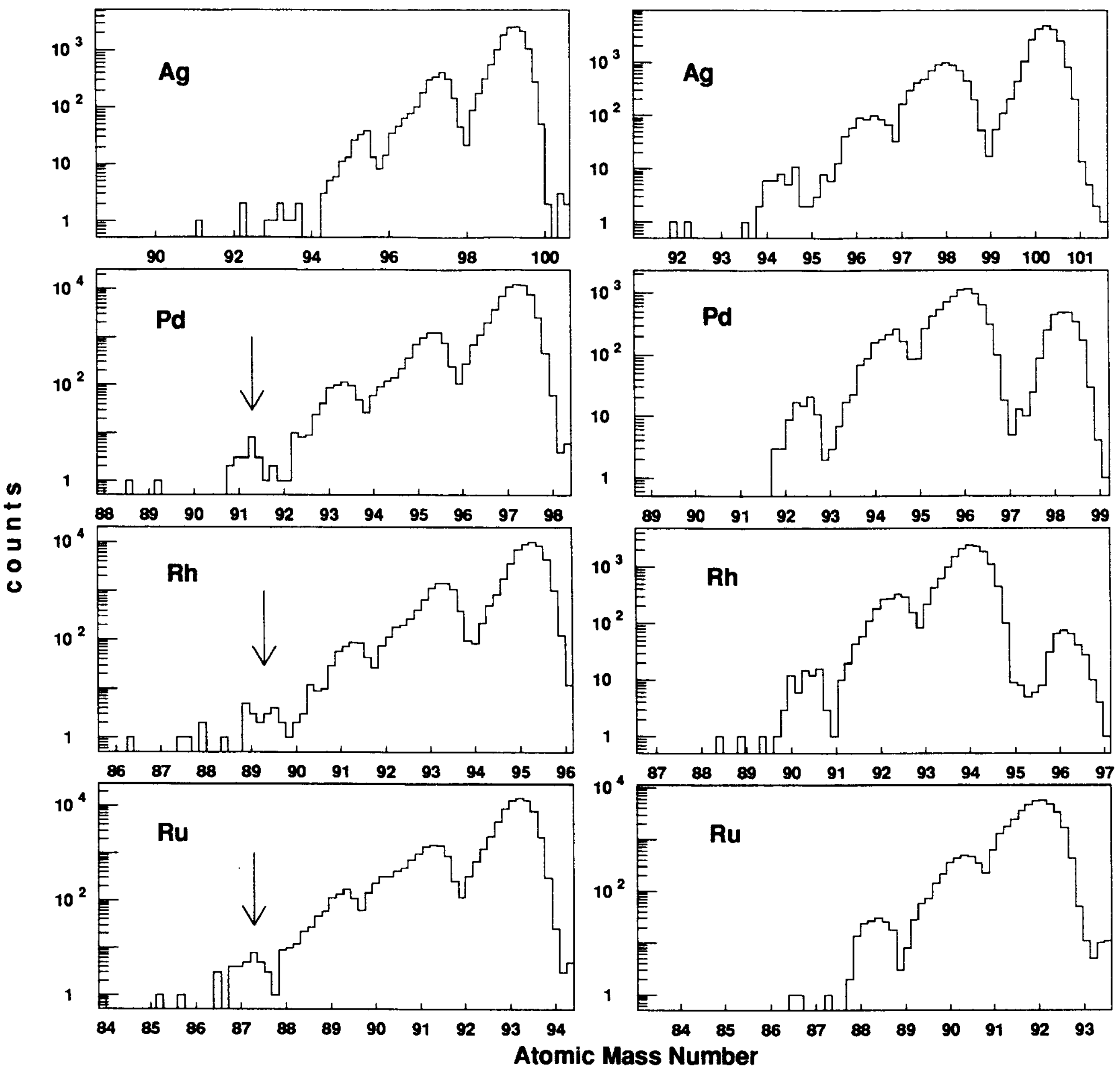

counts
Ag
Ag
Pd
Pd
Rh
Rh
Ru
Ru
1
10
10 2
10 3
10 4
90 92 94 96 98 100
92 93 94 95 96 97 98 99 100 101
88 89 90 91 92 93 94 95 96 97 98
89 90 91 92 93 94 95 96 97 98 99
86 87 88 89 90 91 92 93 94 95 96
87 88 89 90 91 92 93 94 95 96 97
84 85 86 87 88 89 90 91 92 93 94
84 85 86 87 88 89 90 91 92 93
Atomic Mass Number

Fig. 2b