# NEUTRON SEPARATION AND PAIRING ENERGIES IN THE REGION $82 \leq N \leq 126$*

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Results of a systematic study of atomic-mass differences in the region $82 \leq N \leq 126$ are presented as plots of double-neutron separation energy and neutron-pairing energy. These plots provide information concerning the extent of the nuclear deformation which begins in the region of 90 neutrons, its dependence upon $Z$, and its gradual dissappearance in the region $106 \lesssim N \lesssim 116$.

In 1964[1,2] and 1965[3] some of us reported a series of precise atomic-mass differences in the region $N \sim 90$, which provided accurate information concerning the mass effect associated with the onset of nuclear deformation in that region. We have since extended this work substantially, using improved techniques and employing both the original high-resolution mass spectrometer[4] and a newly constructed one,[5] and can now provide a fairly complete picture of the mass surface between the 82- and 126-neutron shells. The details of this work, including the major comments on its interpretation, will be reported in due course in a series of papers, but the overall picture is sufficiently informative to warrant its prior presentation.

As in earlier work, most of the mass differences have been obtained by studying doublets of the type

$$\Delta M = {}^{A}X_1{}^{35}\mathrm{Cl} - {}^{A-2}X_2{}^{37}\mathrm{Cl}, \qquad (1)$$

where $X_1$ and $X_2$ may or may not be isotopes of the same element. The fractional spacing of the various doublets studied ranged from one part in 8400 to one part in 115 800. The error associated with $\Delta M$ was usually in the range 1-4 keV. Since the $^{37}\mathrm{Cl}-{}^{35}\mathrm{Cl}$ mass difference is known to 0.4 keV,[6,7] double-neutron separation energies $S_{2n}$ can be calculated to virtually the same precision as $\Delta M$, viz.

$$S_{2n} = 2n - ({}^{A}X_1 - {}^{A-2}X_1)$$
$$= 2n - ({}^{37}\mathrm{Cl} - {}^{35}\mathrm{Cl}) - \Delta M \qquad (2)$$

for cases in which the doublet contains isotopes of the same element. For cases in which isotopes of different elements are involved, the available data are frequently accurate enough to introduce negligible error in the calculation of $S_{2n}$ for the nuclides concerned.

The upper portion of Fig. 1 is a plot of $S_{2n}$ for even-$Z$, even-$N$ nuclides from $N = 74$ to $N = 126$. The many data relating to odd-$Z$ and/or odd-$N$ nuclides are omitted in order to avoid congestion in the figure. The values for Xe and Ce (taken from the 1965 mass table[8] which in this region is based primarily on the work of Johnson and Nier[9] and Damerow, Ries, and Johnson[10]) are included to show the characteristically "regular" shape of the curves of $S_{2n}$ vs $N$ in the region $50 \leq N \leq 82$,[11] and to remind the reader of the sudden decrease in $S_{2n}$ which occurs as the 82-neutron shell is exceeded. The values for the other elements are based mainly on some 70 mass differences determined in our laboratory during the past four years. Most of these values are derived directly from Eq. (2), but a few require for their calculation the use of accurate reaction $Q$'s or disintegration energies.

As was mentioned, some of the curves shown in the upper portion of Fig. 1 for $N \sim 90$ were published earlier, at which time attention was drawn to the major discontinuity in slope at $N = 88$, the apparent charge dependence of this effect, and the suggestion that the slopes for $N \geq 92$ are similar to those for $N < 88$. Also, the relationship between these effects and the deformation of the nucleus was commented upon. Additional points now to be noted include these:

(a) The injection of the new data has produced a marked increase in the regularity of the $S_{2n}$ curves in the region $92 \leq N \leq 126$. One may now ascribe special significance to the irregularities that remain.

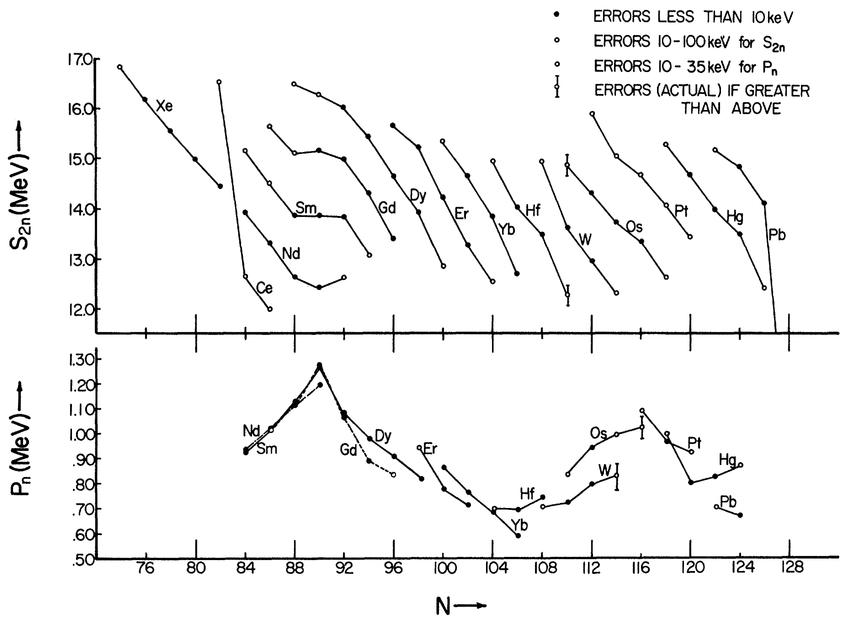


FIG. 1. Plot of double-neutron separation energy ($S_{2n}$) and of neutron-pairing energy ($P_n$), both as functions of neutron number. Data are for isotopes of the even-$Z$ elements in the region $82 \lesssim N \lesssim 126$.

(b) The energy of deformation exhibited by nuclides with $N = 90$ is least for $Z = 60$ (Nd) and shows a small but steady increase in going to $Z = 62$ (Sm) and $Z = 64$ (Dy). The relatively high value of $S_{2n}$ at $^{154}$Dy ($N = 88$, $Z = 66$) may suggest that this nuclide has already acquired a small ground-state deformation. But in going from $N = 90$ to $N = 92$, although there is also a $Z$ dependence, the incremental effect is greatest for $Z = 60$ (Nd).

(c) When viewed over a range of two neutrons the segments of adjacent curves are usually parallel to one another, that is, irregularities are reproduced for the same neutron numbers.

(d) The most conspicuous irregularities lie in the region $106 \leq N \leq 110$.

(e) Below $N \sim 106$ the shape of the curves (which are strikingly different from the "regular" curves referred to earlier) indicates that for certain elements the mass effect associated with deformation continues well beyond 92, but at a more gradual rate.

(f) The curves above $N \sim 110$ do not individually reveal the disapperance of deformation, rather, this disappearance is indicated by the large separations between the curves for $Z = 74$ (W), $Z = 76$ (Os), and $Z = 78$ (Pt).

In the lower portion of Fig. 1 is a plot of neutron-pairing energies for the majority of nuclides represented in the upper portion, calculated according to the relationship[12]

$$P_n(N) = (-1)^N \tfrac{1}{4}[2S_n(N) - S_n(N-1) - S_n(N+1)]. \quad (3)$$

These pairing-energy curves are a refinement and an extension of the pioneer work of Johnson and Nier[9] and Johnson and Bhanot[13] who drew attention to maxima in the region of 90 and 116 neutrons. With reference to the lower portion of Fig. 1, attention is now drawn to the following specific features:

(g) At $N = 90$ the neutron-pairing energies show a definite maximum for $Z = 62$ (Sm) and $Z = 64$ (Gd), a probable maximum for $Z = 60$ (Nd), and a possible maximum for $Z = 66$ (Dy). The greatest effect appears to occur at $Z = 62$ (Sm) and $Z = 64$ (Gd).

(h) A second maximum in the neutron-pairing energy appears to occur at $N = 116$, although the curve for no element actually passes through the maximum. But the curves for $Z = 76$ (Os) and $Z = 78$ (Pt) suggest the existence of this maximum, and those for $Z = 74$ (W) and $Z = 80$ (Hg) are not inconsistent with this hypothesis.

(i) Between these two maxima, the neutron-pairing energy appears to decline steadily to a minimum in the region $106 \leq N \leq 108$. This is undoubtedly related to the transition region referred to in comments (d), (e), and (f) above.

(j) The pairing energies for $Z = 80$ (Hg) and $Z = 82$ (Pb) appear not to follow the same trend as they approach the 126-neutron shell.

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[1]R. C. Barber, H. E. Duckworth, B. G. Hogg, J. D. Macdougall, W. McLatchie, and P. Van Rookhuyzen, Phys. Rev. Letters 12, 597 (1964).

[2]H. E. Duckworth, R. C. Barber, B. G. Hogg, J. D. Macdougall, W. McLatchie, and P. Van Rookhuyzen, in Congrès International de Physique Nucléaire, edited by P. Gugenberger (Centre National de la Recherche Scientifique, Paris, France, 1964), Vol. II, p. 557.

[3]J. D. Macdougall, W. McLatchie, S. Whineray, and H. E. Duckworth, Z. Naturforsch. 21a, 63 (1966).

[4]R. C. Barber, R. L. Bishop, L. A. Cambey, H. E. Duckworth, J. D. Macdougall, W. McLatchie, J. H. Ormrod, and P. Van Rookhuyzen, in Proceedings of the Second International Conference on Nuclidic Masses (Springer Verlag, Berlin, Germany, 1964), p. 393.

[5]R. C. Barber, J. O. Meredith, R. L. Bishop, H. E. Duckworth, M. E. Kettner, and P. Van Rookhuyzen, in Proceedings of the Third International Conference on Atomic Masses (University of Manitoba Press, Winnipeg, Man., Canada, 1968), p. 717.

[6]J. L. Benson and W. H. Johnson, Phys. Rev. 141, 1112 (1966).

[7]J. W. Dewdney and K. T. Bainbridge, Phys. Rev. 138, B540 (1965).

[8]J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 1 (1965).

[9]W. H. Johnson, Jr., and A. O. C. Nier, Phys. Rev. 105, 1014 (1957).

[10]R. A. Damerow, R. R. Ries, and W. H. Johnson, Jr., Phys. Rev. 132, 1673 (1963).

[11]R. L. Bishop, R. C. Barber, W. McLatchie, J. D. Macdougall, P. Van Rookhuyzen, and H. E. Duckworth, Can. J. Phys. 41, 1532 (1963).

[12]S. G. Nilsson and O. Prior, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 32, No. 16 (1961).

[13]W. H. Johnson, Jr., and V. B. Bhanot, Phys. Rev. 107, 1669 (1957).

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# MEASUREMENT OF THE MEAN LIFE OF THE 4.49-MeV ($5^-$) STATE OF $^{40}$Ca. EFFECTS OF DEFORMED COMPONENTS ON THE LIFETIMES OF THE ODD-PARITY STATES

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We have measured a mean life of $392 \pm 12$ psec for the 4.49-MeV ($5^-$) state of $^{40}$Ca, corresponding to an $E2$ transition strength of $1.04 \pm 0.03$ Weisskopf units which is considerably stronger than that predicted by a one-particle, one-hole description of the states. However, this $E2$ decay rate and those of eight other $E2$ transitions between odd-parity states can be understood when the states are described as admixtures of deformed and spherical wave functions.

The low-lying negative-parity states of $^{40}$Ca are described by Gerace and Green[1] as combinations of random phase approximation (RPA) states and three-particle, three-hole (3p-3h) deformed states. In particular, the 3.74- ($3_1^-$) and 4.49-MeV ($5_1^-$) states are described as largely RPA states, each having of the order of 5% 3p-3h deformed component. Other authors[2,3] describe the odd-parity spectrum as RPA states and obtain good agreement (as do Gerace and Green) for $E3$ and $E5$ transition rates of the $3_1^-$ and $5_1^-$ states to the ground state. These rates are not sensitive to the deformed component of the excited-state wave functions. However, small admixtures of deformed-state components may contribute significantly to transition rates between excited negative-parity levels. This Letter reports the measurement of the lifetime of the 4.49-MeV ($5_1^-$) state, the decay of which reflects deformed-state admixtures.