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MEASUREMENTS OF PROTON SEPARATION-ENERGIES CLOSE TO THE PROTON DRIP LINE IN THE ANTIMONY-CESIUM REGION

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ABSTRACT: The mass-excess values and proton separation energies are determined for ^{114}Cs, ^{110}I and ^{106}Sb - the lightest known isotopes of cesium, iodine and antimony. The localization of the proton drip line is discussed.

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One of the interesting questions concerning the stability of nuclear matter is the location of the limits beyond which the nuclides are unstable towards emission of a single nucleon, the so-called proton and neutron drip lines. While for the light nuclides mass measurements in many cases have been performed all the way out to these border lines, the situation is different for the medium-mass and heavy nuclides, where information on proton-separation energies (S_p) for nuclides close to the drip line is scarce. Yet, this does not imply that no knowledge of the nuclear mass surface is available in such regions, since e.g. series of alpha-particle emitters have made the slope of the surface known via their Q_α-values.

Our extensive studies [1] of very neutron-deficient isotopes of elements ranging from tin to cesium have not only revealed information on Q_α-values [2], but some of the decay chains have also been linked to nuclides with known masses. In this way, the mass-excess (ME) values of several light isotopes of elements from cadmium to xenon were determined [3] with precisions between 30 and 130 keV. In a continuation of these studies, we have now determined S_p values for ^{114}Cs, ^{110}I and ^{106}Sb. These nuclides are close to the predicted proton drip line, as illustrated in fig. 1, and establishing their S_p values represents a step towards a quantitative localization of this border line of nuclear stability.

The decay links of interest here are shown in fig. 1, while the relevant ME values and decay energies are compiled in table 1. Starting with the known mass excess of ^{109}Sn, and using the auxiliary data on ^{113}I and ^{109}Sb decay in table 1, we can obtain the mass excess of ^{114}Cs from a measurement of the mass difference between ^{114}Cs and $(^{113}\mathrm{I}+{}^{1}\mathrm{H})$. This difference is equal to the end-point energy $(Q_{EC} - S_p)$ of the β-delayed proton spectrum (here Q_{EC} is the ^{114}Cs electron-capture decay energy and S_p is the proton separation energy of ^{114}Xe). Before describing the measurement of this end-point energy, we want to point out, that this work combined with our earlier results [2,3,5] yields a series of isotonicly neighbouring ME values allowing S_p determination, as can be seen from fig. 1.

The 0.6 s ^{114}Cs activity was produced by bombarding a ^{58}Ni target with 290 MeV ^{58}Ni ions from UNILAC [9]. Following separation in the GSI on-line mass separator and implantation into a movable tape, the ^{114}Cs samples were periodically transported to the measuring position. Here proton spectra were recorded by a telescope consisting of 25.3 μm thick and 150 mm^2 large energy-loss (ΔE) and a 732 μm thick, 450 mm^2 large rest-energy (E) surface-barrier silicon detectors subtending a solid angle of 12% of 4 π sr. Simultaneously a 0.1 mm thick scintillator, situated at the opposite side of the tape, detected positrons with an efficiency of about 32%. The data were stored as multiparameter events on magnetic tape by a PDP-11/45 computer.

To determine the (Q_{EC} - S_p) value for ^{114}Cs, we followed the procedure applied by Karnaukhov et al. [10] in studies of $^{109,111}Te$, namely to measure the proton spectrum simultaneously in singles mode and in coincidence with positrons, and to analyze these data with references to the energy dependence of the theoretical β^+ [11] and EC [12] probability ratios. The proton spectra were generated by summing coincident pulses from the ΔE and E detectors, and in addition a small correction was introduced to the singles spectrum to account for summing of proton and positron pulses [14].

The ratio of β-coincident to singles proton events is shown in fig. 2 as a function of the proton energy E_p. With increasing E_p, the ratio systematically decreases, reflecting the energy dependence of the fraction of beta decays proceeding by positron emission. Fig. 2 also shows theoretical ratios obtained from statistical-model [13] calculations, taking feeding of excited states of ^{113}I into account.

To estimate the role of excited states of ^{113}I, we have carried out auxiliary measurements of γ-rays in coincidence with protons from ^{114}Cs (see ref. [14] for detailed results). Unfortunately, the γ-ray data cannot be unambiguously converted into information on energies and relative feeding of the excited states of ^{113}I, mainly due to lack of knowledge on coincidence relationships between the individual transitions. We have therefore assigned an uncertainty of about 50 keV to the derived end-point energy coming from this source. The final result of a fitting procedure is $Q_{EC} - S_p = 8730 \pm 150$ keV, yielding the ME and S_p values of ^{114}I and ^{106}Sb presented in table 2.

The systematics of mass data for neutron-deficient nuclides in the cadmium to barium region (including our new results) and a detailed comparison with predictions of various mass formulae will be given in a forthcoming paper. Here we concentrate the discussion on the S_p data shown in fig. 3 for the light isotopes of cesium, iodine and antimony. The experimental results are compared with predictions of the Jänecke and Eynon [15] and Hilf et al. [6] mass formulae. These two formulae have been selected for comparison because they give good agreement with the previously measured S_p values for light antimony, iodine and cesium isotopes (with the exception of ^{117}Cs: the ME values of ^{117}Cs [16] and ^{116}Xe [4] lead to a negative S_p

for ^{117}Cs, a result which is surley in error considering the observed proton stability of ^{114}Cs). The difference between our S_p values for ^{109}Sb and ^{106}Sb is smaller than predicted by the mass formulae, suggesting that the actual value for ^{106}Sb, which is less accurately measured than ^{109}Sb, is near the lower experimental limit. If this is the case, the same applies to ^{110}I and ^{114}Cs, since the S_p differences between these isotopes and ^{106}Sb depend only on α-energies. The lower limits are close to the theoretical values of Hilf et al., who predict that ^{114}Cs, ^{110}I and ^{105}Sb are the last isotopes before the proton drip line.

The small and positive S_p value measured for ^{114}Cs is in line with the failure to observe proton radio-activity in this isotope - its partial half-life for proton decay is $>10^3$ s [9]. Searches for ^{113}Cs, which we now propose to be beyond the drip line, have yielded negative results at ISOLDE [17] and GSI [9], perhaps because this isotope has a very short lifetime against proton decay.

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Table 1. Mass-excess values and decay energies used for determining proton binding energies

Nucleus	Mass-excess value or decay Q-values (keV)		References
^{109}Sn	ME:	-82634±11	[7]
^{109}Sb	Q_{EC}:	6386±16	[8]
^{113}I	Q_{α}:	2706±41	[3]
^{114}Cs	$Q_{EC} - S_p$:	8730±150	This work
^{114}Cs	Q_{α}:	3357±31	[3]
^{110}I	Q_{α}:	3574±10	[3]
^{113}Xe	ME:	-62100±130	[5]
^{109}Te	ME:	-67620±130	[5]
^{105}Sn	ME:	-73245±130	[5]

Table 2. Experimental mass-excess values and proton separation energies

Nuclide	^{114}Cs	^{110}I	^{106}Sb
ME(keV)	-55100±160	-60890±160	-66890±160
S_p(keV)	290±200	560±210	930±210

FIGURE CAPTIONS

Fig. 1 Section of the chart of nuclides showing the masses and decay processes applied for determining proton binding energies. Nuclei with known ME values according to the 1977 mass evaluation [4] are marked by hatched squares, new ME data are taken from refs. [3,5] (broken line squares) and from the present work (solid-line squares). The decay links of interest are indicated by arrows. To the left the region is limited by the predicted [6] proton drip line.

Fig. 2 Intensity ratio of protons measured for the ^{114}Cs decay with and without the requirement of coincident positron detection. The experimental points have not been corrected for the efficiency of the beta counter (∼ 32%), which instead was included into the calculated curves. The full-drawn curve represents the best possible fit to the data, taking feeding of excited levels in ^{113}I into account, and yields the energy value given in the figure. The two dashed curves were calculated for the energy values corresponding to the limits of the uncertainty.

Fig. 3 Proton separation energies for neutron-deficient isotopes of antimony, iodine and cesium. Experimental results are from this work and from refs. [3,5] (full circles), from the 1977 mass evaluation [4] (open circles) and from combining data from the latter reference with recent mass-spectrometric results [16] (open squares). Predictions from the HGT (dashed lines) and JE (solid lines) mass formulae are also shown.

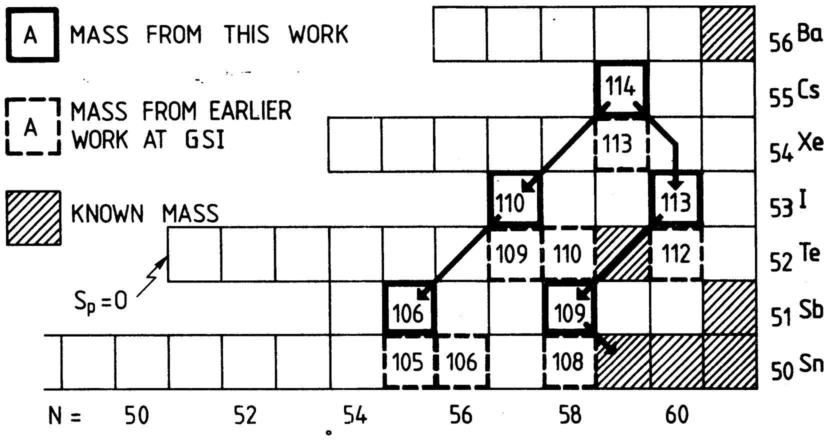

Fig. 1

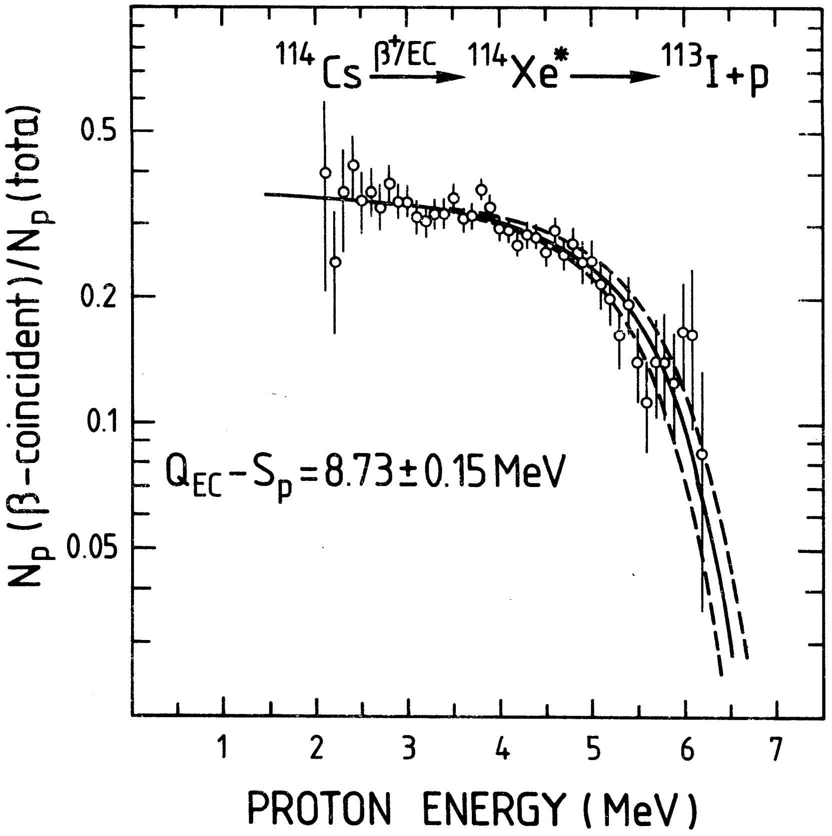
$^{114}Cs \xrightarrow{\beta^+/EC} {}^{114}Xe^* \longrightarrow {}^{113}I + p$
$Q_{EC} - S_p = 8.73 \pm 0.15$ MeV
N_p (β-coincident)/N_p (tota)
0.5
0.2
0.1
0.05
1
2
3
4
5
6
7
PROTON ENERGY (MeV)

Fig. 2

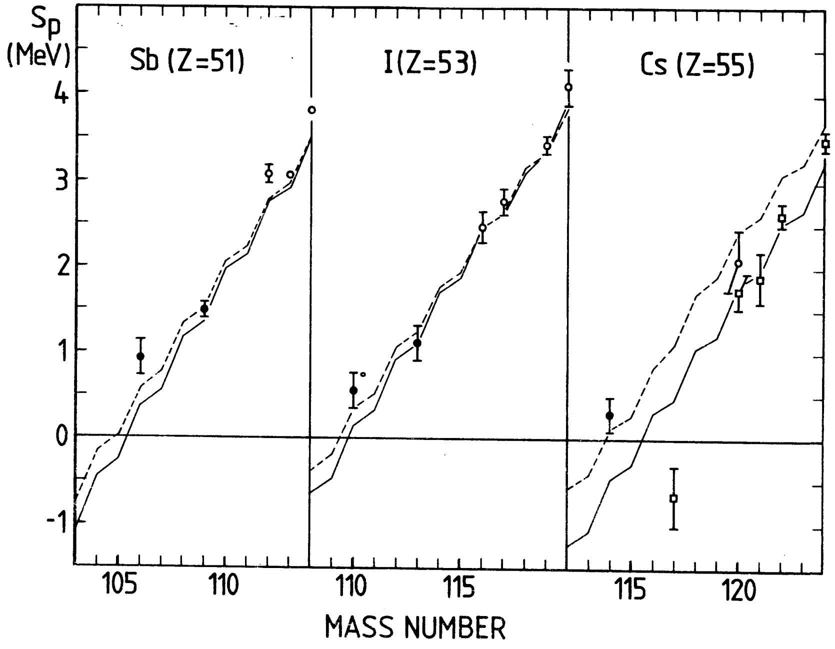
S_p (MeV)
Sb (Z=51)
I (Z=53)
Cs (Z=55)
4
3
2
1
0
-1
105
110
110
115
115
120
MASS NUMBER

Fig. 3