NUCLEAR Q_β-VALUES FOR FISSION PRODUCTS. A COMPARISON WITH MASS FORMULA PREDICTIONS

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Abstract

Experimental Q_β-values for fission products are presented. The sources were produced as mass separated fission products at the OSIRIS on-line isotope separator Recently determined Q_β-values for ^{79,81}Ga, ^{79,81,82}Ge, ^{89,90}Br, $^{116-121}$Ag, $^{119-121}$Cd and ^{139}I are, together with 40 earlier measured values, compared with mass formula predictions.

1. Introduction

The shape of the nuclear mass surface far out on the neutron-rich side of β-stability is of considerable interest both from the nuclear structure point of view and because of important applications e.g. theories about the r-process in nucleosynthesis. Indirect mass determinations have formed part of the experimental programme at the OSIRIS facility for many years. The mass is deduced from the total β-decay energy which is experimentally obtained by measuring βγ-coincidences and summing the energy of the β-branches and the energy of the states depopulated by the γ-rays. The mass of the nuclide is then determined by adding Q_β-values to known daughter masses. This method requires good knowledge of the level structure. In cases where such information is lacking it is only possible to give a lower limit for the Q_β-value.

The accuracy of the Q_β-determinations is typically 2-3 % and in some cases better than 1 %. This accuracy is sufficient for tests of mass formulas.

Very far out on the neutron-rich side of stability the nuclides are delayed neutron precursors. This provides another possibility to get a lower limit for the Q_β-value of the precursor by adding the neutron separation energy of the emitter to the sum of the "beta branch" energy in coincidence with a γ-transition in the final nucleus.

Until now, the technique for direct mass measurements is only elaborated for few elements. Our systematic study spans over many elements covering around 55 fission products in the mass regions A = 75 - 90 and A = 116 - 139, including isotopes of zinc, gallium, germanium, arsenic, bromine, silver, indium, tin, antimony, tellurium, and iodine.

Although total β-decay energies are sometimes difficult to determine with high accuracy for nuclides far from stability, a systematic mapping of the mass surface will always give important information about its structure and will, in addition, serve as a useful tool for testing mass formula predictions.

2. Experimental technique

The OSIRIS on-line-isotope-separator, described in detail in ref.[1], has been used for the βγ-determinations. With a normal ion source the elements zinc, gallium, germanium, bromine, krypton, rubidium, strontium, silver, cadmium, indium, tin, antimony, tellurium, iodine, xenon, cesium, and barium can be processed When exposing the target to carbon tetrafluorid molecular ions are obtained. The efficiency of the separation of some of the above-mentioned elements is improved, and a number of other elements appear as fluorides, e.g. yttrium, zirconium and the lanthanides. The addition of aluminium vapour to the target produces good yields of the ions $AlBr^+$ and AlI^- [2]. The latter method has been used for the Q_β-determinations of ^{89,90}Br[3] and ^{139}I. It is advantageous since these nuclides then appear at mass numbers 116, 117, and 167, respectively. Around mass 116 the situation for Q_β-determinations of the bromine isotopes is more favourable than around A = 89 because of the absence of rubidium. The large difference in the fission yield between the bromine isotopes and the isotopes of silver and cadmium makes the presence of the latter activities little disturbing. At mass 167 the measurement is undisturbed by contaminating activities.

The βγ-coincidence spectrometer used in the experiments consists of a system of Si(Li)-detectors for β-detection and, for the γ-registration, either two NaI-detectors or two 80 cm^3 Ge(Li)-detectors coupled in a multiplexing mode. With the tape system used for collecting samples it is possible to perform accurate Q_β-determinations for nuclides with half-lives down to 0.5 s. Details about the experimental procedure and the calibration procedure are given in refs.[4,5]. The time-resolution for the system is of the order of 15-20 ns yielding a negligible accidental coincidence rate. The γ-gates contained contribution from the Compton background, which was corrected for by subtracting background spectra obtained by setting gates in the neighbourhood of the chosen γ-lines.

3. Experimental results and comparison with mass formula predictions

Total β-decay energies have recently been determined at OSIRIS for the nuclides $^{79-81}$Ga, ^{79,81,82}Ge[6], ^{89,90}Br[3], $^{116-121}$Ag, ^{119,121}Cd[7] and ^{139}I. Some of these nuclides have been investigated before at this laboratory, but the accuracy is now improved. The resulting Q_β-values and those of about 40 cases studied earlier[8-11] have been compared with a number of

predictions from current mass formulas. We have chosen for this comparison the formulas of Myers [12a], Seeger-Howard[12b], and Möller-Nix[13] representing liquid drop model formulas, Liran-Zeldes[12c] representing a semi-empirical shell model formula and Jänecke[12d] and Comay-Kelson[12e] representing empirical mass relations. The comparison is given in Table 1. The differences between predicted and experimentally determined Q_β-values for two types of theoretical investigations are shown in Fig. 1 for the liquid drop model formula of Myers and in Fig. 2 for the shell model calculation by Liran and Zeldes.

Table 1

Experimental Q_β-values and differences between predicted and experimental Q_β-values

Nuclide	Exp. Q_β-value	Q_β, pred. - Q_β, exp. M[12a]	S-H[12b]	M-N[13]	L-Z[12c]	J[12d]	C-K[12e]
^{75}Zn	≥ 5.62±0.20	≤ 0.85	≤ -0.29	≤ 0.05	≤-0.02	≤0.29	≤0.15
^{76}Zn	3.98±0.12	-1.00	-0.93	-0.72	-0.06	-0.17	-0.34
^{77}Zn	6.91±0.22	-0.76	-0.27	0.23	0.32	0.30	0.18
^{78}Zn	6.01±0.18	-1.64	-1.43	-0.59	-0.20	-0.65	-0.89
^{76}Ga	6.77±0.15	-0.74	0.17	0.46	0.15	0.09	-0.04
^{77}Ga	5.34±0.06	-1.07	-0.63	-0.38	-0.32	-0.58	-0.72
^{78}Ga	8.14±0.15	-0.72	0.12	0.44	0.13	0.03	-0.14
^{79}Ga	6.77±0.08	-1.12	-0.51	-0.15	-0.11	-0.45	-0.75
^{80}Ga	10.0 ±0.3	-1.3	-0.5	0.2	-0.4	-0.3	-0.8
^{81}Ga	8.32±0.15	-1.35	-0.45	-0.30	0.22	-0.38	-0.96
^{79}Ge	4.11±0.10	-0.33	-0.06	-0.32	0.35	-0.05	-0.04
^{80}Ge	2.64±0.07	-0.61	-0.56	-0.08	0.32	-0.37	-0.61
^{81}Ge	6.23±0.12	-1.09	-1.00	-0.21	-0.13	-0.61	-0.94
^{82}Ge	4.70±0.14	-1.30	-1.08	-0.88	0.03	-0.81	-1.34
^{80}As	5.37±0.12	-0.30	-0.34	0.62	0.27	0.26	0.32
^{81}As	3.76±0.08	-0.44	0.08	0.50	0.16	0.03	0.01
^{83}As	5.46±0.22	-0.80	0.05	0.45	0.16	-0.05	-0.40
^{85}Br	2.87±0.02	-0.45	-0.14	0.31	-0.02	0.14	-0.07
^{86}Br	7.62±0.06	0.10	-0.08	0.91	0.09	0.18	-0.04
^{87}Br	6.83±0.12	-0.86	-0.40	0.54	0.08	0.06	-0.23
^{88}Br	8.97±0.12	-0.04	0.21	1.47	0.68	0.23	-0.10
^{89}Br	8.14±0.14	-0.94	-0.30	0.05	0.44	0.03	-0.24
^{90}Br	9.8 ±0.4	0.3	0.9	1.59	1.5	0.8	0.80
^{116}Ag	6.2 ±0.2*)	-0.7	-1.0	-0.2	-0.4	0.0	-0.2
^{117}Ag	4.17±0.05	-0.21	-0.7	-0.15	-0.31	0.10	-0.11
^{118}Ag	7.13±0.10	-0.64	-0.9	-0.06	-0.49	0.15	-0.17
^{119}Ag	5.37±0.04	-0.45	-0.7	-0.28	-0.61	-0.05	-0.37
^{120}Ag	8.21±0.10	-0.79	-0.7	0.35	-0.77	0.08	-0.18
^{121}Ag	6.39±0.15	-0.54	-0.5	0.26	-0.74	-0.10	-0.27
^{119}Cd	3.79±0.06	-0.23	0.2	0.82	-0.10	-0.15	-0.25
^{121}Cd	4.96±0.09	-0.45	0.2	0.72	-0.29	-0.26	-0.49

*) Preliminary result

Table 1 cont.

Nuclide	Exp. Q_β-value	Q_β, pred. - Q_β, exp. M[12a]	S-H[12b]	M-N[13]	L-Z[12c]	J[12d]	C-K[12e]
^{120}In	5.30±0.17	-0.61	-0.47	0.52	0.04	0.07	0.07
^{121}In	3.41±0.05	-0.24	-0.58	0.27	0.21	-0.02	-0.02
^{122}In	6.51±0.23	-0.84	-0.60	0.40	-0.31	-0.16	-0.16
^{123}In	4.44±0.06	-0.33	-0.41	0.37	0.16	-0.07	-0.07
^{124}In	7.18±0.05	-0.44	-0.29	0.68	0.04	0.01	0.01
^{125}In	5.48±0.08	-0.48	-0.35	0.22	0.01	-0.20	-0.20
^{126}In	8.21±0.08	-0.75	-0.24	0.53	-0.30	-0.25	-0.25
^{127}In	6.49±0.07	-0.56	-0.24	0.19	-0.20	-0.32	-0.32
^{128}In	9.31±0.16	-0.98	-0.44	0.18	-0.60	-0.59	-0.59
^{129}In	7.60±0.12	-0.80	-0.40	0.06	-0.62	-0.60	-0.60
^{127}Sn	3.20±0.02	-0.34	0.13	-0.25	-0.16	-0.11	-0.06
^{128}Sn	$1.29^{+0.06}_{-0.04}$	0.07	0.19	-0.16	0.04	0.01	0.12
^{129}Sn	3.99±0.12	-0.20	0.11	-0.18	-0.03	-0.13	-0.06
^{130}Sn	2.19±0.03	0.08	0.24	0.34	0.08	-0.06	-0.02
^{131}Sn	4.59±0.20	0.07	0.43	0.09	0.29	-0.05	-0.06
^{132}Sn	3.08±0.04	0.08	0.32	0.35	0.29	0.17	0.16
^{128}Sb	$4.39^{+0.04}_{-0.06}$	-0.39	-0.11	0.08	0.11	-0.05	0.16
^{130}Sb	5.02±0.10	-0.12	0.19	-0.07	0.36	0.08	0.32
^{131}Sb	3.19±0.07	0.20	0.35	0.04	0.44	0.19	0.39
^{132}Sb	5.53±0.07	0.24	0.58	0.14	0.75	0.25	0.41
^{134}Sb	8.24±0.24	0.42	0.55	0.94	0.96	0.31	0.30
^{134}Te	1.56±0.09	-0.04	-0.18	0.00	-0.04	0.05	0.11
^{135}Te	5.95±0.24	-0.06	-0.27	0.22	0.28	-0.27	-0.38
^{139}I	6.56±0.20	-0.23	-0.47	1.14	0.88	0.01	0.17

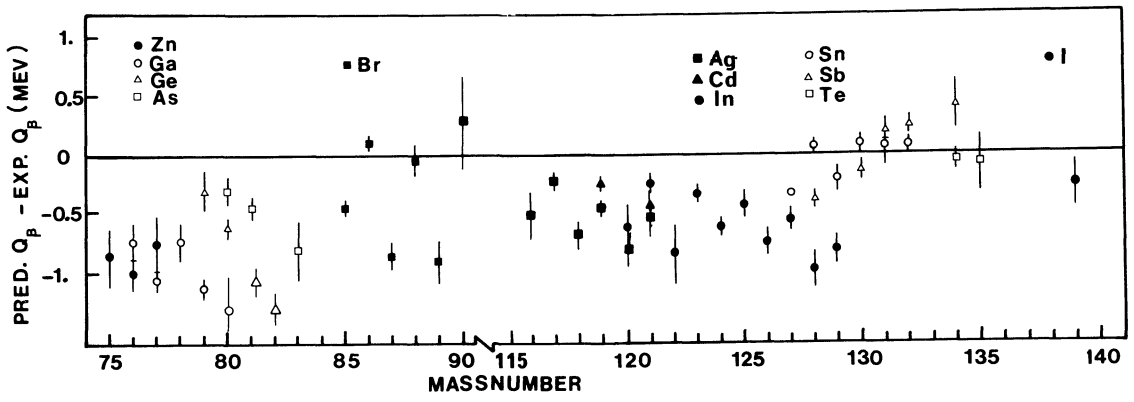

Fig. 1. Differences between predicted and experimental Q_β-values concerning the mass formula of Myers[12a]

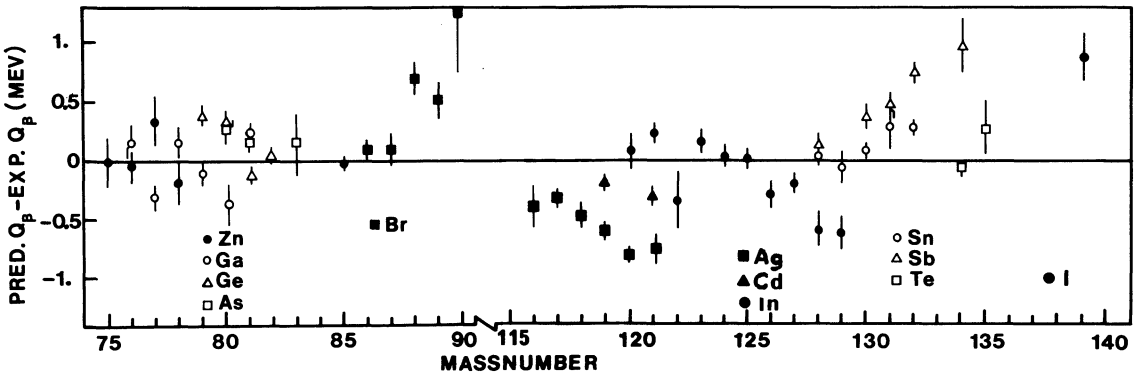

Fig. 2. Differences between predicted and experimental Q_β-values concerning the mass formula of Liran and Zeldes[12c]

4. Discussion

A convenient way of expressing the precision of a mass formula is to use the root-mean square deviation. In Table 2 the experimental accuracy is compared with this quantity for five different mass regions.

Table 2

The experimental accuracy and the root mean square deviation between predicted and experimental Q_β-values

Mass region (element)	$\lvert Q_{\beta,\text{pred.}} - Q_{\beta,\text{exp.}} \rvert$ M[12a]	S-H[12b]	M-N[13]	L-Z[12c]	J[12d]	C-K[12e]	Exp. accuracy
$75 \leq A \leq 83$ (Zn,Ga,Ge,As)	0.91	0.47	0.39	0.20	0.32	0.51	0.15
$85 \leq A \leq 90$ (Br)	0.45	0.34	0.81	0.47	0.24	0.25	0.14
$116 \leq A \leq 121$ (Ag,Cd)	0.50	0.70	0.35	0.46	0.11	0.26	0.10
$120 \leq A \leq 129$ (In)	0.60	0.40	0.34	0.25	0.23	0.23	0.11
$127 \leq A \leq 139$ (Sn,Sb,Te,I)	0.18	0.29	0.29	0.34	0.12	0.19	0.11

In this connection it should be borne in mind that the number of parameters used in the different mass formulas varies greatly. It is hardly to be expected that the Myers formula[12a] with only 16 parameters or the one of Seeger and Howard[12b] with 9 parameters should yield as accurate predictions as the one of Liran and Zeldes[12c] with 178 parameters.

As shown in Table 2 the precision of the different mass formulas varies from mass region to mass region. The droplet formula of Myers generally predicts too low Q_β-values except for the region $Z \geq 50$ where it gives a fairly good fit (see Fig. 1). Among the droplet mass formulas the one of Möller and Nix seems to predict Q_β-values far from stability somewhat better than the others (see, for instance, the gallium and indium isotopes in Table 1). The semi-empirical shell model formula of Liran and Zeldes gives the best predictions for the elements zinc, gallium, germanium, and arsenic.

In regions far from stability the predictions get worse. The same tendency is also typical for the empirical mass-relations (see, for instance, heavy isotopes of gallium, germanium, and indium in Table 1).

5. Conclusion

In summary we may conclude that the mass formulas chosen for comparison with the experimental data are reasonably accurate. The difference only rarely exceeds 1 MeV. There are mass regions with systematic deviations, however. An overall tendency is that the mass formulas predict too low Q_β-values. Furthermore, the odd-even effect is sometimes exaggerated. Hopefully, the experimental masses presented here will be used to improve the precision of the predictions by removing these systematic deviations.

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