Spacing of Nuclear Ground-State Levels in the Region $94 \leqslant N \leqslant 114$*

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New atomic-mass determinations are reported which establish the masses of ^{174}Hf and ^{180}W with significantly improved precision, and lead to new values for the double-neutron separation energies S_{2n} of ^{176}Hf, ^{180}W, and ^{182}W. A plot of S_{2n} in the region $94 \leqslant N \leqslant 114$ now shows systematic downward breaks at $N=98$, 104, and 108. These features are interpreted in terms of energy gaps above the Nilsson single-particle levels $\frac{9}{2}^+[624]$ ($N=108$), $\frac{5}{2}^-[523]$ ($N=98$), and $\frac{1}{2}^-[512]$ ($N=104$).

In an earlier work,[1] some of us reported the results of a systematic study of precise atomic mass determinations by which a general picture of the nuclear mass surface for the region between the 82- and 126-neutron shells might be derived. At that time the variation in the mass surface was presented in terms of the binding energy of the last pair of neutrons, S_{2n}, for even-even nuclides. The details of this work, along with a substantial body of additional data, appeared subsequently in a series of papers.[2-6]

Using our 1.00-m-radius high-resolution mass spectrometer[7] and taking advantage of improved data-handling techniques,[8] we have recently obtained, for the region Yb to W, twenty new mass differences, of which ten represent improved values for existing data. Detailed descriptions of the experimental techniques, the complete list of raw data, a self-consistent table of mass differences based on all available data, and discussion of the results will appear in due course. However, we wish to draw attention here to certain features of the results which are sufficiently interesting to warrant prior presentation.

Of the substantial body of new mass spectroscopic data, the values for two doublets in particular produce significant changes in the believed systematic behavior of the double-neutron separation energies S_{2n}. These doublets, involving the relatively rare isotopes ^{174}Hf (0.17%) and ^{180}W (0.13%), are shown in Table I. As one would expect, the errors associated with these unfavorable doublets much exceed the errors for the remainder of the data, which lie between 0.6 and 1.3 keV. Nevertheless, the values are much more precise than previous mass spectroscopic data for these nuclides and differ from the corresponding values determined from nuclear reaction Q values.

The new mass doublet values may be combined with the values from the 1971 mass table[9] for ^{37}Cl-^{35}Cl, ^{35}Cl-$^{16}O_2$, ^{176}Hf, and ^{183}W to obtain the new atomic mass values shown in Table II. Also shown in the table are the corresponding values of S_{2n} and comparison values, both from the 1971 mass table and from more recent reaction Q values determined at the University of Minnesota[10] and at Copenhagen.[11] The new doublets lead to significantly larger S_{2n} values for both ^{176}Hf and ^{182}W. The calculation of the mass of ^{178}W is not affected by the new data. Hence the changed value of the mass of ^{180}W leads to a reduced value of S_{2n} for ^{180}W.

Figure 1 is a plot of S_{2n} for even-N nuclides for both even and odd Z from $N=94$ to 114. Except for the value[12] for ^{162}Er, the values used for Gd, Tb, Dy, Ho, and Er are taken from Ref. 6, those for Tm, Yb, Lu, Hf, and W are based primarily on new measurements in this laboratory and, in particular, incorporate the new values in Table II, and those for Ta, Re, and Os are from the 1971 mass table.[9]

As we have noted previously,[1,6] the curves throughout the region shown exhibit a remarkably systematic behavior, viz., that when viewed

TABLE I. Some new mass difference determinations.

Doublet	ΔM (10^{-6} amu)
^{176}Hf^{35}Cl-^{174}Hf^{37}Cl	4106 ±16
^{183}W$^{16}O_2$-^{180}W^{35}Cl	24421 ± 9

TABLE II. Comparison between some new and existing double-neutron separation energies for hafnium and tungsten.

	Mass (amu)		S_{2n} (keV)	
Nuclide	This work	1971 mass table	This work	Comparison values
^{174}Hf	173.940 273 ± 16	173.940 140 ± 34	...	...
^{176}Hf	...	175.941 429 ± 13	15 067 ± 15	14 942 ± 30[a]
				14 879 ± 5[b]
^{178}W	...	177.945 870 ± 110	...	...
^{180}W	179.946 821 ± 15	179.946 700 ± 210	15 260 ± 100	15 370 ± 220[a]
^{182}W	...	181.948 248 ± 13	14 815 ± 8	14 700 ± 200[a]
				14 743 ± 10[b]
				14 760 ± 18[c]

[a]Ref. 9 [b]Ref. 10 [c]Ref. 11

over a range of two neutrons, the segments of adjacent curves (including both even and odd Z) are almost parallel. Thus, irregularities in the curve for one element are reproduced for other elements at the same neutron numbers. The injection of the new data from Table II has the effect that the curves for Hf and W exemplify this behavior even more so than before.

On the basis of this regular behavior, certain features of the curves in Fig. 1 may be noted: (1) In the curves for Dy ($Z=66$), Ho ($Z=67$), Er ($Z=68$), and Tm ($Z=69$), there is a small but well-defined break downward at $N=98$. (2) A second and smaller downward break occurs at $N=104$ in Tm and Yb curves and is supported by similar slopes in the Lu and Hf curves. (3) A third, and largest, downward break occurs at $N=108$, in curves for Hf, Ta, and W.

These extra large decreases in S_{2n} at $N=98$, $N=104$, and $N=108$ are reminiscent of the very

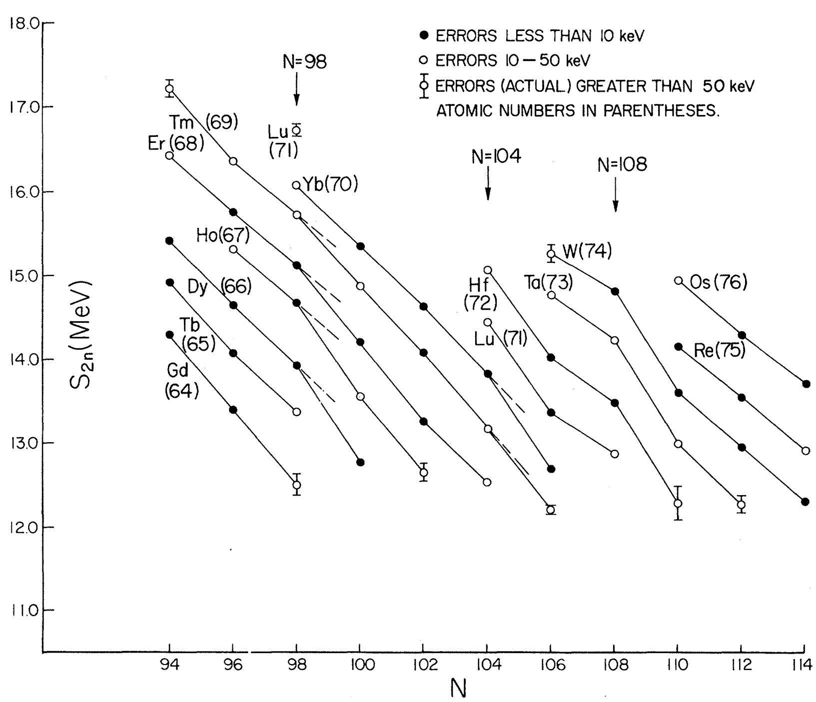

FIG. 1. Plot of the double-neutron separation energy S_{2n} as a function of neutron number. Data are for even-N nuclides only in the region $94 \leq N \leq 114$.

large decreases following the major shell closures and show that the energy differences between the ground states, $E(N=100)-E(N=98)$, $E(N=106)-E(N=104)$, and $E(N=110)-E(N=108)$, are greater than between their even-N neighbors. As the region in question is that of nonspherical nuclei and the nuclear deformations are sufficiently well known, one may interpret these results in terms of Nilsson single-particle levels.[13] Thus, one would predict a relatively large energy gap above the $\frac{9}{2}^{+}[624]$ level ($N=108$), and smaller, but still significant, gaps above the levels $\frac{5}{2}^{-}[523]$ ($N=98$) and $\frac{1}{2}^{-}[512]$ ($N=104$).

Finally, it should be noted that the curves break upward at $N=106$ and 110, as one might expect following a subshell closure. Such an effect appears not to occur, however, at $N=100$. This difference in behavior, as well as the fact that the upward break at $N=106$ is particularly large, may yield additional information relating to single-particle level spacings.

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