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MASSES OF VERY NEUTRON-DEFICIENT ISOTOPES IN THE CADMIUM-TO-CESIUM 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 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. Furthermore, the measured mass-excess values and their differences are discussed systematically, e.g. in terms of semi-empirical mass formulae, for the cadmium-to-cesium region.

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RADIOACTIVITY ^{104}Cd, ^{104}In, ^{105,106,108}Sn, ^{106,109}Sb, ^{109,110,112}Te, ^{110,113}I, ^{113}Xe, ^{114}Cs [from ^{58}Ni (^{58}Ni, xpyn)]; measured E_α, E_p, $\beta\gamma$-coinc, βp-coinc; deduced Q_α, Q_{EC}, $Q_{EC} - S_p$, mass excess. On-line mass separation, enriched targets; surface-barrier Si, plastic scintillator and Ge(Li) detectors.

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 calculated with measured ME values of very 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 separator[1]). 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 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 α-decay energies[3]), 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 separation energies S_p. The latter aspect has been discussed in a separate paper[4]). Furthermore, the results are discussed in terms of current mass formulae[5]), in particular with the droplet model formula in the version of Hilf, von Groote and Takahashi[6]) (HGT) and with the inhomogeneous-partial-difference equations of Jänecke and Eynon[5]) (JE). Finally, systematics of the mass-differences $(Q_{EC}-S_p)$ and Q(4β) are presented.

2. Experimental studies and results

The way of ME determination for ^{112}Te and ^{114}Cs, starting-out from the known ME values of ^{113}Xe (ref.2) and ^{109}Sn (ref. 8), is illustrated in fig. 1. The measurement of the Q_{EC} value for ^{109}Sb (Q_{EC}=6380±16 keV) was described in ref. 9. In order to obtain $(Q_{EC}-S_p)$ for ^{113}Xe and ^{114}Cs the endpoint energies of β-delayed proton spectra were determined. The radioactive sources were produced in ^{58}Ni + ^{58}Ni reactions at the GSI on-line mass separator[10]). The proton spectra were measured in singles mode and in coincidence with positrons, using a surface-barrier detector telescope 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, $(Q_{EC}-S_p)$ was deduced by comparing[11]) the energy-dependent coincidence-to-singles ratio with theoretical $\beta^+/(EC + \beta^+)$ probability ratios. This was done 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[13]). The resulting $(Q_{EC}-S_p)$ values for ^{113}Xe and ^{114}Cs are 7920±150 and 8730±150 keV. More experimental informations were presented in ref. 13 and will be described in details separately[14]).

From these Q_{EC} and $(Q_{EC}-S_p)$ data and by improving some of the earlier ME results[2]) on the basis of remeasured Q_α values[3]), we obtained the 14 new ME values compiled in table 1, including the one for ^{104}In deduced from the measured endpoint energy[16]).

3. Discussion

3.1. MASS EXCESS VALUES

A comparison of the new ME values with predictions from various mass formulae (see table 1), confirms the conclusion drawn in our earlier work[2]): The best overall agreement with the epxeriment 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 MEvalue of ^{114}Cs as an extension of the isotopic series $^{117-145}Cs$ obtained from mass spectrometry by Epherre et al. [19]). 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.

As can be seen from the comparison of predictions from the JE mass formula with experimental data for cesium-to-tin isotopes, shown in fig. 2, this formula yields a good representation of measured masses for far-unstable tin-to-xenon isotopes. There is, however, a systematical deviation for light cesium isotopes.

When the other mass formulae are examined, the ones of Myers and Liran-Zeldes (see also table 1) have systematical shifts with respect to the experimental mass surface in that region. On the other hand, it is interesting to note that Myers' droplet-model is most appropriate for describing mass differences such as Q_α values[3]).

The recent mass formula of Möller and Nix[15]) appears to give particularly the tin isotopes much too strongly bound, and to fit badly the mass-differences (e.g. Q_α for tellurium isotopes), too.

3.2 THE Q(4β) SYSTEMATICS

We want to discuss the Q(4β) systematics as proposed by Wapstra and Bos[20]):

$$Q(4\beta) = ME(A,Z) - ME(A,Z-4) \ . \qquad (1)$$

This quantity does not depend on the influence of pairing effects and, as the daughter nuclei are on or close to the beta stability line, offers a quite accurate description of mass properties of nuclei far from stability.

In fig. 3, experimental Q(4β) values for cadmium-to-barium isotopes from refs. 7, 8, 16, 21 and from our work are given together with predictions resulting from systematical extrapolations. The following conclusions can be drawn:

1. The Q(4β) values measured for neutron-deficient indium-to-antimony isotopes are systematically smaller than predictions from systematics[7]).

2. For cesium isotopes, the Q(4β) values deduced[19]) from mass spectrometry are systematically larger and the slope is different from the one measured for other elements.

3.3 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[22]):

$$\Delta Q_\alpha(N) = Q_\alpha({}^{A}_{52}Te_{N+1}) - Q_\alpha({}^{A-2}_{50}Sn_{N+1}) \ . \qquad (2)$$

The ΔQ_α systematics (fig. 4) shows experimental evidence for the inter-dependence of proton and neutron shell strength (see ref. 2 for a detailed discussion).

3.4 $Q_{EC}-S_p$ VALUES

In addition to determining the endpoint energies of β-delayed proton spectra for ^{114}Cs and ^{113}Xe by the positron-coincidence method, $Q_{EC}-S_p$ values were deduced for ^{110}I and ^{105}Sn from the new ME values (see table 1 and and ref. 2) to be 8080±160 keV and 3190±130 keV, respectively. These results are shown in fig. 5 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 $(Q_{EC}-S_p)$ values are dominated in this region by the Z=50 shell closure resulting in a large gap between antimony and tellurium precursors. $(Q_{EC}-S_p)$ values are of special interest for interpreting the measured energy spectra, intensities and intermediate-nucleus lifetimes for β-delayed particle spectra[13]). Besides the 4 new endpoint energies determined in this work, the systematics shown in fig. 5 may be used for estimating additional $(Q_{EC}-S_p)$ 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 $(Q_{EC}-S_p)$, but also the two energy parameters themselves are known, which allow more reliable conclusions from β-delayed particle studies.

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 allowing a systematical discussion of ME values, proton separation energies[4]), α decay energies[3]) and isobaric four-beta-decay energies. These systematics 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[23]) indeed showed that the original data[19]) underestimate stability, e.g. for ^{117}Cs by approximately 0.2 MeV. However, this correction cannot fully account for the observed discrepancy. An experiment, which would help to clarify this discrepancy, would be the search for α decay of ^{117}Cs, since the corresponding Q_α value would represent a decay link to ^{113}I. The known ME value of ^{113}I together with the one of ^{117}Cs measured by Epherre et al.[19]) corresponds to a Q_α value for ^{117}Cs of about 3.38 MeV and, assuming a reduced width similar to ^{114}Cs (ref. 3, 12), to a branching

of $\sim 4\cdot10^{-3}$. On the other hand, the Q_α value of about 2.4 MeV expected from systematics of α decay energies is considerably lower, corresponding to an α branching ratio as small as $7\cdot10^{-12}$. Since, under present experimental conditions, the smallest detectable α branching for ^{117}Cs is of the order of 10^{-8}, a negative result of a search experiment would allow to determine an upper limit of Q_α around 2.7 MeV.

It is interesting to note that there are two decay paths from ^{113}Xe to ^{108}Sn, namely $^{113}\text{Xe} \xrightarrow{\alpha} {}^{109}\text{Te} \xrightarrow{\beta p} {}^{108}\text{Sn}$ and $^{113}\text{Xe} \xrightarrow{\beta p} {}^{112}\text{Te} \xrightarrow{\alpha} {}^{108}\text{Sn}$ (see fig. 1). Since three decay energies involved in this closed loop are known, the fourth one can be deduced to be $Q_\alpha(^{112}\text{Te}) = 2.31 \pm 0.18$ MeV. This result is in accordance with the non-observation of α decay of ^{112}Te, since even the upper limit of the corresponding α energy is lying more than 150 keV below the lower limit of the so far smallest α-energy observed[3]) in this region, $E_\alpha(^{113}\text{I}) = 2610 \pm 40$ keV. From Q_α systematics of the lighter tellurium isotopes, however, one would expect a Q_α-value for ^{112}Te close to 2.15 MeV, thus suggesting that the actual ME of ^{112}Te is near the lower experimental limit, an argument which becomes additional support from the Q(4β) value of ^{112}Te (see fig. 3).

The results of the present work, e.g. the information gained of 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, $(Q_{EC}-S_p)$ and S_p values, the droplet mass formula in the version of Hilf et al.[6]) 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]), β-delayed particle emission[13]) and more recently also direct proton decay[24,25]) may serve as examples for the application of measured (or extrapolated) Q-values.

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Table 1. New mass-excess data compared to predictions from mass formulae

Nuclide	M_{exp}-A (keV)	$M_{cal} - M_{exp}$ (keV)					
		M a)	LZ a)	CK a)	JE a)	HGT b)	MN c)
^{104}Cd	- 83 720±30 d)	- 340	- 220	- 310	- 150	620	200
^{104}In	- 76 310±200 e)	- 1000	580	70	190	330	110
^{105}Sn	- 73 245±130 d)	- 1690	920	- 70	- 280	- 120	- 810
^{106}Sn	- 77 460±90 d)	- 1170	800	- 30	- 30	310	- 580
^{108}Sn	- 82 050±90 d)	- 910	320	- 120	- 50	340	- 520
^{106}Sb	- 66 885±160 f,g)	- 1210	2210	400	290	220	1060
^{109}Sb	- 76 254±19 f,g,h)	- 860	840	10	90	320	460
^{109}Te	- 67 620±130 d)	- 1460	980	- 430	- 320	- 280	1020
^{110}Te	- 72 310±90 d)	- 740	990	0	230	370	1210
^{112}Te	- 77 310±200 f)	- 690	310	- 410	- 250	- 220	660
^{110}I	- 60 890±160 f,g)	- 1170	1860	- 300	90	- 70	1870
^{113}I	- 71 120±50 f)	- 790	520	- 680	- 250	70	810
^{113}Xe	- 62 100±130 d)	- 1310	590	- 1240	- 70	- 370	1160
^{114}Cs	- 55 100±160 f,g)	- 1460	1190	- 1270	- 680	- 200	1440
	mean square deviation	1100	1040	560	270	320	970

a) Mass predictions[5] of Myers (M), Liran-Zeldes (LZ), Comay-Kelson (CK), Jänecke-Eynon (JE).
b) Hilf-von Groote-Takahashi[6]. c) Möller-Nix[15]. d) Ref. 2.
e) Determined from the new mass-excess of ^{104}Cd (ref. 2) and the positron endpoint energy of the ^{104}In decay, preferring the result of Cerny et al.[16] against ah earlier measurement[17].
f) Ref. 18. g) Ref. 4. h) Ref. 9.

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Figure Captions

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 to the 1977 mass evaluation[7]) and ref. 8, new ME data are taken from ref. 2 and from the present work. In the first case we consider the $^{113}Xe \rightarrow {}^{113}I \rightarrow {}^{112}Te$ + 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 endpoint energy ($Q_{EC}-S_p$) of the β-delayed proton spectrum, S_p being the proton separation energy in ^{113}I. The second case we start with the ME value obtained for ^{109}Sn from transfer-reaction studies[8]). In order to get the ME of ^{114}Cs one has to measure Q_{EC} for the $^{109}Sb \rightarrow {}^{109}Sn$ decay and ($Q_{EC}-S_p$) for the $^{114}Cs \rightarrow {}^{114}Xe \rightarrow {}^{113}I$ + 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.

Fig. 2 Differences between predictions from the Jänecke-Eynon mass formulae and measured mass-excess values. Experimental results are from this work and ref. 2 (open circles), from the 1977 mass evaluation[7]) (full circles) and from recent mass-spectrometric measurements[19]) (open squares). The value for ^{109}Sn is taken from ref. 8.

Fig. 3 Q(4β) systematics: Data are taken from this work and ref. 2 (open circles), from the 1977 mass evaluation[7]) (full circles), from experimental data not accepted in ref. 7 (open circles within brackets), from systematical extrapolations[7]), from recent mass-spectrometric measurements[19]) (open squares) and from other recent experiments[8,16]) (open triangles). The lines are drawn in order to guide the eye.

Figure Captions (continued)

Fig. 4 Systematics of experimental ΔQ_{α} (N) values for Z=50 in comparison with predictions from mass formulae. Full circles show data from the 1977 mass compilation[7]), open circles represent results from this work and from ref. 2.

Fig. 5 Experimental (Q_{EC}-S_p) values above 1 MeV for odd-N presursors ($50 \leq Z \leq 56$, $N \leq 65$) compared with predictions from the Hilf-von Groote-Takahashi (dashed lines) and Jänecke-Eynon (solid lines) mass formulae. Results from this work are shown as open symbols, literature data as full symbols.

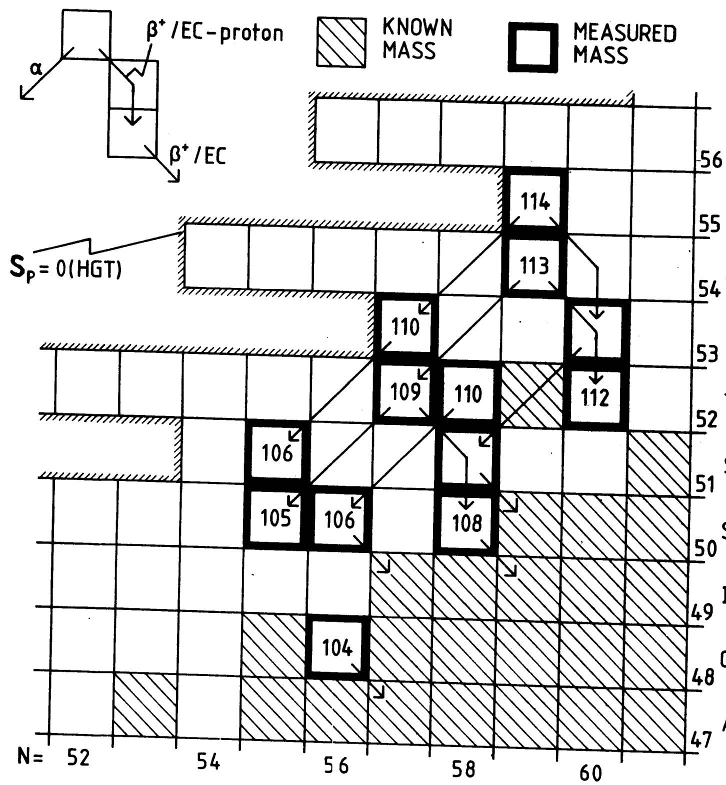
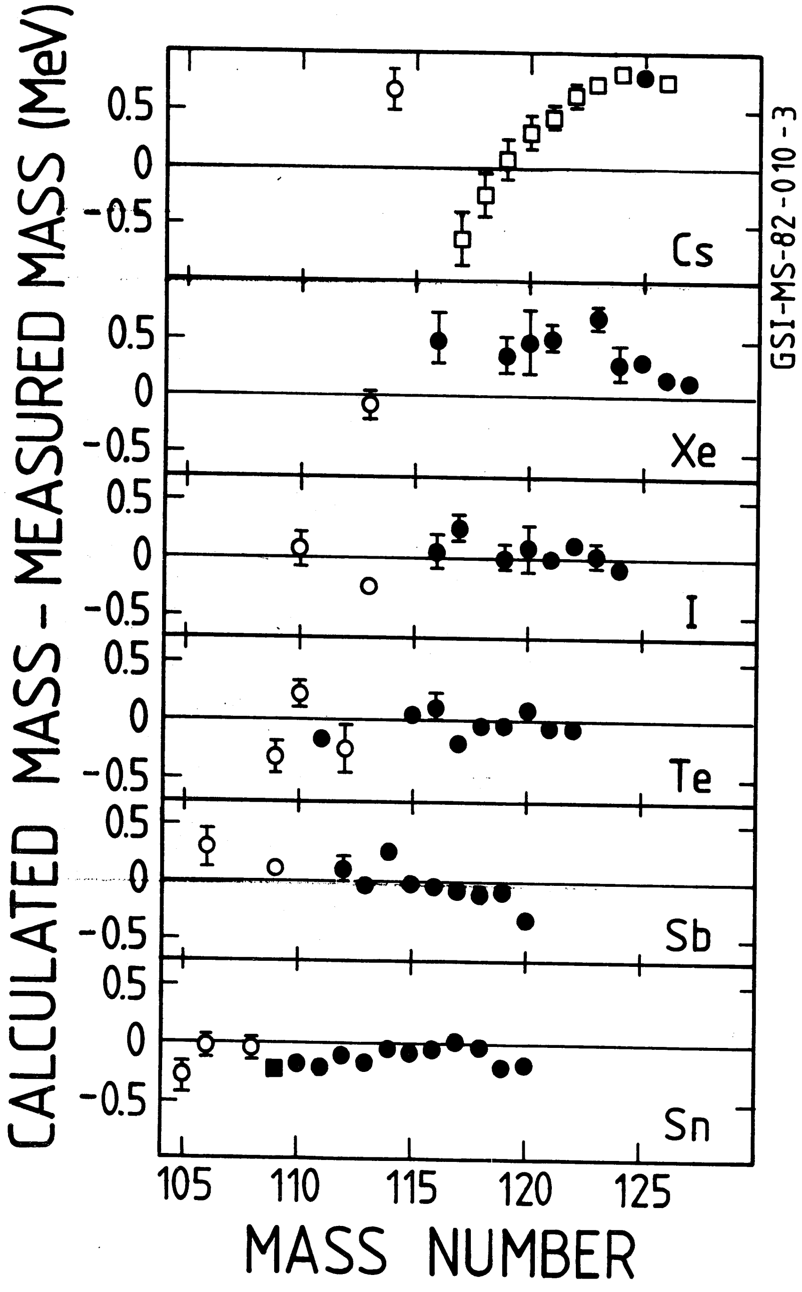


Fig. 1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-0.5
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Te
Sb
Sn
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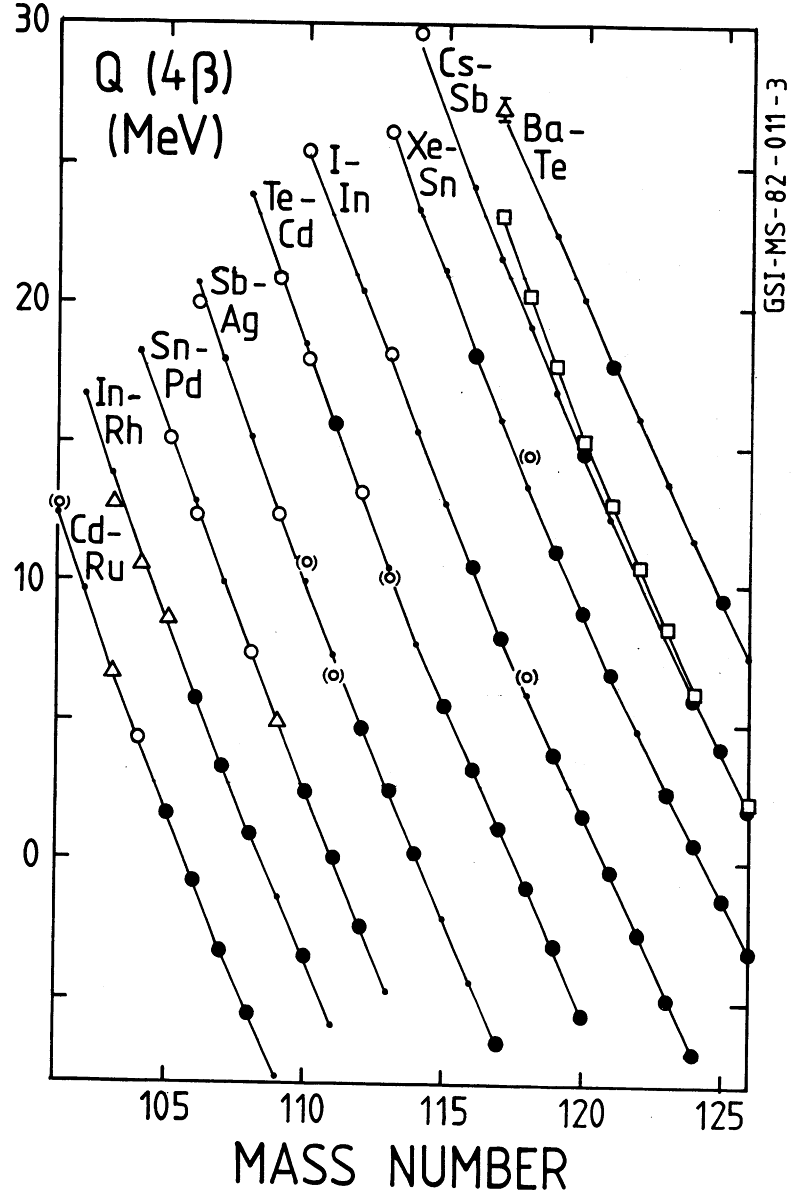
120
125
MASS NUMBER
GSI-MS-82-010-3

Fig. 2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(MeV)
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20
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Ba-Te
Xe-Sn
I-In
Te-Cd
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Cd-Ru
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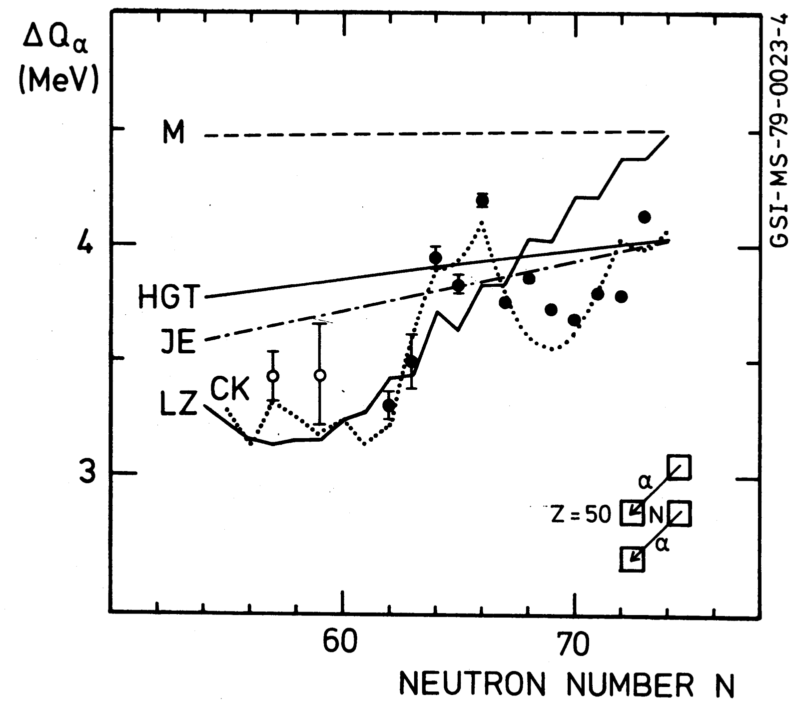
GSI-MS-82-011-3

Fig. 3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(MeV)
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HGT
JE
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CK
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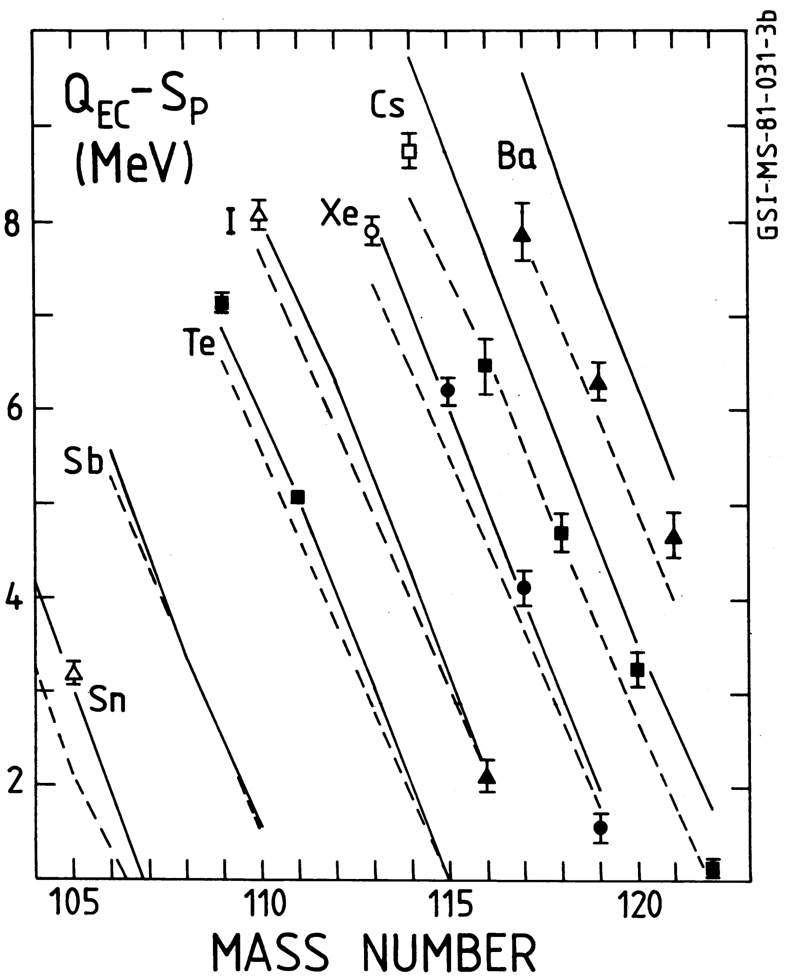
α
α
GSI-MS-79-0023-4

Fig. 4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GSI-MS-81-031-3b

Fig. 5