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ISOSPIN EFFECTS IN NUCLEAR VIBRATIONS*

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ABSTRACT

A review of the evidence that the ratio of neutron and proton multipole matrix elements for collective vibrations in single-closed-shell nuclei differ systematically from N/Z is presented. A theoretical framework is given for understanding the data on the basis of the ideas of core polarization. It follows that nuclear deformation parameters are probe dependent and that analysis of excitations by two different probes such as (p, p') and (n, n') can, in principle, give the ratio M_n/M_p . Application is made to first 2^+ states of open shell nuclei. Trends of M_n/M_p for higher 2^+ states are presented. Expected systematics of M_n/M_p ratios for giant isoscalar quadrupole transitions are presented.

INTRODUCTION

Historically, in the 1960's there were many measurements of the excitation of low-lying collective states by various external probes, electromagnetic, (p, p') , (α, α') , and (n, n') . It was noticed and expected on the basis of the collective model that for the excitation of the 2^+ first excited state of any given even nucleus, the deformation parameter β was independent of excitation mechanism. The absolute errors in the measurements would not have excluded, however, small systematic differences.

Whereas the collective model described the low-lying collective states in terms of vibrations or rotations of a homogeneous neutron-proton fluid with a single deformation parameter, the microscopic model described them in terms of linear combinations of neutron and proton single-particle transitions. Because of the shell structure and the Pauli principle, differences in the freedom of neutrons and protons to vibrate could be expected. This is particularly true in single-closed-shell (SCS) nuclei, where one type of nucleon is "frozen in" by the shell closure. The collective model and the shell model would therefore disagree on the degree of participation of the neutrons and protons in nuclear vibrations. Furthermore, since different external fields or probes such as electromagnetic, (p, p') , (n, n') , (α, α') , etc., interact differently with the nuclear neutrons and protons, one would expect on the basis of the shell-model picture that deformation parameters β determined by a collective-model analysis of excitation of vibrational states would vary greatly from one probe to another.

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The resolution of this contradiction comes from core polarization and the greater strength of the nuclear force between nucleons of the opposite type. In a proton SCS nucleus, for example, the valence neutrons will polarize "core" protons more strongly than core neutrons, thereby tending to restore the proportionality of neutron to proton amplitudes toward N/Z , in agreement with the collective model. However, the restoration need not be complete. A schematic model¹ which treats core polarization as a virtual excitation of giant resonances and includes unequal like and unlike particle forces predicts² that for SCS nuclei there should be systematic differences between deformation parameters obtained by analysis of data from different external fields.

In this talk, following a brief statement of the schematic model of core polarization, we review the evidence for systematic differences in the deformation parameters β_n and β_p of nuclear neutrons and protons and the consequent probe dependence of measured β values. Next an application is made to the systematics of first 2^+ states in open-shell nuclei, and a comparison is made with available data. Evidence is presented that for excitation of other low-lying 2^+ states there is a reversal in the trend of neutron and proton deformation parameters ratios from those of the first 2^+ state. Last, some expectations and information are presented concerning neutron and proton differences in excitation of giant resonances.

THEORETICAL FORMULATION OF CORE POLARIZATION

The neutron and proton multipole matrix elements are defined as

$$M_{\begin{smallmatrix} n \\ p \end{smallmatrix}} = \langle f \parallel \sum_{i=1}^{\begin{smallmatrix} N \\ Z \end{smallmatrix}} r_i^\lambda Y_\lambda(\hat{r}_i) \parallel i \rangle \quad (1)$$

The formulation of the collective model³ relates this quantity to the nuclear deformation parameters, β such that M_p is proportional to $Z\beta$:

$$\frac{M_n}{M_p} = \frac{N\beta_n}{Z\beta_p} \quad (2)$$

We have allowed in Eq. (2) for the possibility that the nuclear neutrons and protons have different deformation parameters β_n and β_p for a particular excited vibrational state, although, as stated in the introduction, the conventional collective model assumes a homogeneous nuclear fluid, for which $\beta_n = \beta_p$.

In the microscopic picture we must deal with a limited model space, where M_n and M_p may vary rapidly from nucleus to nucleus but in which one has the capability of calculating the multipole matrix elements accurately, such as the $0h\omega$ space in the shell model. It is expected that additional contributions vary slowly and systematically and can therefore be treated as core polarization.

We have formulated core polarization^{1,4} within the context of the TDA or RPA approximations using separable multipole forces and breaking the Hamiltonian matrix into two pieces,

$$H = \begin{pmatrix} H_{aa} & 0 \\ 0 & H_{bb} \end{pmatrix} + \begin{pmatrix} 0 & H_{ab} \\ H_{ba} & 0 \end{pmatrix}, \quad (3)$$

where a represents the $0\hbar\omega$ model space and b, the $2\hbar\omega$ core-polarization space. The first term in Eq. (3) is to be treated exactly, giving a description of low-lying 2^+ states in a and giant resonance states in b, and the second term, which connects the spaces, is to be treated in perturbation theory.

The perturbation mixes the high and low-lying states, giving the following results⁴ for M_n and M_p of Eq. (1) for a state *s* in the lower space,

$$M_s \approx M_s^{(a)} + 2 \sum_t M_t^{(b)} \frac{[m_t^{(b)} \quad V \quad m_s^{(a)}] E_t^{(b)}}{[E_s^{(a)}]^2 - [E_t^{(b)}]^2}, \quad (4)$$

where *V* is a 2×2 matrix of like (diagonal) and unlike (non-diagonal) nucleon-nucleon force constants. The matrix M_s is defined as

$$M_s = \begin{pmatrix} M_{ns} \\ M_{ps} \end{pmatrix} \quad (5)$$

and *m* is defined similarly but with r^λ and Eq. (1) replaced by $w_\lambda(r)$, the radial function in the separable multipole force.⁵ If, in Eq. (1), r^λ is replaced by $\delta(r-r')/rr'$, Eq. (4) becomes an equation for the transition densities ρ_s with their contribution from the model space $M_s^{(a)} \rightarrow \rho_s^{(a)}$ and from the $2\hbar\omega$ core-polarization space $M_s^{(b)} \rightarrow \rho_s^{(b)}$. The rest of the factor in the second term of Eq. (4) is a numerical coefficient, common for matrix elements of all operators of multipolarity λ . The presence of the $[E_s^{(a)}]^2$ and $[E_t^{(b)}]^2$, coming from the energy-squared eigenvalues of the RPA equations,⁵ takes into account ground-state correlations.

If we take $w_\lambda(r) = r^\lambda$, then $m = M$, and Eq. (4) may be factored to give the result,

$$M_s = \left\{ 1 + 2 \sum_t \frac{E_t^{(b)} M_t^{(b)} M_t^{(b)\dagger} V}{[E_s^{(a)}]^2 - [E_t^{(b)}]^2} \right\} M_s^{(a)} \equiv (1 + \delta) M_s^{(a)}, \quad (6)$$

where δ is defined to be the core-polarization matrix.

$$\delta = \begin{pmatrix} \delta^{nn} & \delta^{np} \\ \delta^{pn} & \delta^{pp} \end{pmatrix} \quad (7)$$

In Eq. (7), δ^{np} is the parameter describing polarization of core neutrons by valence protons, etc. The schematic model^{1,4} consists of treatment of the *b*-space configurations as degenerate.

Equation (6) may be transformed to the isoscalar notation, in which the core-polarization matrix δ becomes nearly diagonal. The unequal off-diagonal matrix elements cause $\delta_{np} \neq \delta_{pn}$, $\delta_{nn} \neq \delta_{pp}$, which is important in the systematics of core polarization.

REVIEW OF RESULTS FOR FIRST 2^+ STATES OF SINGLE-CLOSED-SHELL NUCLEI

In Fig. 1 is shown a collection⁶ of data for the ratios M_n/M_p for the first excited 2^+ states of SCS nuclei for various pairs of probes. The symbol α/EM means, for example, that measurements of (α, α') and electromagnetic excitation of the nucleus were used together for the determination of the multipole matrix element-ratio. The mirror method⁷ consists of determination of M_n in a given nucleus with $N > Z$ by measuring M_p in an isobaric analog of the 2^+ state transition in question and making corrections, where necessary, for isospin impurities. In view of the extreme ratios M_n/M_p which would result from a calculation in a limited shell-model basis (∞ or 0 for neutron or proton valence nuclei, respectively), the results are remarkably close to the homogeneous collective model value of N/Z .

FIG. 1. Ratios of neutron to proton multipole matrix elements of single-closed-shell nuclei.

For the purposes of the neutron conference it is important to note that n/p was used in establishing M_n/M_p ratios in ^{18}O , isotopes of Ca, ^{58}Ni , ^{88}Sr , ^{90}Zr , and the isotopes of Sn.

Also shown in Fig. 1 are the results of the schematic model described in the previous section. The dashed and solid lines are the no (free) parameter and one-parameter versions of the model.¹ In the simple case of SCS nuclei, in which either $M_n^{(a)}$ or $M_p^{(a)}$ is zero, the ratio is a function only of the core-polarization parameters:

$$\frac{M_n}{M_p} = \frac{1 + \delta^{nn}}{\delta^{pn}} \quad (\text{neutron valence}) , \quad (8a)$$

$$\frac{M_n}{M_p} = \frac{\delta^{np}}{1 + \delta^{pp}} \quad (\text{proton valence}) . \quad (8b)$$

It is clear from Fig. 1 that the schematic model describes correctly the trend of the data. The data imply that $(1 + \delta^{nn})/\delta^{pn}$ is a little greater than N/Z and that $\delta^{np}/(1 + \delta^{pp})$ is a little less than N/Z . However, the closeness of the ratios M_n/M_p to N/Z tell us also that $\delta^{nn} < \delta^{pn}$, $\delta^{pp} < \delta^{np}$, and that $[(1 + \delta^{nn})/(1 + \delta^{pp})] [\delta^{np}/\delta^{pn}] \approx N^2/Z^2$. In words the first two of these relationships means that nucleons polarize unlike nucleons more than like nucleons, and the third means that neutrons give larger core polarization contributions than protons. Both of these results are easy to understand. The first follows from the greater interaction between unlike than like nucleons, and the second is due to the fact of a neutron excess.

Figure 2 shows the trend of probe dependences⁸ of the nuclear deformation parameters resulting from the departure of M_n/M_p from N/Z for three examples of SCS nuclei as a function of the ratio of strengths of interaction of the probe F with nuclear neutrons to that of nuclear protons. There is evidently a rising trend in $\delta = \beta R$ with increasing ratio b_n^F/b_p^F for the two neutron valence nuclei ^{116}Sn and ^{58}Ni and a falling trend for the proton valence nucleus ^{90}Zr . The schematic model calculations have been made using the relationship

$$\beta_F = \frac{N b_n^F \beta_n + Z b_p^F \beta_p}{N b_n^F + Z b_p^F} . \quad (9)$$

FIG. 2. Dependence of deformation parameter $\delta \equiv \beta R$ on external field (probe).

The most sensitive pairs of probes for determining M_n/M_p are those with the most extreme differences in neutron and proton strengths. From the abscissa of Fig. 2 we see that these are p/EM , n/p , and π^-/π^+ .

FIRST 2^+ STATES IN OPEN-SHELL NUCLEI

Equation (6) applies also to open-shell nuclei, but one requires then a model for the valence neutron and proton matrix elements $M_n^{(a)}$ and $M_p^{(a)}$. One would normally use shell-model calculations for this purpose. However, we have taken advantage of the empirical fact that the major shell closures dominate the systematics of nuclear collectivity. At or near magic numbers deformation parameters are small, and away from them they are large. We have used⁹ schematic model in the Oħw model space for calculating $M_n^{(a)}/M_p^{(a)}$. The use of a pairing force and the resulting pairing gap makes the rough assumption of degeneracy of the single-particle states reasonable though not accurate. In the degenerate model, the pairing equations can be solved in closed form, as can the RPA equations for degenerate two quasi-particle states. Parameters from our earlier work¹ were used in Eq. (6) for the core polarization matrix δ .

Figure 3 shows the results of these simple calculations for the trends of β_n/β_p for several sets of isotopes and isotones along with values determined from 50 MeV P/EM by Matoba¹⁰ and a few other measurements.⁹ Several features should be noted. First, as in Fig. 1, SCS nuclei such as the Sn isotopes, the $N=50$ isotones, and the $N=82$ isotones have ratios β_n/β_p rather different from 1. Second, there is a sudden jump in the direction of unity as the number of neutrons or protons is changed from a magic number by even a single pair of nucleons. This effect is seen in the isotopes of Mo which include in ^{92}Mo a SCS member and in the comparison of isotopes of ^{48}Cd and ^{52}Te with magic number nuclei ^{50}Sn . Third, the crude schematic model, which ignores all details of shell structure within a major shell, but does take into account the magic numbers within a major shell, agrees with the trends of the data. We note also that away from closed shells ratios of β_n/β_p are near 1, so therefore hard to establish that $\beta_n \neq \beta_p$.

OTHER LOW-LYING 2^+ STATES

Besides the first 2^+ states of nuclei discussed so far, there are other low-lying states with some collective strength. It is interesting to see whether there are also trends of β differences for these states. In the SCS nucleus ^{90}Zr with N closed at magic number 50, the first 2^+ state at 2.19 MeV has¹¹⁻¹⁵ $\beta_n/\beta_p = .82 \pm .18$, so $\beta_n < \beta_p$ as anticipated from the shell structure. At 3.31 MeV there is another much weaker collective state with $\beta_n/\beta_p = 1.49 \pm .40$, reversed from the direction of the ratio of β_n and β_p from that of the first 2^+ state. This reversal behavior has been seen¹¹ in several nuclei, ^{18}O , ^{26}Mg , ^{30}Si , ^{42}Ca , ^{54}Fe , and ^{58}Ni . Core polarization, which treats all low-lying nuclear states nearly alike [See Eq. (6)], cannot be solely responsible when this phenomenon occurs in SCS nuclei. The reversal states must be due to some other configurations from those dominating the first 2^+ state. In an SCS nucleus, such as ^{18}O , proton configurations in the low-energy range must come from more complicated configurations than $(2d)^2$, $(2d,2s)$ such as two valence particles plus two-particle two-hole configurations, known to be important for the phenomenon of nuclear coexistence.

FIG. 3. Ratios of neutron and proton deformation parameters for open-shell nuclei. Lines are results of a $0h\omega$ schematic model plus core polarization. Dashed lines reach to unmeasured isotopes.

The question of the sign of M_n/M_p has been discussed by Miskeman et al.¹⁶ If $|M_n| \approx |M_p|$ the state is nearly isoscalar or nearly isovector in character. In a nucleus with only one neutron configuration and one proton configuration, the interaction would mix the two, giving one state of $M_n/M_p > 0$ and one with $M_n/M_p < 0$. The former would be pushed down in energy by the interaction and the latter would be pushed up. Furthermore, the sense of the inequality of $|M_n/M_p|$ would be reversed. If there are several neutron and several proton configurations, the interaction will likewise mix them, producing some isoscalar-like states, which will be pushed down in energy, and some isovector like states, which will be pushed up. Under these circumstances there will be a tendency for the lower lying of these states to be isoscalar like, therefore having $M_n/M_p > 0$.

For determination of the relative sign, measurements with three different probes are needed. Some interesting work from Ohio university on 2^+ states in ^{34}S will be discussed in a contributed paper in this session by Alarcon.¹⁷ There is a strong indication from this^{17,18} and other work that the measurements of M_n/M_p , including the sign, will be of considerable importance in discovering the structure of the low-lying 2^+ states in even nuclei.

GIANT RESONANCE STATES

As we have seen the systematics of M_n and M_p of first 2^+ states, the primary determiner of M_n/M_p is the nature of the shell structure in the N and Z region of the nucleus in question. The results of the previous section showed that SCS nuclei are special in the extent of the departure of M_n/M_p from the collective model ratio of N/Z. On the other hand, shell structure should be nearly irrelevant for giant states because they are inherently shell-breaking transitions.

As an example consider the isotopes of Sn. The important low-lying transitions come from neutrons within the primarily positive parity states of the N=4 harmonic oscillator, which implies that for the first 2^+ state $M_n/M_p > N/Z$. For the giant resonances the dominant configurations involve protons in the N=2 and 3 major shells excited by $2\hbar\omega$ into the N=4 and 5 shells and neutrons in the N=3, 4, and 5 shells also excited by $2\hbar\omega$ into the N=5, 6, and 7 shells. The shell structure should be practically irrelevant for the question of neutron and proton multipole matrix elements. What effect remains from shell structure is, in fact, in the opposite direction from that of the low-lying states. In Sn greater neutron strength in the low-lying states implies simply on the basis of the sum rule that the neutron strength in the giant resonance will be decreased. This is a weak effect (typically ~10%) however, because of the large disparity in the energies of the $0\hbar\omega$ and $2\hbar\omega$ transitions. Another way of saying the same physics is that the core polarization of giant 2^+ states due to low-lying 2^+ states is small and in the opposite direction from the core polarization of the latter by the former. This effect can be seen in Eq. (6) with the reversed identification of b with the $0\hbar\omega$ space and a with the $2\hbar\omega$ space.

Although the schematic model^{1,4} is normally used for calculating M_n and M_p for low-lying states, its results are also relevant for giant resonances because M^b used by Eq. (6) is the 2×1 matrix of neutron and proton multipole matrix elements for the giant resonance states (without the small coupling to the low-lying states). In a neutron-excess nucleus the neutrons have a larger number of $2\hbar\omega$ particle-hole pairs than do the protons. However the isoscalar interaction mixes the neutron and proton configurations and tends to give the protons a larger weighting, reducing M_n/M_p and producing a nearly isoscalar vibration.

The schematic model¹ with pure harmonic-oscillator wave functions, a separable quadrupole interaction, degenerate $2\hbar\omega$ particle-hole states, and the constraint of equal RMS radii $r_n = r_p$ gives the ratio

$$\frac{M_n}{M_p} \approx \left(1 + \frac{2}{3} \frac{V_0}{V_0 - V_\tau} \frac{N-Z}{A}\right) / \left(1 - \frac{2}{3} \frac{V_0}{V_0 - V_\tau} \frac{N-Z}{A}\right) \quad (10)$$

for an assumed relation of isoscalar to $\tau \cdot \tau$ interaction strength $V_0 = -2V_\tau$. This ratio is $M_n/M_p = 1.15$ for ^{118}Sn compared to $N/Z = 1.25$. If we allow the $r_n = r_p + .2$ fm, the calculated value becomes $M_n/M_p = 1.26$, still somewhat lower than N/Z. These results are well corroborated by our full RPA calculations in a harmonic-oscillator basis, also using separable quadrupole interactions. The latter calculations for ^{208}Pb with equal neutron and proton rms radii, experimental single-particle energies, and a single choice of quadrupole interaction strength give a satisfactory description of the energy, the B(E2) value, and M_n/M_p of the first 2^+ state and of the isoscalar giant

resonance energy (although slightly low). They are also in good agreement with an RPA calculation¹⁹ using the Migdal force and a discretized continuum, except that M_p in our calculations is about 10% larger than Ref. 19. This may indicate a suppression of proton strength when Coulomb forces are included.

Experimentally, M_n/M_p for giant resonances may be measured with two different probes just as for low-lying states. Excitation by inelastic scattering of both π^+ and π^- projectiles gives, in principle, a fairly sensitive measurement of M_n/M_p because of 3:1 ratio of the interaction of $V_{\pi^-,n}/V_{\pi^-,p} = V_{\pi^+,p}/V_{\pi^+,n}$. Recent experiments^{20,21} have given surprisingly large ratios of M_n/M_p . Ignoring differences in the scattering between π^- and π^+ and neglecting terms of the order $(M_n/M_p)^2$, we have

$$\frac{\sigma_{\pi^-}}{\sigma_{\pi^+}} \approx \left| \frac{3M_n + M_p}{M_n + 3M_p} \right|^2 \approx \frac{M_n}{M_p} \quad (11)$$

For ^{118}Sn the measured ratio²⁰ is 1.9 and for ^{208}Pb it is²¹ 2.8, for which Eq. (11) would give $M_n/M_p \approx 1.9$ and 2.8 respectively, much larger than the schematic-model predictions.

A recent theoretical calculation²² does self consistent RPA using Skyrme III forces, based on Hartree-Fock neutron and proton single-particle orbitals including the continuum. Calculated and experimental results are shown in Table I. Several important points are to be noted in the table: First M_n/M_p is somewhat larger than the schematic-model results for Sn and generally is not proportional to N/Z . The ratio of cross sections $R = \sigma_{\pi^-}/\sigma_{\pi^+}$ is not proportional to M_n/M_p , showing that distortion effects make a difference for π^- and π^+ projectiles. The large ratios R_{exp} do agree within errors with the RPA calculations for Ca and Sn but disagree for Pb. The RPA calculations treated ^{120}Sn as a double-closed-shell nucleus and so did not find a low-lying 2^+ state. Its inclusion and the correction for the fact that the measurement was done in ^{118}Sn would reduce the calculated value by 8-10%, reducing R_{calc} to ~ 1.5 , barely on the limits of error compared with the experimental ratio. A ratio M_n/M_p would also be close to a schematic value result given above.

It should also be mentioned that the pion scattering experiment, while indicating quite a large ratio M_n/M_p for the giant resonance in Sn, gives a small value $\leq N/Z \approx 1.36$ for the lowest-lying 2^+ state. The systematics⁶ of multipole moment ratios for Sn give $M_n/M_p \sim 1.6$ to 1.8, larger than N/Z because of the shell closure on protons.

All of these comparisons make it difficult to understand why the pion scattering experiments are giving such large values of M_n/M_p for giant resonances. It would be good to have corroborating experiments. At low energy (p,p') and (n,n') used together are about equally as sensitive as pion scattering. If we consider energies of 135 to 300 MeV, at which giant resonances could readily be excited, the V_{τ}/V_0 ratio has dropped to so low a value that n/p is rather insensitive to neutron-proton differences. At 60-70 MeV, however, there is still considerable sensitivity, so (n,n') and (p,p') scattering experiments on giant resonances at this energy would be valuable in establishing systematics of M_n/M_p values for giant resonances. Interpretation of such experiments would not be trivial. Background subtraction problems, which have sometimes given misleading information for giant resonances, would have somehow to be solved.

TABLE I. Results from Ref. 22: Calculated neutron and proton multipole matrix elements and comparison of calculated cross section ratios with experiment.

Nucleus	M_n/M_p	N/Z	R_{calc}^a	R_{exp}
^{40}Ca	.91	1.00	1.19	$1.05 \pm .35$
^{48}Ca	1.40	1.40	1.29	---
^{90}Zr	1.10	1.25	1.22	---
$^{120}\text{Sn}^b$	1.45	1.40	1.61	$1.9 \pm .4$
^{208}Pb	1.44	1.54	1.70	$2.8 \pm .8$
$^{208}\text{Pb}^c$	1.55			

^a $R = \sigma_{\pi^-} / \sigma_{\pi^+}$

^b measurement for ^{118}Sn

^c Ref. 19.

SUMMARY

We have seen that for first 2^+ states of even nuclei there are systematic departures of multipole matrix element ratios M_n/M_p from N/Z in SCS nuclei. The nearness of M_n/M_p to N/Z is explained by the greater polarization of core nucleons of the opposite type than of the same type by valence nucleons. For open-shell nuclei M_n/M_p may also depart from N/Z but the differences tend to be much smaller than for SCS nuclei. All of these trends are explainable in terms of simple schematic models.

For higher 2^+ states there is also collective strength found, and it typically has a reversal of the sense of ratios of M_n/M_p from those of the ground states. This tendency and the establishment of the sign of M_n/M_p for higher 2^+ states promises to become an important experimental tool for investigating the nuclear structure of low-lying states.

For giant states, shell effects should play a very minor role. Schematic model values for M_n/M_p are lower than N/Z, because of the strong coupling between neutron and proton configurations. Self-consistent RPA calculations give somewhat higher ratios, indicating possible importance of the differences between the neutron and proton orbits in the continuum. Inelastic pion experiments on ^{118}Sb and ^{208}Pb give ratios which are even larger and difficult to understand on the basis of theory. Corroborating experiments are needed.

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