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Octupole states in ^{63}Cu and the weak-coupling picture

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A high-resolution experiment of proton inelastic scattering by ^{63}Cu at $E_p = 40$ MeV has resolved three octupole states at $E_x = 3.81$, 3.84, and 3.89 MeV for the first time, thus showing the existence of seven strong octupole states in ^{63}Cu. This finding is direct evidence that the traditional simple weak-coupling model in terms of one quartet $2p_{3/2} \otimes 3_1^-$ is inadequate for the octupole core-excited states in ^{63}Cu. This is not evidence, however, that the weak-coupling picture in general is incorrect for the octupole states in ^{63}Cu. It is shown that to be consistent with the present experimental data, the weak-coupling picture for the octupole states requires a ground-state wave function substantially different from the ground-state wave function of the conventional particle-core-coupling model.

[NUCLEAR REACTIONS ^{63}Cu(p,p'), $E_p = 40$ MeV, strong octupole transitions, resolved new levels. Measured differential cross sections. Discussion in terms of the weak-coupling picture for the octupole states.]

In the particle-core-coupling picture, the nucleus ^{63}Cu consists of a single proton coupled to the proton-closed-shell nucleus ^{62}Ni, which is called the core.[1] Inelastic scattering is known to be an effective means of selectively exciting collective degrees of freedom of the core.[2–5] We have studied the inelastic scattering of protons by ^{63}Cu at $E_p = 40$ MeV, and have found seven strong octupole transitions leading to states at $E_x = 2.51$, 3.32, 3.48, 3.72, 3.81, 3.84, and 3.89 MeV in ^{63}Cu. The three states at $E_x = 3.81$, 3.84, and 3.89 MeV have been resolved for the first time. Since previous experiments using (α,α')[3], (p,p')[4] and (e,e')[5] reactions did not resolve these three states, up till now only five strong octupole states have been reported. Four of them have been suggested to be members of a quartet that arises from the coupling of the $2p_{3/2}$ proton orbital with the octupole state of the core (the 3_1^- state at $E_x = 3.75$ MeV in ^{62}Ni)[1,6] in accordance with the excited-core model.[2,3,7] The remaining one at $E_x = 2.51$ MeV is a predominantly single-particle state containing the $1g_{9/2}$ proton orbital with a large amplitude.[8,9] The strongly enhanced octupole transition to the state is a puzzle for which an explanation has been offered recently.[6] There are, however, two more strong octupole states. This new finding corrects the experimental information upon which the traditional weak-coupling excited-core model[1,6] has been based.

Fig. 1 shows part of the ^{63}Cu(p,p') spectrum at a laboratory angle of 24° measured in the Enge split-pole magnetic spectrograph using a delay-line counter.[10] The overall energy resolution is about 20 keV. The seven octupole states are indicated by arrows. Fig. 2 shows the differential cross sections for the transitions to the octupole states. All the angular distributions have the characteristic L = 3 shape.[11] Fig. 3 shows that there is no ambiguity in distinguishing between the L = 2, 3, and 4 angular distributions. The third column of Table I gives the relative cross sections for the octupole transitions.

The existence of two extra octupole states is direct evidence that the simple weak-coupling model in terms of the $2p_{3/2} \otimes 3_1^-$ quartet[1,3,6] is inadequate. This raises the question whether the weak-coupling picture in general is incompatible with the present experimental data. If the weak-coupling picture is assumed for the six higher octupole states, these states are excited in the (p,p') reaction by a simple core-excitation mechanism. In addition to the quartet of the simple weak-coupling model,[1,3,6] we are naturally led to consider a doublet of states with $J^\pi = 5/2^+$ and $7/2^+$ arising from the weak coupling of the $2p_{1/2}$ proton orbital with the 3_1^- state of the core, since two additional states have been found. These doublet states can be excited only by the octupole transition from the 2_1^+ state to the 3_1^- state of the core, since the $2p_{1/2}$ orbital is occupied in the ground state of ^{63}Cu only as a result of the coupling with the lowest quadrupole state of the core, i.e. only in the form $[2p_{1/2} \otimes 2_1^+(\text{core})]_{3/2}$. Let us denote the reduced

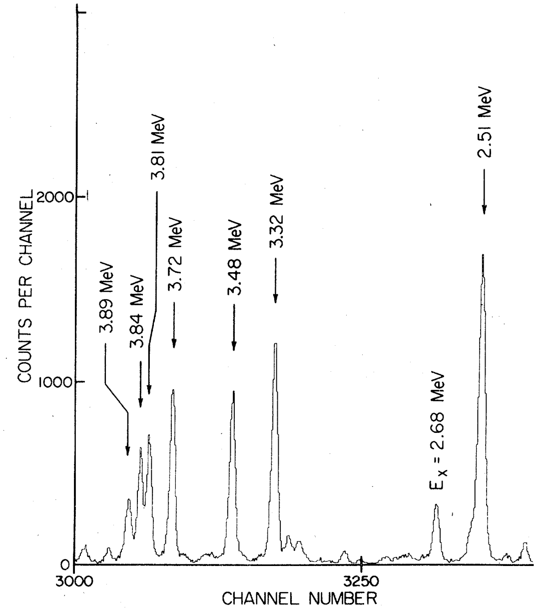

FIG. 1. Part of the ^{63}Cu(p,p')^{63}Cu spectrum at 24° lab. Arrows indicate octupole states. Overall energy resolution is about 20 keV. The state at $E_x = 2.68$ MeV is excited by a hexadecapole transition (see Fig. 3).

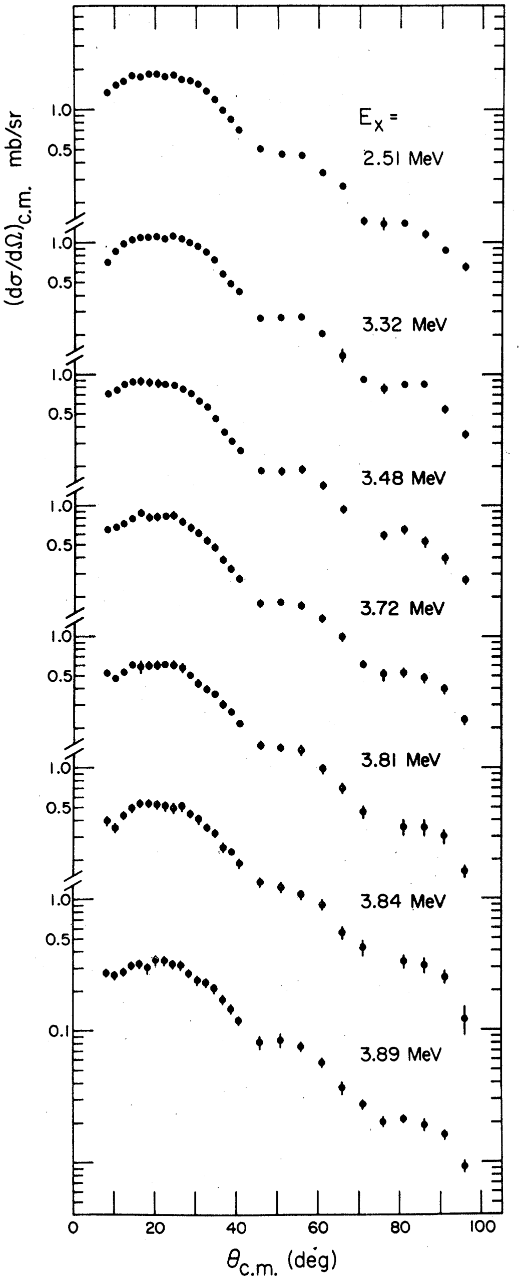

FIG. 2. Differential cross sections for the (p,p') transitions to the octupole states. Error bars include uncertainties in background subtraction and peak separation.

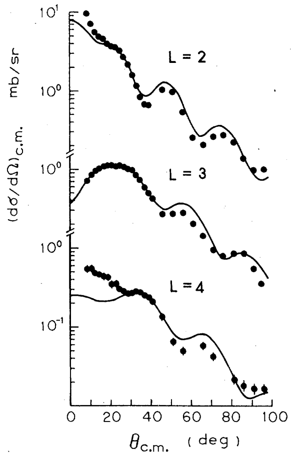

FIG. 3. L = 2, 3, and 4 angular distributions. Solid lines represent DWBA calculations using the standard Becchetti-Greenlees optical potential.[25] Data points are for the L = 2, 3, and 4 transitions to the states at E_x = 1.33, 3.32, and 2.68 MeV.

matrix element for the transition by $<3_1^- \| \hat{0} \| 2_1^+>$, where $\hat{0}$ is the octupole core-excitation operator due to the nuclear interactions between the core and the incident proton. The ratio of the cross section for the $5/2^+$ state to that for the $7/2^+$ state is determined only by 6-j symbols,[7] and is equal to 1.80 (the well-known $(2J + 1)$ rule[2,3] holds for a multiplet excited only by the reduced matrix element $<3_1^- \| \hat{0} \| 0_1^+>$). Only the ratio of the experimental cross section for the 3.81 MeV state to that for the 3.89 MeV state (1.83) is close to this value. Consequently, these states are to be identified with the doublet $[2p_{1/2} \otimes 3_1^-]_{5/2,\,7/2}$, and the other four states at E_x = 3.32, 3.48, 3.72, and 3.84 MeV should form the quartet $[2p_{3/2} \otimes 3_1^-]_{3/2,\,5/2,\,7/2,\,9/2}$. The quartet states can be excited by both the reduced matrix elements $<3_1^- \| \hat{0} \| 0_1^+>$ and $<3_1^- \| \hat{0} \| 2_1^+>$, since the ground-state wave function contains a component of the form $[2p_{3/2} \otimes 2_1^+]_{3/2}$ added to the dominant $[2p_{3/2} \otimes 0_1^+]_{3/2}$.[1,12] For a given wave function of the ground state, the relative cross sections for the members of the quartet depend strongly on the ratio

$$\lambda = <3_1^- \| \hat{0} \| 2_1^+>/<3_1^- \| \hat{0} \| 0_1^+>$$

because of the interference between the two excitation paths. The ratio λ also determines the cross section ratio between the quartet and the doublet. Although the reduced matrix element $<3_1^- \| \hat{0} \| 0_1^+>$ can be derived from experimental data of proton inelastic scattering by ^{62}Ni, there is no practical way of deriving $<3_1^- \| \hat{0} \| 2_1^+>$ from experimental data. Therefore, λ has been treated as an adjustable parameter in an attempt to reproduce the experimental relative cross sections for the six higher octupole states. No value of λ reproduces the observed relative cross sections, if a conventional particle-core wave function[1,12] is assumed for the ground state. Only if the amplitude of the component $[2p_{3/2} \otimes 2_1^+]_{3/2}$ is very small and the amplitude of the $[2p_{1/2} \otimes 2_1^+]_{3/2}$ large in the ground-state wave function, is it possible to get reasonable agreement between the experimental and model values of the relative cross sections, as is shown in Table I. In this case, the spin sequence for the quartet states is uniquely predicted as in Table I. No other choice of spins can give a similar result. This spin sequence is the same as predicted by Thankappan and True.[1] Table II compares the ground-state wave function used to get the result in Table I with the ground-state wave function of Thankappan and True[1] as a typical example of the conventional particle-core-coupling model taking into account the dipole-dipole and quadrupole-quadrupole particle-core interactions.[1,12,13] It is thus shown that the weak-coupling picture for the octupole

Table I. Relative cross sections for the octupole states. Relative experimental cross sections are the sums of the differential cross sections over the 17 angles from 8.1° to 40.6° c.m. normalized to 1.00 for the 3.32 MeV state.

E_x (MeV)	J^π	Relative experimental cross section	Relative model cross section	Spin-parity predicted by the weak-coupling picture
2.51	$9/2^+$	1.65		
3.32		1.00	1.00	$9/2^+$
3.48		0.76	0.76	$7/2^+$
3.72		0.72	0.58	$5/2^+$
3.81		0.53	0.53	$5/2^+$
3.84		0.45	0.41	$3/2^+$
3.89		0.29	0.29	$7/2^+$

states requires a ground-state wave function substantially different from the ground-state wave function of the conventional particle-core-coupling model. There is additional experimental evidence against the ground-state wave function of the conventional particle-core-coupling model from (p,t) reaction studies. The experimental angular distribution for the ground-state transition in the reaction ^{65}Cu(p,t)^{63}Cu at $E_p = 40$ MeV[14] is almost identical with that for the corresponding "core" transition ^{64}Ni(p,t_o)^{62}Ni at the same energy.[15] This means that the L = 2 amplitude is very small in the transition ^{65}Cu(p,t_o)^{63}Cu. If the ground-state wave function of the conventional particle-core-coupling model (Table II) is assumed for ^{63}Cu and ^{65}Cu,[16] the L = 2 contributions[17] to the differential cross sections, which are relatively large at the minima of the L = 0 angular distribution, make the peak-to-minimum ratios of the angular distribution for the ^{65}Cu(p,t_o)^{63}Cu smaller than those for the ^{64}Ni(p,t_o)^{62}Ni by several tens of percent.[18] Such differences are not observed between the experimental angular distributions for the transitions ^{65}Cu(p,t_o)^{63}Cu and ^{64}Ni(p,t_o)^{62}Ni. To be consistent with the (p,t_o) data, the amplitude of the component $[2p_{3/2} \otimes 2_1^+]_{3/2}$ in the ground-state wave function must be far smaller than that of the conventional particle-core-coupling model. On the other hand, the ground-state wave function needed by the weak-coupling picture for the octupole states (Table II) is consistent with the (p,t_o) data, since it predicts that there is virtually no L = 2 amplitude in the ^{65}Cu(p,t_o)^{63}Cu transition.

The wave functions of the conventional particle-core-coupling model were determined so as to give a best fit to low-lying energy levels ($E_x < 2.10$ MeV) and electromagnetic transition rates for the low-lying states which were known in the 1960's.[1,12,13] A large amount of experimental data on ^{63}Cu has been accumulated since then.[5,9,14,19-23] A comprehensive theoretical study that accounts for all the data has not yet been done. Such a study in the future would be able to prove or disprove the weak-coupling picture for the octupole states. There is no evidence so far that the octupole-octupole particle-core interaction in ^{63}Cu is so strong as to invalidate the weak-coupling picture. A calculation using only the dipole-dipole and quadrupole-quadrupole particle-core interactions reproduced the energy levels of the quartet $2p_{3/2} \otimes 3_1^-$ remarkably well.[1] Experimental data from the ^{63}Cu(d,^{3}He)^{62}Ni reaction at $E_d = 34.2$ MeV give no evidence of the existence of the component $[1g_{9/2} \otimes 3_1^-]_{3/2}$ in the ground-state wave function of ^{63}Cu.[24] A strong octupole-octupole particle-core interaction would mix such a component into the ground-state, and further the angular-momentum-matching condition for the reaction ^{63}Cu(d,^{3}He)^{62}Ni would favor pickup of the proton from an orbital with a large orbital angular momentum such as $1g_{9/2}$. However, the 3_1^- state at $E_x = 3.75$ MeV in ^{62}Ni was not observed by the

Table II. Ground-state wave function.

	$[2p_{3/2} \otimes 0_1^+]_{3/2}$	$[2p_{3/2} \otimes 2_1^+]_{3/2}$	$[2p_{1/2} \otimes 2_1^+]_{3/2}$	$[1f_{5/2} \otimes 2_1^+]_{3/2}$
Thankappan-True	0.9221	-0.3264	0.1779	0.1076
Present model	0.87	±0.014[a]	0.48	0.1076

[a] The double sign corresponds to the double sign for the ratio $\lambda = \langle 3_1^- \| \hat{O} \| 2_1^+ \rangle / \langle 3_1^- \| \hat{O} \| 0_1^+ \rangle = \pm 2.2$. The wave function has some ambiguities, which are not discussed here.

^{63}Cu(d,^{3}He)^{62}Ni reaction.

In summary, direct experimental evidence has been given that the simple weak-coupling model in terms of one quartet $2p_{3/2} \otimes 3_1^-$ is inadequate for the octupole core-excited states in ^{63}Cu. Still, it is possible to make a weak-coupling-picture interpretation of the new data.

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[1] V.K. Thankappan and W.W. True, Phys. Rev. 137, B793 (1965).

[2] F. Perey, R.J. Silva, and G.R. Satchler, Phys. Lett. 4, 25 (1963).

[3] B.G. Harvey, J.R. Meriwether, A. Bussiere, and D.J. Horen, Nucl. Phys. 70, 305 (1965).

[4] A.L. McCarthy and G.M. Crawley, Phys. Rev. 150, 935 (1966).

[5] A.A.C. Klaasse *et al.*, in *Problems of Vibrational Nuclei*, Vol. II, eds. G. Alaga, V. Paar, and L. Sips, Fizika 7, Suppl. 2 (1975), p. 128.

[6] A.A.C. Klaasse and V. Paar, Nucl. Phys. A297, 45 (1978).

[7] A. de-Shalit, Phys. Rev. 122, 1530 (1961).

[8] A.G. Blair, Phys. Rev. 140, B648 (1965).

[9] R.M. Britton and D.L. Watson, Nucl. Phys. A272, 91 (1976).

[10] R.G. Markham and R.G.H. Robertson, Nucl. Instr. and Meth. 129, 131 (1975).

[11] N. Lingappa and G.W. Greenlees, Phys. Rev. C 2, 1329 (1970); B.M. Preedom, C.R. Gruhn, T.Y.T. Kuo, and C.J. Maggiore, Phys. Rev. C 2, 166 (1970); C.R. Gruhn, T.Y.T. Kuo, C.J. Maggiore, and B.M. Preedom, Phys. Rev. C 6, 944 (1972).

[12] R.G. Markham and H.W. Fulbright, UR-NSRL-41.

[13] J.L. De Jager and E. Boeker, Nucl. Phys. A216, 349 (1973).

[14] Y. Iwasaki, G.M. Crawley, R.G. Markham, J.E. Finck, and J.H. Kim, to be published.

[15] D.H. Kong-A-Siou and H. Nann, Phys. Rev. C 11, 1681 (1975).

[16] Existing experimental data indicate that the structures of ^{63}Cu and ^{65}Cu are very similar.

[17] To the first order, the L = 2 transition amplitude connects the component $[2p_{3/2} \otimes 0_1^+]_{3/2}$ of the ground state of ^{65}Cu with the component $[2p_{3/2} \otimes 2_1^+]_{3/2}$ of the ground state of ^{63}Cu, as well as the component $[2p_{3/2} \otimes 2_1^+]_{3/2}$ of the ground state of ^{65}Cu with the component $[2p_{3/2} \otimes 0_1^+]_{3/2}$ of the ground state of ^{63}Cu. The proton is a spectator.

[18] Y. Iwasaki, to be published.

[19] Y. Iwasaki, M. Sekiguchi, F. Soga, and N. Takahashi, Phys. Rev. Lett. 29, 1528 (1972).

[20] R.G. Markham and H.W. Fulbright, Nucl. Phys. A203, 244 (1973).

[21] C.P. Swann, Phys. Rev. C 13, 1104 (1976).

[22] R. Dayras, B. Cujec, and I.M. Szoghy, Nucl. Phys. A257, 118 (1976).

[23] C.T. Papadopoulos, A.G. Hartas, P.A. Assimakopoulos, G. Andritsopoulos, and N.H. Gangas, Phys. Rev. C 15, 1987 (1977).

[24] J.C. Hiebert and E. Newman, Nucl. Phys. A113, 176 (1968).

[25] F.D. Becchetti, Jr. and G.W. Greenlees, Phys. Rev. 182, 1190 (1969).