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NUCLIDE MASSES CLOSE TO THE PROTON DRIP LINE IN THE TIN REGION

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Abstract

Recently measured Q-values for alpha decays, β^+/EC decays and β-delayed proton decays in the tin region are used to link from known mass-excess values to new ones close to the proton drip line. The strength of the Z=50 proton shell is derived from experimental data in a model-independent way. Proton binding energies are deduced, showing that e.g. ^{114}Cs is barely bound against proton emission with a proton binding energy of 290 ± 200 keV. The results are discussed in terms of semi-empirical mass formulae.

1. Introduction

The binding energies or mass excess (ME) values of nuclear ground-states represent properties of basic interest, e.g. for testing nuclear-matter calculations. With respect to the applicability of such calculations for predicting properties of yet unknown nuclei very far from the β stability line, it is particularly important to compare with measured ME values of far unstable nuclei in a systematic way. One of the most powerful experimental methods used for this purpose is the determination of mass differences as decay Q-values, establishing thereby links from known to new ME values. This type of nuclear mass measurements represents one of the main goals of studies on very neutron-deficient nuclides in the tin region which are extensively carried out at the GSI on-line mass separator1). In a first series of experiments, the electron-capture decay energies Q_{EC} for the decay of ^{104}Cd and ^{106,108}Sn were determined. These results, combined with the mass-difference data from other particle spectroscopy studies, have yielded ME values with precisions between 30 and 130 keV for several nuclides from ^{104}Cd to ^{113}Xe (ref.2). In continuing these studies, we determined the ME values for ^{112}Te and ^{114}Cs. From the ME of ^{114}Cs, using the α-decay energies3), we deduce ME values for ^{110}I and ^{106}Sb. A combination of these ME values with those from ref.2 allows to derive the Z=50 proton shell strength and to obtain new information on proton binding energies B_p in the neighbourhood of the proton drip line. The results are discussed in terms of current mass formulae4), in particular with the droplet model formula in the version of Hilf, von Groote and Takahashi5) (HGT) and with the inhomogeneous-partial-difference equations of Jänecke and Eynon4) (JE).

2. Experimental studies and results

The way of ME determination for ^{112}Te and ^{114}Cs is illustrated in fig. 1. In the

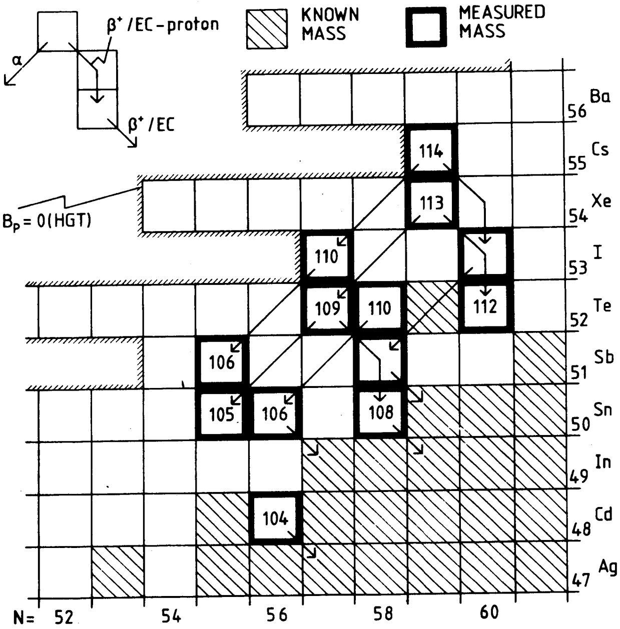

Fig.1 Section of the chart of nuclides illustrating the determination of decay energies and masses. The decay links of interest are indicated by arrows. Nuclei with known ME values are marked due to the 1977 mass evaluation6), new ME data are taken from ref. 2 and from the present work.

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Table 1 Compilation of auxiliary data and new ME and Q_p values. The nuclei are arranged in a sequence reflecting the method of linking from known to new ME values via Q_{EC}, Q_α or (Q_{EC}-B_p) values.

NUCLEUS	MASS-EXCESS VALUES AND DECAY Q-VALUE (keV)	REFERENCES
^{109}Sn	ME: -82634 ± 11	7
^{109}Sb	Q_{EC}: 6380 ± 16 ME: -76254 ± 19 Q_p: -1490 ± 90	8 This work ME(^{108}Sn) = -82050 ± 90 keV taken from ref. 2
^{113}I	Q_α: 2706 ± 41 ME: -71120 ± 50 Q_p: -1110 ± 200	3 This work This work
^{114}Cs	Q_{EC}-B_p: 8730 ± 150 ME: -55100 ± 160 Q_p: -290 ± 200 Q_α: 3357 ± 31	9 This work ME(^{113}Xe) = -62100 ± 130 keV taken from ref. 2 3
^{110}I	ME: -60890 ± 160 Q_p: -560 ± 210 Q_α: 3574 ± 10	This work ME(^{109}Te) = -67620 ± 130 keV taken from ref. 2 3
^{106}Sb	ME: -66890 ± 160 Q_p: -930 ± 210	This work ME(^{105}Sn) = -73245 ± 130 keV taken from ref. 2
^{113}Xe	ME: -62100 ± 130 Q_{EC}-B_p: 7920 ± 150	2 9
^{112}Te	ME: -77310 ± 200	This work

first case we consider the ^{113}Xe→^{113}I→^{112}Te + p decay chain. The ME value of ^{113}Xe is known[2]. Hence, in order to get the ME of ^{112}Te one has to measure the end-point energy (Q_{EC} - B_p) of the β-delayed proton spectrum, B_p being the proton binding energy in ^{113}I. In the second case we start with the ME value obtained for ^{109}Sn from transfer-reaction studies[7]. In order to get the ME of ^{114}Cs one has to measure Q_{EC} for the ^{109}Sb→^{109}Sn decay and (Q_{EC} - B_p) for the ^{114}Cs→^{114}Xe→^{113}I + p decay. The missing link between the ME values of ^{113}I and ^{109}Sb is provided by the known[3] Q_α value of ^{113}I. As the determination of Q_{EC} for ^{109}Sb (ref.8) and of (Q_{EC}-B_p) for ^{113}Xe and ^{114}Cs (ref.9) will be described separately, it suffices here to briefly summarize the main features of the experiments. The radioactive sources were produced in ^{58}Ni + ^{58}Ni reactions at the GSI on-line mass separator[10]. The Q_{EC}-value of ^{109}Sb was found by measuring positron endpoint energies for the main decay branches via β^+-γ coincidences between a plastic scintillator telescope and a Ge(Li) detector. The endpoint energies of β-delayed proton spectra were determined for the precursors ^{113}Xe and ^{114}Cs, measuring the proton spectra in singles mode and in coincidence with positrons and comparing[11] the energy-dependent coincidence-to-singles rates with theoretical $\beta^+/(EC + \beta^+)$ probability ratios. A surface-barrier detector telescope was used for the proton energy analysis and a thin plastic scintillator for positron counting. After correcting the measured proton singles spectra for positron-proton summing effects, (Q_{EC}-B_p) was deduced in a least-squares fitting procedure on the basis of the model assumptions used for interpreting the β-delayed particle decay of ^{114}Cs (ref.12), taking proton decay to excited states of the final nucleus into account[9].

The Q_{EC} and (Q_{EC}-B_p) values together with auxiliary ME and Q_α data are compiled in table 1 together with the resulting B_p values.

3. Discussion

3.1 Mass-excess values

A comparison of the 13 new ME values, obtained in this work (see table 1) and in ref.2, with predictions from various mass formulae[4] confirms the conclusion drawn in our earlier work[2]: The best overall agreement with the experiment is provided by the HGT and JE calculations, yielding root-mean-square deviations of the order of 0.3 MeV. However, even for the two formulae with best overall agreement there are discrepancies of up to 0.7 MeV for certain nuclei in this region.

It is interesting to consider the ME value of ^{114}Cs as an extension of the isotopic series $^{117-145}$Cs obtained from mass spectrometry by Epherre et al.[13]. The trend towards too high experimental ME values compared to most mass formulae for $^{117-120}$Cs does not continue for ^{114}Cs, which seems to break this trend.

3.2 The Z=50 proton shell strength

Assuming spherical nuclear shape and neglecting a small contribution from the droplet-energy change, the Z=50 proton shell strength may be approximated by the following difference of α-decay energies[14]:

$$\Delta Q_\alpha(N) = Q_\alpha({}^{A}_{52}\mathrm{Te}_{N+1}) - Q_\alpha({}^{A-2}_{50}\mathrm{Sn}_{N+1}).$$

The ΔQ_α systematics (fig.2) shows experimental evidence for the interdependence of proton and neutron shell strength (see ref.2 for a detailed discussion).

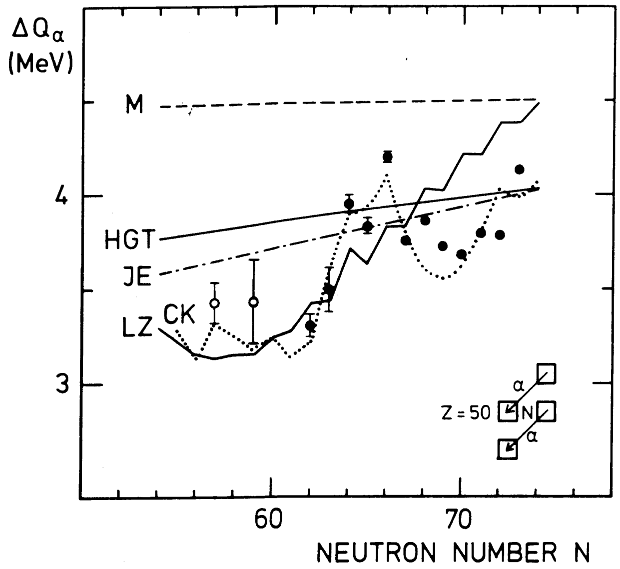

Fig. 2 Systematics of experimental $\Delta Q_\alpha(N)$ values for Z=50 in comparison with predictions from mass formulae. Full circles show data from the 1977 mass compilation[6], open circles represent results from this work and from ref. 2.

3.3. $(Q_{EC}-B_p)$ values

In addition to determining the end-point energies of β-delayed proton spectra for ^{114}Cs and ^{113}Xe by the positron-coincidence method, $(Q_{EC}-B_p)$ values were deduced for ^{110}I and ^{105}Sn from the new ME values (see table 1 and ref. 2) to be 8080 ± 160 keV and 3190 ± 130 keV, respectively. These results are shown in fig. 3 together with data from the literature and with the predictions from the HGT and JE mass formulae. Similar to the Q_α systematics[3], the $(Q_{EC}-B_p)$ values are dominated in this region by the Z=50 shell closure resulting in a large gap between tin and tellurium precursors. $(Q_{EC}-B_p)$ values are of special interest for interpreting the measured energy spectra, intensities and intermediate-nucleus lifetimes for β-delayed particle spectra[3]. Besides the 4 new end-point energies determined in this work, the systematics shown in fig. 3 may be used for estimating additional $(Q_{EC}-B_p)$ values by extrapolating the smooth linear relationships emerging for the tellurium-to-barium region. In this context it is interesting to note, that proton binding energies are known for ^{105}In (ref. 2,15), ^{109}Sb (this work and ref. 2), ^{110}Te (this work and ref. 2) and ^{113}I (this work), which represent intermediate nuclei for the β-delayed particle decays of ^{105}Sn, ^{109}Te, ^{110}I and ^{113}Xe, respectively. In these cases, not only the differences $(Q_{EC}-B_p)$, but also the two energy parameters themselves are given, which allow more reliable conclusions from β-delayed particle studies.

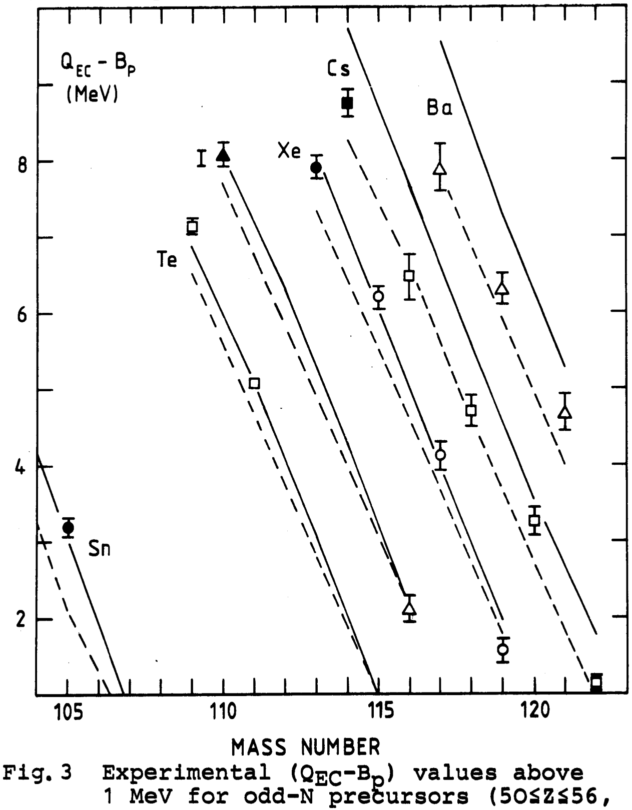

Fig. 3 Experimental $(Q_{EC}-B_p)$ values above 1 MeV for odd-N precursors (50≤Z≤56, N≤65) compared with predictions from the HGT (dashed lines) and JE (solid lines) mass formulae. Results from this work are shown as full symbols, literature data as open symbols.

3.4. Proton binding energies

B_p values obtained in this work (see table 1) are plotted in fig. 4 together with literature data and mass-formulae predictions. It becomes evident, that this work represents a significant extension of our knowledge about the nuclear mass surface close to the proton drip line in the tin region. ^{114}Cs appears to be barely bound against proton emission with a proton binding energy of 290 ± 200 keV. The result of B_p = -660 ± 350 keV for ^{117}Cs obtained as a difference between mass-spectrometric[13] and decay-spectrometric[4] ME measurements is puzzling in view of the deviation from the general trend of B_p systematics (fig. 4) and in view of the fact, that the ^{117}Cs half-life of 6.5 s[16] does not seem to allow for a significant direct proton-decay branch. Neglecting the ^{117}Cs result, one would expect on the semi-empirical basis of the B_p systematics shown in fig. 4 the nuclei ^{109}I and ^{113}Cs to be unbound against proton emission. Attempts to detect direct proton decay of these isotopes have been unsuccessful so far[3].

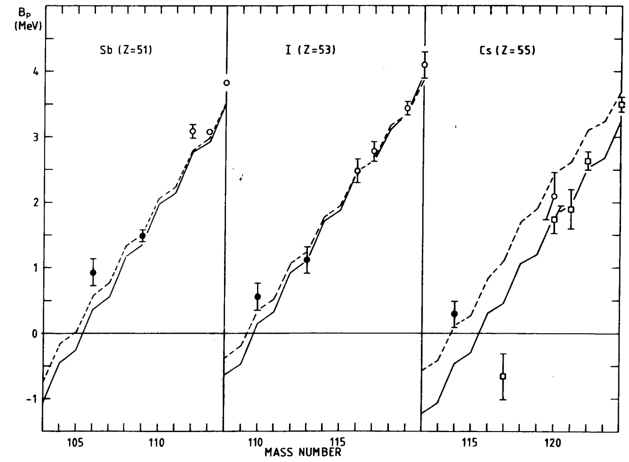

Fig. 4 Proton binding energies for neutron-deficient isotopes of antimony, iodine and cesium. Experimental results are from this work (full circles), from the 1977 mass evaluation[6] (open circles) and from combining data from the latter reference with recent mass-spectrometric results[13] (open squares). Predictions from the HGT (dashed lines) and JE (solid lines) mass formulae are also shown.

4. Summary and conclusion

By measuring total decay energies for neutron-deficient isotopes and linking them with known ME values, we succeeded in gaining precise information on the structure of the mass-energy surface in the tin region. Systematics for ME values, for proton binding energies and also for isobarice four-beta-decay energies[17] seem to suggest that the mass-spectrometric ME values for very neutron-deficient cesium isotopes, in particular for ^{117}Cs, are somewhat too high. A recent reevaluation[18] indeed showed that these data underestimate stability by approximately 0.2 MeV. However, this correction cannot fully account for the observed discrepancy.

The results of the present work, e.g. the information gained on the Z=50 proton shell strength, might be incorporated into future improvements of nuclear mass calculations. So far, taking into account experimental results on mass-excess, Q_{α}[3], ($Q_{EC}-B_p$) and B_p values, the droplet mass formula in the version by Hilf et al.[5] seems to offer a good overall description. Although such an agreement for a subset of nuclear masses far from stability is quite satisfactory in general, even more reliable predictions of certain mass differences are desired for interpreting the related decay phenomena or for estimating properties of yet unknown nuclei. Alpha decay[3] and β-delayed particle emission[9] may serve as examples for the application of measured (or extrapolated) Q-values.

Finally, this work represents also a step towards a quantitative localization of the proton drip line. ^{114}Cs is shown to be one of the most loosely bound nuclei, comparable to ^{11}Li with a two-neutron binding energy of 160 ± 120 keV.

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