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Information on octupole deformation from the systematics of $B(E3;0_1^+ \rightarrow 3_1^-)$ values

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A study of the systematics of $B(E3;0_1^+ \rightarrow 3_1^-)$ values for nuclei throughout the Periodic Table shows clear enhancements at certain neutron numbers. These neutron numbers are in remarkably good agreement with those predicted by Strutinsky-type calculations to be likely candidates for static octupole deformation. The comparison with predicted proton numbers is more ambiguous.

During the past decade there has been much interest in the octupole excitation modes of nuclei (see, for example, Refs. 1–4 and references contained therein) and specifically in the question of whether some nuclei exist with static octupole deformation, corresponding to reflection-asymmetric intrinsic shapes.[5,6] The present work examines the systematics of $B(E3;0_1^+ \rightarrow 3_1^-)$ values in order to test the predictions of theories that include octupole deformation. Other experimental evidence has been summarized by Żylicz,[7] and a review of both the experimental work and the theoretical situation has been given by Rohoziński.[8] Early calculations of the ground-state shapes of nuclei, and their stability with respect to octupole deformation, gave no support for the existence of stable octupole shapes. However, subsequent more refined calculations, using the Strutinsky method with a folded Yukawa potential, indicated that some nuclei in the radium-thorium region, and also near ^{146}Ba, could have equilibrium octupole-deformed shapes, i.e., reflection-asymmetric intrinsic ground states with octupole deformation parameter $\beta_3 \neq 0$ (see, for example, Refs. 5, 6, 9, and 10).

Previous experimental evidence to support the existence of octupole deformation has been identified in ground-state mass systematics and in both low- and high-lying excited-state spectra. The relevant literature is extensive; illustrative works are cited below and more detailed references may be found in Ref. 8. Briefly, mass systematics for nuclei in the region beyond ^{208}Pb are better described by calculations that include nonzero equilibrium values of β_3 than by those that are restricted to reflection-symmetric intrinsic shapes.[5,9] The existence of very low-lying negative parity states in some even-even heavy nuclei, coupled with the nonobservation of harmonic two-photon states that would be expected if the excitations were vibrational, has been interpreted as evidence for static octupole deformation,[11] as also has the observation of almost-degenerate parity doublets in the low-lying spectra of some odd-A nuclei.[12,13] In addition, several nuclei in the radium region[14] and in the barium region[15] display alternating-parity sequences of high spin states, consistent with the establishment of intrinsic octupole deformation with increasing rotational frequency.[14] However, the published evidence for octupole deformation is indirect and subject to ambiguity of interpretation. Rohoziński[8] has recently summarized the situation as follows: "It is not completely clear at the moment whether a static octupole deformation really appears in some nuclei. Nevertheless, it is at least a serious possibility that this is the case."

In this context, Rohoziński and others have stressed the importance of $B(E3)$ values as a measure of octupole collectivity. Just as the largest values of $B(E2;0_1^+ \rightarrow 2_1^+)$ occur in regions of large static quadrupole deformation [see, for example, Fig. 7(b) of Ref. 16], so it might be expected that the largest values of $B(E3;0_1^+ \rightarrow 3_1^-)$ would occur in regions of static octupole deformation, where the $1_1^-,2_1^+,3_1^-,\ldots$ states correspond to rotational excitation of an octupole-deformed intrinsic shape.[17,18] Detailed calculations have confirmed that the values of $B(E3;0_1^+ \rightarrow 3_1^-)$ in even-even nuclei depend strongly on the octupole deformation at the potential-energy minimum.[19,20] Recently, one of us[16] has compiled values of $B(E3;0_1^+ \rightarrow 3_1^-)$ for even-even nuclei throughout the Periodic Table. It is of interest, therefore, to determine whether the systematics are consistent with theoretical expectations. For example, Nazarewicz *et al.*[6] predict that the largest octupole correlations, and hence the greatest tendency towards octupole deformation, will occur at particle numbers Z or $N = 34$, 56, 88, and 134.

Figure 1 shows a plot of $|M(E3)|^2$ as a function of neutron number N, where $|M(E3)|^2$ is the $E3$ transition strength in Weisskopf units (W.u.) deduced from the "adopted" values[16] of $B(E3;0_1^+ \rightarrow 3_1^-)$. The smallest values of $|M(E3)|^2$ occur in the region of $N = 100$–110, which is a region of large static quadrupole deformation; these small values are presumably due to fragmentation of the $E3$ strength corresponding to the four possible projections K of the total angular momentum on the nuclear symmetry axis. In contrast to the systematics of excitation energies $E_x(3_1^-)$ [e.g., Fig. 3(a) of Ref. 16], there is no obvious correlation with the standard magic numbers $N = 28$, 50, and 82. There are, however, significant peaks at $N = 34$, 56, 88, and 134, in remarkable agreement with the values of N predicted to favor static octupole deformation. (Note that the identification of a peak at $N = 134$ rests on the assumption that there is no sudden dip between $N = 128$ and 138, there being no data for $N = 130$, 132, 134, and 136.)

A plot of $|M(E3)|^2$ versus proton number Z (Fig. 2)

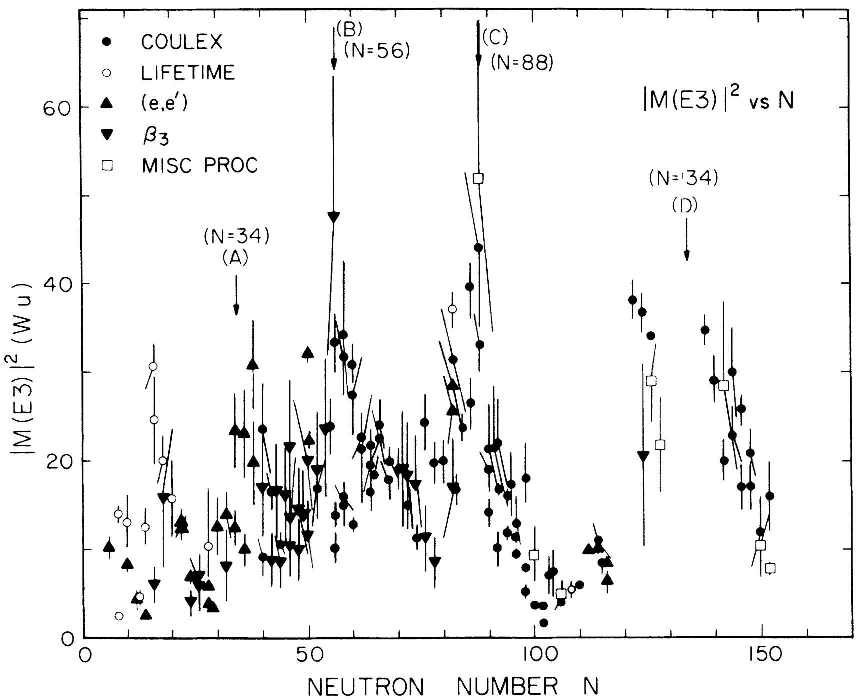

FIG. 1. Plot of $|M(E3)|^2$, the $E3$ transition strength of $0_1^+ \to 3_1^-$ transitions for even-even nuclei, as a function of neutron number N. The various symbols indicate the experimental procedures used to obtain the data (Coulomb excitation, lifetime measurements, inelastic electron scattering, deduction from β_3 values determined from inelastic scattering of particles, and miscellaneous procedures). This figure is based upon Fig. 7(a) of Ref. 16.

shows less-well-defined peaks at $Z=30$, 40, 62, and 88. There are no peaks at $Z=34$ and 56, the predicted values for stable octupole deformation. It is possible that the absence of peaks at the predicted values of Z may be explained by a mechanism similar to that suggested by Sheline and Sood[13] for the rare-earth region: since the $d_{5/2}$ and $g_{9/2}$ proton orbitals are nearly degenerate in energy, octupole correlation effects for protons (arising from the $d_{5/2}$ and $h_{11/2}$ orbitals combining in the low-energy region) may be somewhat less visible than for neutrons, being diluted and extended over a larger range. Alternatively, it may be that octupole-correlation effects for protons

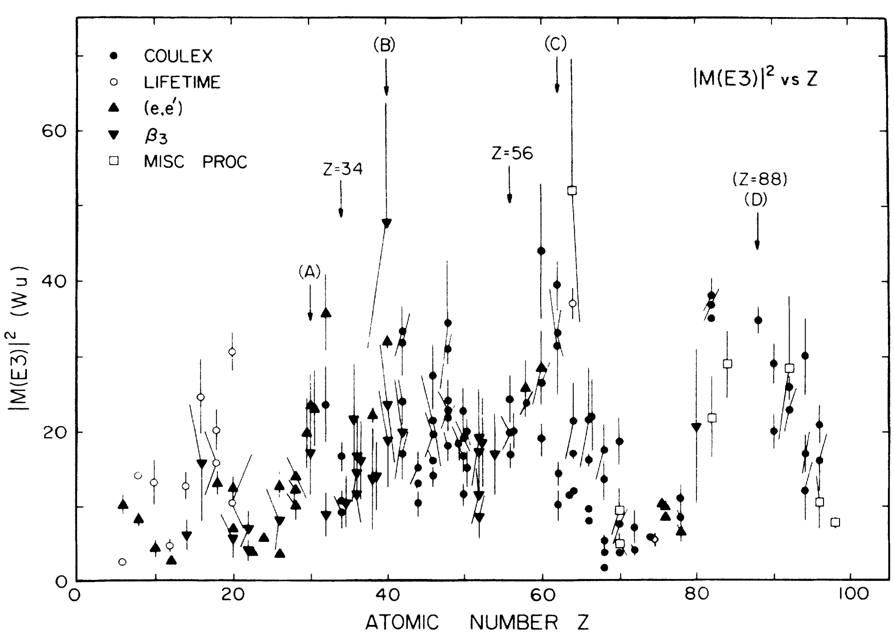

FIG. 2. As for Fig. 1, but as a function of Z. This figure is based upon Fig. 6(a) of Ref. 16.

peak at larger values of Z than predicted, thus indicating the need for refinement in the theory. There is some experimental support for these possibilities, e.g., effects characteristic of those expected for octupole deformation have been observed in europium nuclei ($Z=63$).[21] On the other hand, it is possible that the structure observed in Fig. 2 is entirely due to the effects of varying neutron number. For experimental reasons, determinations of $B(E3;0_1^+ \rightarrow 3_1^-)$ have been largely confined to stable nuclei, and the peaks labeled *A*, *B*, *C*, and *D* in Fig. 2 occur at Z values of the stable nuclei having N values corresponding to peaks *A*, *B*, *C*, and *D*, respectively, of Fig. 1. That is, the peaks with the same labels in the two plots contain the same data points.

The experimental situation may be clarified by reference to Fig. 3, where the nuclei with known values of $B(E3;0_1^+ \rightarrow 3_1^-)$ are displayed as points in the N-Z plane. As indicated above, the nuclei concerned are mostly stable. Nazarewicz *et al.*[6] state that their calculations predict four specific groups of nuclei as likely to possess octupole-deformed equilibrium shapes: neutron-deficient isotopes with $Z\simeq 90$ and $N\simeq 134$, neutron-rich isotropes with $Z\simeq 34$, $N\simeq 56$, and $Z\simeq 56$, $N\simeq 88$, and neutron-deficient nuclei with $Z\simeq N\simeq 34$. These four Z,N combinations are shown as crosses in Fig. 3. Also shown, by squares, are the Z,N values corresponding to the four peaks *A*, *B*, *C*, and *D* of Figs. 1 and 2. The correspondence between the predictions of Nazarewicz *et al.* and the peaks in the $B(E3;0_1^+ \rightarrow 3_1^-)$ values is clear. In case *D*, the experimental peak coincides very closely with the prediction, and in the other cases it corresponds to a translation from the predicted Z,N values along a line of constant N. For the region near *D* in the N-Z plane, there are published predictions for the shape of the nuclear potential-energy surface plotted as the correction to the energy obtained by including octupole deformation, relative to the reflection-symmetric minimum (see Fig. 3 of Ref. 5); there is a clear minimum in the potential energy at $Z,N=88,134$ and a valley extending towards increasing Z and decreasing N. For the regions near *A*, *B*, and *C*, the suggestion from the plot shown here (Fig. 3) is that the valleys should follow lines of constant N, i.e., the contours of constant potential energy may be elongated in the Z direction. The results from studies of possible octupole-band structure in $N\simeq 88$ ("barium") region are also suggestive of this (cf. Fig. 1 of Ref. 15).

In the region denoted *D* in Figs. 1 and 2, centered at $Z=88$ and $N=134$, it is reasonable to suppose that the existing data are on the sloping edges of the postulated peak, and that the values of $B(E3;0_1^+ \rightarrow 3_1^-)$ for the unmeasured nuclei will be very large, possibly with $|M(E3)|^2 > 50$ W.u. Enhancements of this order were obtained by Baranowski *et al.*[20] when static octupole deformation was included in their calculations. Most of the nuclei concerned are very short lived and the measurement of $B(E3;0_1^+ \rightarrow 3_1^-)$ constitutes a formidable experimental challenge.

In summary, the systematics of $B(E3;0_1^+ \rightarrow 3_1^-)$ values for even-even nuclei show particularly strong octupole collectivity at precisely the N values predicted by Leander and co-workers[5,6] to be likely candidates for static octupole deformation. The evidence for an analogous Z effect is more ambiguous, possibly because the data for $B(E3;0_1^+ \rightarrow 3_1^-)$ are largely restricted to stable nuclei. Although the values of N displaying enhanced octupole collectivity are in good agreement with the predictions of the theory, they do not themselves prove the existence of static octupole deformation in the ground states of the nuclei concerned. It may be possible (cf. Ref. 20) to interpret the magnitudes of the peaks so as to distinguish between static deformation effects and strong vibrational collectivity. Finally, there is an obvious need for more and

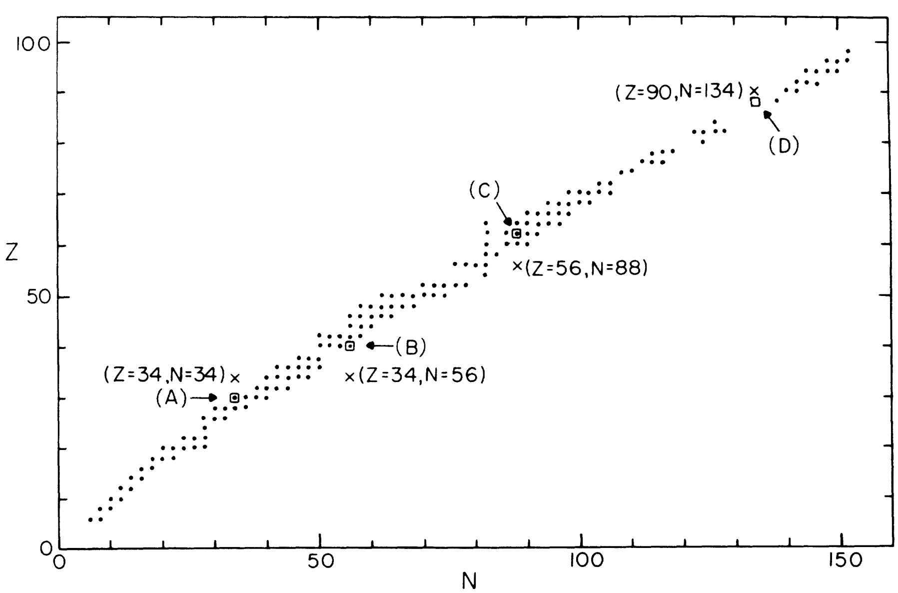

FIG. 3. The points indicate nuclei for which $B(E3;0_1^+ \rightarrow 3_1^-)$ values have been adopted in Ref. 16. The crosses show regions predicted by Nazarewicz (Ref. 6) to be likely candidates for stable octupole deformation. The squares correspond to the peaks labeled in the $|M(E3)|^2$ plots of Figs. 1 and 2.

better data on $B(E3;0_1^+ \rightarrow 3_1^-)$ values in order to delineate more precisely the regions of enhanced octupole strengths.

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[1]P. D. Cottle and D. A. Bromley, Phys. Lett. B **182**, 129 (1986).

[2]P. D. Cottle and D. A. Bromley, Phys. Rev. C **35**, 1891 (1987).

[3]P. D. Cottle, K. A. Stuckey, and K. W. Kemper, Phys. Rev. C **38**, 365 (1988).

[4]N. V. Zamfir, R. F. Casten, and P. Von Brentano, Phys. Lett. B **226**, 11 (1989).

[5]G. A. Leander, R. K. Sheline, P. Möller, P. Olanders, I. Ragnarsson, and A. J. Sierk, Nucl. Phys. **A388**, 452 (1982).

[6]W. Nazarewicz, P. Olanders, I. Ragnarsson, J. Dudek, G. A. Leander, P. Möller, and E. Ruchowska, Nucl. Phys. **A429**, 269 (1984).

[7]J. Zylicz, in *Proceedings of the International Conference on Nuclear Structure, Reactions and Symmetries, Dubrovnik, Yugoslavia, 1986,* edited by R. A. Meyer and V. Paar (World-Scientific, Singapore, 1986) Vol. 1, p. 79.

[8]S. G. Rohoziński, Rep. Prog. Phys. **51**, 541 (1988).

[9]P. Möller and J. R. Nix, Nucl. Phys. **A361**, 117 (1981).

[10]G. A. Leander, W. Nazarewicz, P. Olanders, I. Ragnarsson, and J. Dudek, Phys. Lett. B **152**, 284 (1985).

[11]W. Kurcewicz, E. Ruchowska, N. Kaffrell, T. Björnstad, and G. Nyman, Nucl. Phys. **A356**, 15 (1981).

[12]I. Ahmad, J. E. Gindler, R. R. Betts, R. R. Chasman, and A. M. Friedman, Phys. Rev. Lett. **49**, 1758 (1982).

[13]R. K. Sheline and P. C. Sood, Mod. Phys. Lett. A **4**, 1329 (1989).

[14]A. Celler, Ch. Briancon, J. S. Dionisio, A. Lefebvre, Ch. Vieu, J. Żylicz, R. Kulessa, C. Mittag, J. Fernandez-Niello, Ch. Lauterbach, H. Puchta, and F. Riess, Nucl. Phys. **A432**, 421 (1985).

[15]W. R. Phillips, R. V. F. Janssens, I. Ahmad, H. Emling, R. Holzmann, T. L. Khoo, and M. W. Drigert, Phys. Lett. B **212**, 402 (1988).

[16]R. H. Spear, At. Data and Nucl. Data Tables **42**, 55 (1989).

[17]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, 1975), Vol. 2, p. 19.

[18]R. R. Chasman, in *Proceedings of the International Conference on Nuclear Structure, Reactions and Symmetries* (Ref. 7), p. 6.

[19]K. Böning, A. Sobiczewski, B. Nerlo-Pomorska, and K. Pomorski, Phys. Lett. B **161**, 231 (1985).

[20]R. Baranowski, K. Böning, and A. Sobiczewski, in *Proceedings of the International Conference on Nuclear Structure, Reactions and Symmetries* (Ref. 7), p. 121.

[21]R. K. Sheline, Phys. Lett. B **219**, 222 (1989).