Low-energy octupole modes in the $A = 24-54$ region

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When the low-energy octupole state and low-energy octupole resonance are considered as a single composite mode in $A = 24-54$ even-even nuclei, a regular pattern for the energy centroids is found. The location of the energy centroid as a function of nuclear mass can be explained in terms of the effects of shell structure on collective octupole excitations. It is predicted that the energy of the centroid of the composite mode in the stable isotope ^{50}Cr, where it has not yet been measured, is 5.7±0.4 MeV.

Octupole vibrations in nuclei are generally classified into three types:[1] the low-energy octupole state (LEOS), which in many nuclei corresponds to the 3_1^- state; the low-energy octupole resonance (LEOR), which is generally found[1] at an energy of $31A^{-1/3}$ MeV; and the high-energy octupole resonance (HEOR), which is located[1] near $116A^{-1/3}$ MeV. A recent series of proton inelastic scattering measurements[2,3] has shown that the LEOS and LEOR overlap in ^{46,48}Ti, making any analysis of the 3_1^- state independent of the LEOR incomplete. In the present work, we consider the LEOS and LEOR together as a single excitation mode, which we call the low-energy composite octupole mode (LECOM). The centroid of the LECOM, found from the centroid of all strength contained in the LEOS and LEOR, falls nearly on a single parabola for the even-even nuclei throughout the $A = 24-54$ mass range. The observed behavior can be explained by taking into account the effects of shell structure on collective octupole states.

Octupole vibrations are coherent superpositions of one-particle–one-hole (1p-1h) excitations that couple to $J^\pi = 3^-$. The three types of octupole modes are made up of 1p-1h excitations of different energies. The HEOR consists of $3\hbar\omega$ excitations, the LEOR is composed of $1\hbar\omega$ excitations, and the LEOS consists of excitations to the lowest available opposite parity orbit. In $A = 24-54$ nuclei, the LEOS is formed by promotions of particles from *s-d* shell orbits to the $f_{7/2}$ orbit, and the LEOR involves excitations to the $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ orbits.

The distributions of octupole strength found via (p,p') measurements[2–5] in ^{48}Ca, ^{46,48,50}Ti, ^{52}Cr, and ^{54}Fe, shown in Fig. 1, illustrate the proximity of the LEOS and LEOR. In three of these nuclei, ^{48}Ca, ^{50}Ti, and ^{52}Cr, the LEOS is located near 4 MeV and is distinct from the LEOR, which is found above 5 MeV. However, in ^{46,48}Ti and ^{54}Fe the separation of the two octupole modes is not so obvious. Because of the proximity of the LEOS and LEOR, we consider a composite mode consisting of a combination of the LEOS and LEOR for the purposes of studying the strong mass dependence of the octupole strength centroids. We call this mode the LECOM and define it to be the centroid of all octupole strength observed up to an excitation energy of $1\hbar\omega$ $(=41/A^{1/3}$ MeV). The amount of octupole strength that should be present in this composite mode can be estimated by referring to the compilation of Kirson[1] on the distribution of

TABLE I. $E_{\rm LECOM}$ from (p,p') data.

Nucleus	Reference	E_p (MeV)	Centroid (MeV)	Centroid ($\hbar\omega$)	%EWSR
^{24}Mg	6	40	8.40	0.59	16.3
^{26}Mg	7	800	7.64	0.55	10.7
^{28}Si	8	65	7.81	0.58	10.2
^{30}Si	9	51.9	5.49	0.42	9.5
^{32}S	8	65	5.01	0.39	9.7
^{40}Ar	10	800	3.68	0.31	8.1
^{40}Ca	11	800	4.06	0.34	19.5
^{42}Ca	12	22.9	3.67	0.31	12.8
^{44}Ca	12	22.9	3.60	0.31	12.7
^{46}Ti	2	65	4.49	0.39	11.6
^{48}Ti	3	65	4.87	0.43	9.3
^{48}Ca	5	65	6.74	0.60	23.9
^{50}Ti	4	65	6.12	0.55	16.3
^{52}Cr	4	65	6.23	0.57	18.0
^{54}Fe	4	65	6.86	0.63	18.0

octupole strength among the LEOS, LEOR, and HEOR. In a survey of observed octupole strength distributions, Kirson finds that approximately 5% of the energy-weighted sum rule is found in the LEOS, and approximately 20% in the LEOR, with 50% residing in the HEOR. Consequently, the amount of strength found in the LECOM should be 25%.

The centroids of the LECOM, E_{LECOM}, in $A=24$–54 nuclei extracted from (p,p') data[2–12] may be found in Table I; the dependence of E_{LECOM} on A is illustrated in Fig. 2. The table includes an energy-weighted sum rule (EWSR) fraction, which is calculated with the prescription of Ref. 13. Among the 17 measurements compiled, the EWSR fraction ranges between 8% and 24%; the 24% maximum is consistent with the total amount of octupole strength expected in the LECOM. The abscissa of Fig. 2 is also labeled with the quantity N_p+N_n, where N_p (N_n) is the number of protons (neutrons) outside of the $Z=8$ ($N=8$) closed shell. Therefore, N_p+N_n is the total number of nucleons outside of the closed ^{16}O core. This parameter was used in two previous studies[14,15] of 3_1^- states in this region.

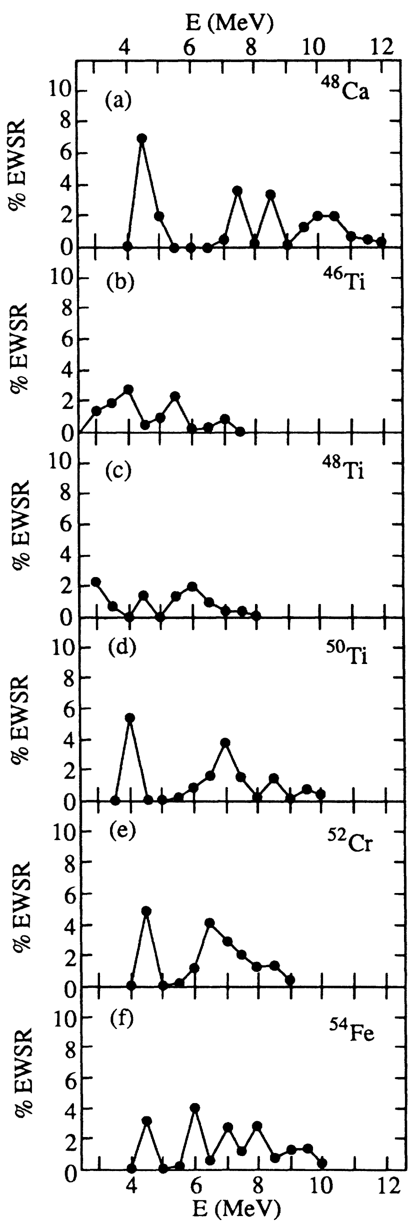

FIG. 1. The distribution of low-energy octupole strength in (a) ^{48}Ca; (b) ^{46}Ti; (c) ^{48}Ti; (d) ^{50}Ti; (e) ^{52}Cr; and (f) ^{54}Fe. The strength is summed in 500-keV intervals. Data are taken from Refs. 2–5.

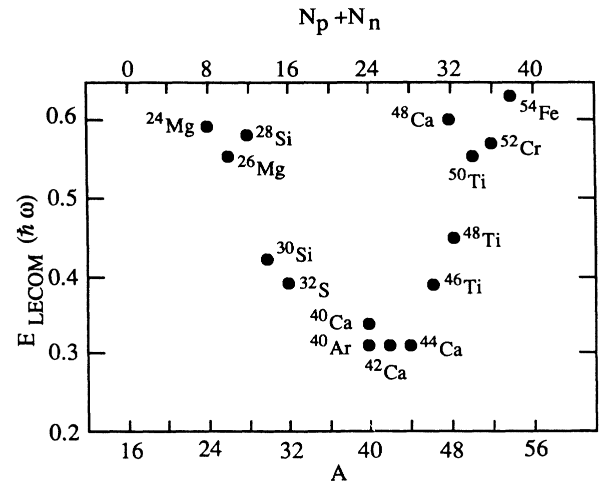

FIG. 2. E_{LECOM} (in units of $\hbar\omega$) vs A and N_p+N_n for the nuclei listed in Table I. The parameter N_p+N_n is defined in the text.

Figure 2 reveals that E_{LECOM} decreases as a function of mass for $A=24$–40 ($N_p+N_n=8$–32) and increases for $A=44$–54 ($N_p+N_n=28$–38), with a minimum occurring near $A=40$–44 ($N_p+N_n=24$–28). The trends observed here can be explained qualitatively by taking into account the effects of shell structure on the 1p-1h components of the collective octupole states. The LECOM is composed primarily of particle promotions from *s-d* shell orbits to *f-p* shell orbits. As the *s-d* shell fills above $A=20$ ($N_p+N_n=4$), more particles are available for promotion, so that more 1p-1h components are available to contribute to the octupole excitation. Consequently, E_{LECOM} declines with increasing A. Near $A=40$ ($N_p+N_n=24$), the *s-d* shell is completely filled, so that E_{LECOM} reaches a minimum. Above $A=40$, particles begin to fill the $f_{7/2}$ orbits, blocking 1p-1h excitations. As more of these excitations are blocked, E_{LECOM} increases.

Because of the nearly linear behavior exhibited by the $Z\geq22$ elements (Ti,Cr,Fe), it is possible to make predictions for E_{LECOM} in isotopes for which no measurements exist. For example, we predict that in ^{50}Cr, for which no data exist, E_{LECOM} would be found at an energy of $(0.51\pm0.04)\hbar\omega$, or 5.7 ± 0.4 MeV.

Quadrupole deformation may play a role in determining the distribution of octupole strength in Ti and Cr nuclei. In ^{46,48}Ti the ratios of the energies of the 4_1^+ states to the 2_1^+ states are 2.3, signaling weak quadrupole deformation. The LEOS is fragmented in these two nuclei and the boundary between the LEOS and LEOR becomes obscured. In ^{50}Ti and ^{52}Cr, in which the LEOS and LEOR are well separated, these ratios are 1.7, indicating spherical shapes. In ^{50}Cr, the energy ratio of the 4_1^+ and 2_1^+ states is 2.4; consequently, we would expect that its octupole strength distribution would resemble those in ^{46,48}Ti, having no clear boundary between the LEOS and LEOR.

In conclusion, we have devised an analysis for octupole states in the $A = 24-54$ region in which the LEOS and LEOR are considered to be a single collective mode, the LECOM. The systematic behavior observed here allows us to make a prediction for E_{LECOM} in ^{50}Cr.

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