Contr. to Proc. Fifth Int. Symp. on Capture Gamma-Ray Spectroscopy and Related Topics, September, 1984, editor S. Raman (AIP Conference Proceedings Series)

CONF-840906--9

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DE85 001671

SHELL EFFECTS ON THE E1 MOMENTS OF RA-TH NUCLEI

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ABSTRACT

Large systematic shell effects on intrinsic E1 moments are found, which should modulate any E1 moment induced by β_3 deformation. The calculated shell effects can explain an emerging trend for E1 data in Ra-Th nuclei, if and only if the gross β_3-induced polarization of finite nuclear matter goes in the same direction as the "lightning rod" effect.

INTRODUCTION

If the left-right symmetry of the intrinsic nuclear shape is broken, the nucleus can have an intrinsic dipole moment. The dipole moment, Q_{10}, induced by octupole distortions of a nuclear liquid drop was estimated many years ago as[1,2]

$$Q_{10}^{LD} = C_{LD} \, A \, Z \, \beta_2 \, \beta_3 \tag{1}$$

The estimate for the numerical coefficient is $C_{LD} = +0.00069$ fm in Ref. 1 and -0.00052 fm in Ref. 2, about the same magnitude but with opposite signs (Fig. 1).

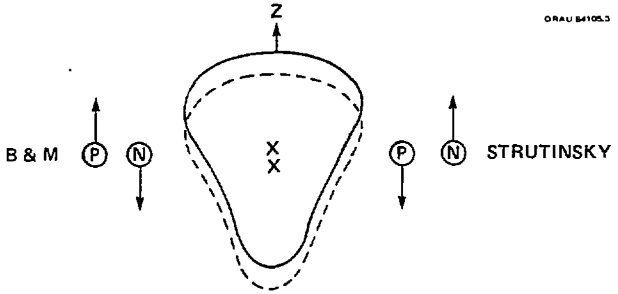

Fig. 1. Schematic drawing of an octupole shape with $\varepsilon_3>0$ ($\beta_3<0$). Strutinsky[1] and Bohr and Mottelson[2] obtained the neutron-proton polarization in opposite directions, because Strutinsky allowed the Coulomb potential to push the protons toward the surface where they are driven by the "lightning rod" effect towards regions of maximum curvature.

Recently, a number of experiments[3-10] on isotopes in the Ra-Th region have revealed unusually fast E1 transitions of apparently collective character. Theoretical potential-energy calculations had previously yielded octupole-deformed intrinsic equilibrium shapes in these nuclei.[11] However, the liquid-drop formula (1) provides at best an order-of-magnitude estimate for the E1 rates in this region. In particular, Eq. (1) does not explain why the E1 enhancement is absent in some heavier Ra and Ac isotopes[10,12-14], where β_2 is large and β_3 is non-zero according to both theory[11] and the spectroscopic evidence.[15] This paper presents a first investigation of shell effects on the E1 moments in an octupole-deformed single-particle potential. It will be seen that such shell effects do in fact lead to substantial systematic fluctuations around the liquid-drop value.

CALCULATIONS

Single-particle wave functions were calculated in the folded Yukawa single-particle potential with octupole deformation as described in Ref. 11. Let us first examine the center of mass for neutrons and protons separately, obtained by summing $\langle z \rangle_{sp}$ for the single-particle orbits at some fixed, representative deformation (Fig. 2). The z axis is defined as in Fig. 1, with the origin at the equivalent sharp-surface center of mass. Fig. 2 shows a systematic shell effect on the sum. Thus the contribution of successive orbitals does not give rise to random fluctuations around some average. For particle numbers in the Ra-Th region the single-particle contributions have coherent signs. The sum peaks at the closed shells and decreases smoothly towards mid-shell. Similar results are obtained at other relevant deformations.

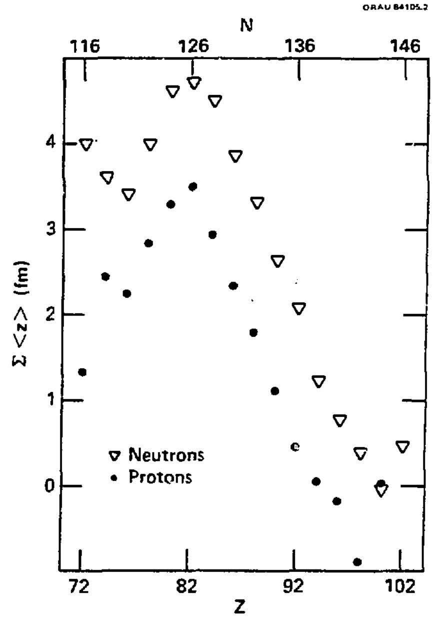

Fig 2. Sum of the single-particle expectation values of z as a function of the number of particles occupying the lowest orbits at $\varepsilon_2 = 0.10$, $\varepsilon_3 = 0.08$.

A nuclear E1 moment,

$$\delta Q_{10}^{sp} = \frac{N}{A} \sum_{p} v^2 \langle z \rangle - \frac{Z}{A} \sum_{n} v^2 \langle z \rangle \qquad (2)$$

was evaluated at the appropriate equilibrium deformations,[11] with BCS occupation factors v^2. This E1 moment from the independent-particle model also varies smoothly and systematically through the Ra-Th region. However, it is only a "raw" shell correction, to be renormalized, reduced by the restoring force of neutron-proton interaction and finally added to Q_{10}^{LD}. Work on these steps is in progress. In particular, the appropriate reduction might be obtained from that dipole-dipole interaction which also reproduces the giant dipole resonance.

COMPARISON WITH EXPERIMENT AND CONCLUSIONS

The δQ_{10} values from Eq. (2) increase as N decreases and Z increases from ^{226}Ra. Both these smooth trends can be represented by plotting vs. N-1.5Z: a single dashed curve goes through the theoretical points for Ra and Th in Fig. 3. The experimental data

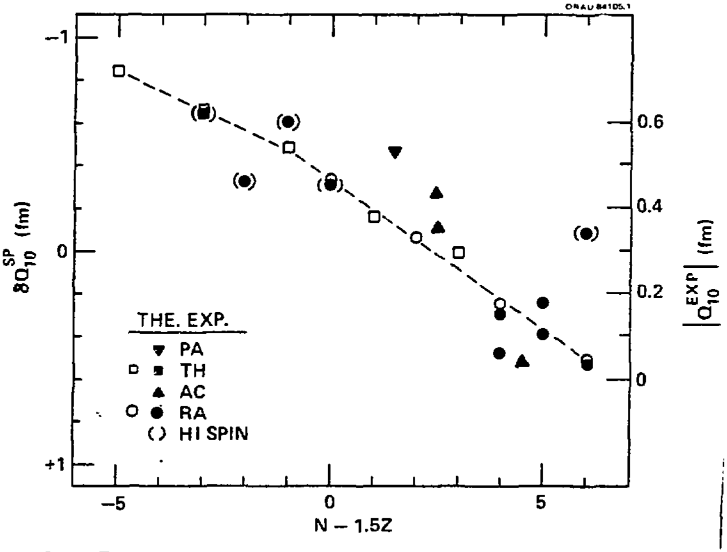

Fig. 3. E1 moments from independent-particle theory (δQ_{10}^{sp}) and absolute moments from experiment ($| Q_{10}^{exp} |$).

points in Fig. 3 have been extracted from a variety of experiments by the formula

$$| Q_{10}^{exp} | = \{ \frac{4\pi}{3} B(E1;I_i \rightarrow I_f) \}^{1/2} / \langle I_i K 1 0 | I_f K \rangle \qquad (3)$$

and using various assumptions about the rate of transitions by competing modes. The data exhibit an overall trend which could be accounted for by the E1 shell effects. Actually, theory and experiment in Fig. 3 seem to agree simply because they are plotted against different scales. Such judicious rescaling can be viewed as a phenomenological renormalization of δQ_{10}. The ad hoc reduction factor in Fig. 3 is 2, to be compared with a factor of about 3.6 that is estimated[16] to arise from a dipole-dipole interaction consistent with the giant dipole resonance.

The value of $|Q_{10}^{exp}|$ at $\delta Q_{10} = 0$ is 0.3 fm, which can be interpreted as the empirical value of $|Q_{10}^{LD}|$. Furthermore, since Q_{10}^{LD} appears to be cancelled by the positive shell corrections in nuclei around ^{226}Ra, and augmented by the negative shell corrections around ^{222}Th, if follows that the sign of Q_{10}^{LD} is negative when the nucleus is oriented as in Fig. 1. In conclusion, the still preliminary empirical trend of E1 rates in the Ra-Th region, and the trend of calculated shell corrections, suggests $C_{LD} \sim +0.001$ and would thereby confirm the presence of "lightning rod" effect[1] in nuclei.

Discussions with P. Vogel are gratefully acknowledged. UNISOR is a consortium of twelve institutions, supported by them and by the Office of Energy Research of the U.S. Department of Energy under Contract No. DE-AC05-76OR00033 with Oak Ridge Associated Universities.

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