Neutron separation energies at $N = 83$ and the isomer position in ^{136}I

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New experimental total β-decay energies of ^{135,136}Te and of the two isomers of ^{136}I have been obtained, giving much improved accuracy for the nuclear masses of these nuclides. The neutron separation energies at $N = 83$ were deduced and are compared to recent theoretical and systematic predictions. The new results resolve the problem with the excitation energy of the isomeric state of ^{136}I. Theoretical calculations of the isomer splitting of ^{136}I are in good agreement with the new data.

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I. INTRODUCTION

The separation (or binding) energy of nucleons in the nuclei near or at the closed shells carries considerable structure information, and was actually one of the earliest known indicators of the nuclear shell structure. In closed shell regions far from the stability line, the separation energies are of particular interest since the shell structure provides a basis for relatively accurate theoretical calculations of nuclear properties. Data on the neutron rich side of stability may also be of interest for theoretical studies of the r-process nucleosynthesis. The masses of the neutron rich $N = 83$ nuclides, having a single neutron outside the closed shell, were recently derived [1] from β-decay energies for nuclides as far from stability as the In and Sn isotones. In contrast, accurate values are missing on the Te and I isotones which are less distant from the line of stability. The evaluation by Audi *et al*. [2] quotes a large uncertainty of 90 keV for the neutron separation energy of ^{135}Te and 50 keV for ^{136}I. However, additional questions remain in the case of ^{136}I, since the input values quoted in the work by Wapstra *et al*. [3] are inconsistent with respect to the position of the β-decaying isomer of ^{136}I. The adopted masses suggest a substantial isomeric energy gap of some 500–800 keV, which is very large compared to theoretical and systematic expectations [4]. The two isomers of ^{136}I should be the 1^- and 7^- members of the $\pi(1g_{7/2})^3\nu(2f_{7/2})$ multiplet which are expected within about 200 keV of each other.

To clarify these questions we have performed new measurements of the total β-decay energies of ^{135}Te and of both of the ^{136}I isomers. Among the results we also obtained a considerably improved value for the decay energy of ^{136}Te.

Direct measurements of nuclear masses, also for short-lived unstable species, have been remarkably successful during the past several years, see, e.g., Refs. [5,6] and references therein. Measurements by means of Penning traps are not easily applicable to all atomic species, however, and may face difficulties [6] if the samples contain different nuclear isomers of a given isotope. Measurements of total decay energies are thus still a powerful means to obtain accurate nuclear mass data over important regions of the nuclear chart. Such mass determinations are by nature relative rather than absolute but have the advantage of being easily able to elucidate, e.g., the positions of isomeric states because the information is obtained through resolved spectroscopy. The current work is entirely based on determinations of total decay energies.

II. EXPERIMENTS AND RESULTS

Total β-decay energies can be determined by measurements of the endpoint energies of β transitions, which usually are selected by $\beta\gamma$ coincidence gating on the γ-ray photons directly de-exciting the state populated by a given β transition. The method is particularly applicable in closed shell regions, where the level density is low and much of the β strength often is concentrated in a few strong transitions. A good knowledge of the decay scheme is needed. Accurate determinations require that the response function of the β-particle detector is well known, and that precautions are taken to reduce pulse pileup effects. The current experiments were made using the specially calibrated HPGe detector and the methods described previously in Refs. [1,7]. The endpoint energies were deduced from the β-particle pulse height distributions by fitting a response corrected simulated β spectrum to the experimental data. The overall uncertainty of this method, due to calibration errors and an incomplete knowledge of the detector response, is about 30 keV at a β-spectrum end point energy of 10 MeV and a few keV at endpoint energies of 3–5 MeV.

The Te and I nuclides of interest here were obtained as mass separated fission products at the OSIRIS ISOL facility [8]

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TABLE I. Total β-decay energies from the present work. The decay energies are weighted averages in cases where more than one gating transition were used.

Nuclide	Final state energy (keV)	Decay energy (keV)
^{135}Te	870.3	5888(13)
^{136}Te	332.8, 630.5	5086(20)
^{136}I	2634.2	6850(20)
^{136m}I	2261.5, 2608.5	7051(12)

at Studsvik, Sweden. The isobaric beam of $A = 135$ or 136 was collected on a tape of aluminized Mylar, with the Ge γ-ray detectors and the HPGe β-detector placed to view the beam collection spot. A window of 0.08-mm-thick Al separated the HPGe β detector from the beam line vacuum. The tape was moved periodically to remove long lived daughter activities.

The effects of pulse pileup, which may distort the end point region of the β spectra, were minimized by keeping the β-particle count rate below about 3 kcps in combination with use of a gated integrator type amplifier set at a short shaping time of 1 μs. The counting system included active pileup rejection circuitry, providing a veto signal to the ADC in case of detection of a pileup event in the amplifier. Some care has to be taken also in the choices of projected coincident β spectra. Typically, gates are selected on all reasonably strong γ transitions depopulating levels having a good feeding by direct β transitions. The projected spectra are inspected for possible distortions caused by γ-ray events in true coincidence with the selected gating transition. The preferred choice of gating transitions are those which go to the ground state or a long lived isomeric state, since any coincident cascading transitions may give rise to a high-energy tail of $\beta + \gamma$ events which reduces the precision in the determinations of the endpoint energies.

The spectra selected for the final analysis of endpoint energies in the current work were obtained from gates on the following γ rays: ^{135}Te 870.3 keV, ^{136}Te 332.8 and 630.6 keV, ^{136}I (1^-) 2634 keV, ^{136}I (7^-) 370.1 keV and a sum of the gates on the γ rays depopulating the 2608.5 keV level. Note that our data support the energy of 332.8 keV reported by Aas [4] for the most intense γ ray in the decay of ^{136}Te. The value of 333.99 keV adopted by the compilers of Ref. [9] is not correct. The data on the total decay energies, obtained by adding the end point and the final state energies, are given in Table I, properly averaged where possible. Examples of the fits to the experimental pulse height data are shown in Fig. 1. A vertical scale using a square root dispersion is employed in this figure to accommodate a large range of counts, while retaining a good view of the low counts in the endpoint region, as well as permitting an easy judgment, by visual inspection, of the quality of the fit. Please note that the points shown represent the function

$$\mathrm{sgn}(N_{\mathrm{peak}} - N_{\mathrm{bgr}}) \times \sqrt{|N_{\mathrm{peak}} - N_{\mathrm{bgr}}|},$$

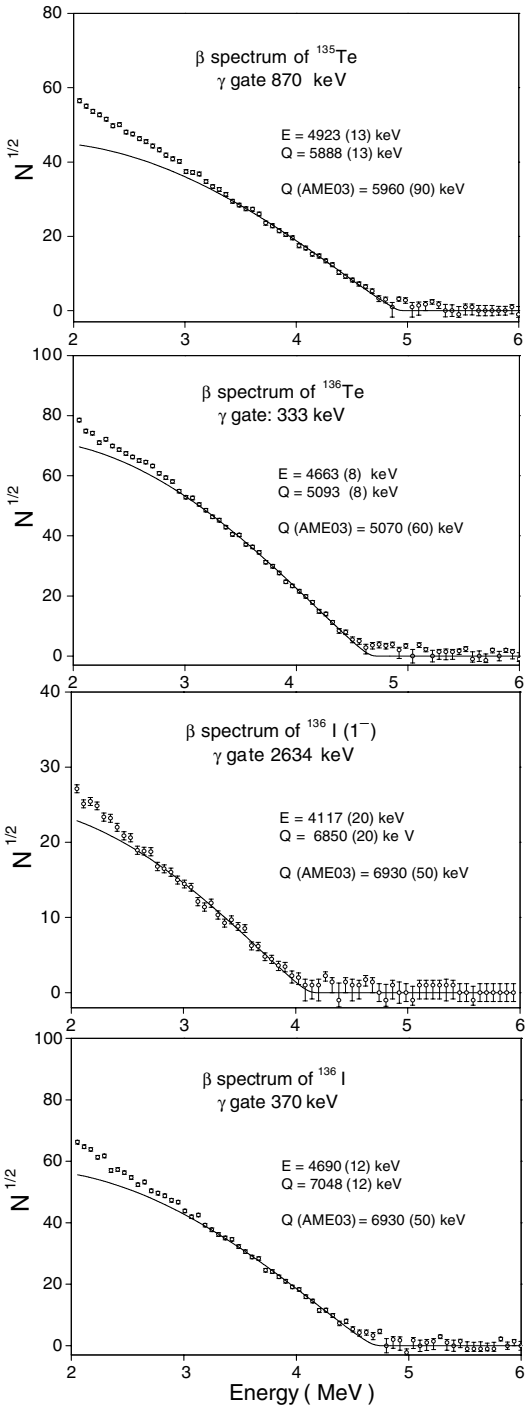

FIG. 1. Examples of fits to projected β-particle pulse height distributions by simulated theoretical β spectra, which were corrected for the detector response. Also additional gated β spectra were used to derive the total energies given in Table I. The endpoint energy values given in the figure do not include the correction for energy loss in the vacuum window. The vertical scale is explained in the text.

where the signum function gives a negative value if the counts N_{peak} of the γ-ray gate was lower than the counts N_{bgr} of the background gate.

The new experimental data on the Te and I nuclides were used to deduce more precise values for the nuclear mass excess

TABLE II. Deduced mass excess values using data on ^{135}I and ^{136}Xe from Ref. [2]

Nuclide	Mass excess (keV) present work	Mass excess (keV) Ref. [10]
^{135}Te	−77902(15)	−77830(90)
^{136}Te	−74489(30)	−74430(50)
^{136}I	−79575(22)	−79500(50)
^{136m}I	−79374(14)	−78850(110)

as given in Table II. The reference mass excess values for the daughter nuclei ^{135}I and ^{136}Xe were taken from Ref. [10].

III. DISCUSSION

A. The isomers of ^{136}I and ^{212}At

The adjusted masses of Audi *et al.* [10] suggest a large energy gap of 650(110) keV between the two β-decaying states of ^{136}I. The known decay properties [4] of the two states strongly indicate that they represent the 1^- and 7^- members of the $\pi(1g_{7/2})^3\nu(2f_{7/2})$ multiplet. The situation is quite similar to that of the low-lying states of ^{212}At, which like ^{136}I has three protons and one neutron outside a doubly closed shell. The analogous multiplet in ^{212}At involves protons in the $h_{9/2}$ orbital coupled to a $g_{9/2}$ neutron and is well known. The splitting between the 1^- ground state and the 9^- high spin isomer is 222 keV, which should be comparable to the isomeric splitting also in ^{136}I, because the *n-p* interactions are quite similar in these two multiplets. The unexpectedly large difference between the adjusted data of Audi *et al.* [10] and the observation for ^{212}At was one of the reasons to perform the current work. The new data presented in Table I show an isomeric splitting of 201(26) keV, which indeed is practically equal to the observed splitting in ^{212}At.

B. Theoretical studies of the $N = 81$ multiplet splittings

A detailed picture of the lowest multiplets in the $N = 81$ nuclides ^{134}Sb and ^{136}I was obtained by calculations of the level properties within the framework of the RPA method for the neutron-proton channel or the multiparticle model, respectively. The calculations were performed as described earlier [11], including (global) parameters adopted from the works by Heyde [12,13], but without free parameters. This method has been successfully applied earlier on different problems [14,15] in the ^{132}Sn region. The full results have taken advantage of the known single-particle energies. In the case of ^{136}I we used interaction"b" in the notation of Ref. [11], which for proton-proton or neutron-neutron interactions is equivalent to the two-body potential used by Heyde [12,13] for description of systems of identical particles. Our interaction also includes a tensor component in the case of unidentical nucleons, which was locally determined by us from the splitting of the lowest 1^- and 0^- levels of ^{136}I.

The calculation gave a good description of both level energies and electro-magnetic transition rates in ^{136}I. See Ref. [4] for the full results and for details of the calculations. The resulting calculated energy of the 7^- state is 160 keV, in excellent agreement with the current experimental result. The calculated energies of all the members of the lowest lying multiplet are shown in Fig. 2, together with the existing experimental information. The new results on the calculated properties of ^{134}Sb are given in Ref. [16].

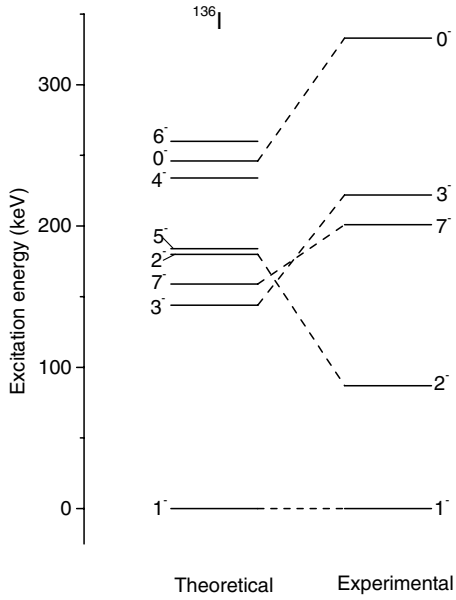

FIG. 2. Calculated and experimentally determined positions of the levels of the lowest multiplet in ^{136}I. Previous data, see Ref. [3], indicated an excitation energy of 500–800 keV for the 7^- isomer of ^{136}I.

C. Neutron separation energies at $N = 83$

The single-particle separation energies are strong indicators on changes in the nuclear structure. The abrupt variations in the separation energies at certain nucleon numbers actually early suggested the presence of shell structure in nuclei. Accurate data on separation energies can give valuable information also on effects less dramatic than the shell closures, such as variations in the nuclear shape or on details of the *n-p* interaction. The more subtle effects are perhaps most easily observed in isotonic or isotopic chains of valence nuclei having a single nucleon outside a closed shell, which offer a possibility to study, e.g., the valence neutron binding as a function of the number of core protons. Local structure changes affecting the core at specific proton numbers are to some extent reflected in the binding of the valence neutron. The valence nucleon systems are also sufficiently simple to be amenable to rather precise theoretical studies. The results of Ref. [1], the updated data on ^{131}In and ^{131}Sn given in Ref. [7], and the new results obtained here for ^{135}Te and ^{136}I, have clarified the remaining ambiguous or uncertain mass values for the lighter of the known $N = 83$ isotones. One may thus now deduce accurate neutron separation energies for these unstable isotones from ^{132}In at $Z = 49$ up to ^{136}I at $Z = 53$, see Table III. Adopting the evaluation of Ref. [10] for the

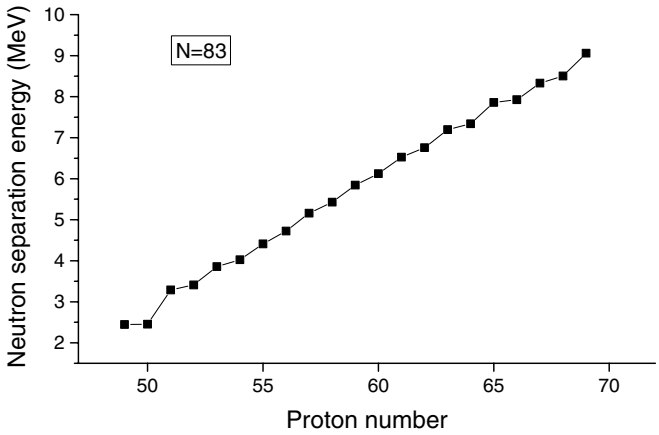

FIG. 3. All known experimental neutron separation energies along the $N = 83$ isotones. Three of the five lowest points are based on data from the current work and the updated $A = 131$ results from Ref. [7]. The uncertainties are smaller than the point size. The kink near $Z = 51$ is a nuclear structure effect that is well reproduced by multiparticle calculations [17].

heavier isotones, the experimental data on neutron separation energies are extended up to ^{152}Tm at $Z = 69$, as shown in Fig. 3.

Apart from the general increase in the separation energy with increasing proton to neutron ratio seen in the graph, one can note a clear effect of the proton subshell closure at $Z = 64$. The influence of the proton shells is also seen near $Z = 50$. The kink in the systematics at $Z = 51$, which has become visible through the new and more precise data presented here and by Refs. [1,7], is a proton number dependent structure effect. A theoretical study of valence nucleon separation energies conducted separately, see Ref. [17], reproduces such a kink in the systematics as well as additional influence by the core structure. This theoretical work also demonstrates that the separation energies are quite strongly dependent on the relative energies and filling order of the orbitals of the core nucleons. Such dependence needs to be considered when attempting to define the limits of nuclear stability with respect to nucleon emission near the drip lines.

TABLE III. Neutron separation energies in keV at $N = 83$ obtained using the present data on ^{135}Te and ^{136}I. Mass excess data on ^{132}In, ^{134}Te, and ^{135}I were taken from Ref. [10]. The separation energies for ^{133}Sn and ^{134}Sb were adopted from Audi *et al.* [2].

Nuclide	Present work	Reference [2]
^{136}I	3856(23)	3780(50)
^{135}Te	3414(19)	3340(90)
^{134}Sb	3290(50)	3290(50)
^{133}Sn	2470(40)	2470(40)
^{132}In	2423(70)[a]	2350(70)

[a]The mass excess value of ^{131}In had been corrected using the new data [7] on ^{131}Sn and ^{131}In in the derivation of this value

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