less than 5 nucleons were emitted or when the ratio of emitted neutron to protons varied greatly from ~1.

ACKNOWLEDGMENTS

Photoexcitation of the 7.64-MeV Magnetic Dipole Levels in Cd^{112} and Ni^{62} by Iron Capture Gamma Rays*

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The elastic and inelastic scattering of iron capture γ rays from the 7.64-MeV $M1$ levels in Cd^{112} and Ni^{62} were studied with a Ge(Li) spectrometer. Eleven energy levels in Cd^{112} and three in Ni^{62} observed in this experiment are compared with the levels excited in (d, p) experiments. Angular distribution measurements were made for four strong transitions in Cd^{112} and two in Ni^{62}, giving the following spin assignments: Cd^{112}: 0.62-MeV level (2), 1.23-MeV (0), 1.88-MeV (0), 7.64-MeV (1); Ni^{62}: 2.06-MeV (0), 7.64-MeV (1). In both nuclei, only the 0$^+$ member of the two-quadrupole phonon triplet (0$^+$, 2$^+$, 4$^+$) is strongly excited in this experiment, indicating very different components in the wave functions of the 0$^+$ and 2$^+$ members.

I. INTRODUCTION

THE nuclear fluorescence of neutron-capture γ rays is a relatively new method to study the individual nuclear levels near the neutron binding energies.[1,2] Since resonance fluorescence preferentially excites the levels immediately *below* the neutron binding energy where the γ reemission is the only possible deexcitation mode, this type of experiment supplements the slow neutron spectroscopy which probes the individual nuclear levels above the neutron binding energy.

Some 50 different resonances involving the use of about 20 capture sources have been reported.[3] In most cases, the spectra of the reasonably scattered photons were measured by a NaI detector. Because of its limited energy resolution and complex energy response, the detailed study of nuclear properties (energy, spin, parity, and the radiation width) was usually confined to the scattering level. More recently, some of the previously observed resonances were restudied using either NaI spectrometers working in coincidence or a Ge(Li) spectrometer. These new measurements show that a resonant level excited by the neutron-capture γ rays has an appreciable branching to the lower excited states even though the ground-state transition seems to be generally the most dominant. The inelastic scattering of the neutron-capture γ rays thus provides a useful method to study the nuclear properties of the lower excited states. Of particular spectroscopic interest is the determination of nuclear spins of the excited states by angular distribution measurements of the inelastically scattered photons. The angular distribution of resonantly scattered photons is identical to that of two successively emitted γ rays,[4] and the interpretation is made simple by the fact that the extreme monochromaticity of the incident capture γ rays insures that the resonance fluorescence is due to a single level.

The nuclear fluorescence of the 7.64-MeV iron capture γ rays in cadmium and nickel has been previously

[1] C. S. Young and D. J. Donahue, Phys. Rev. **132**, 1724 (1963).
[2] G. Ben-David and N. Huelschmann, Phys. Letters **3**, 82 (1963).
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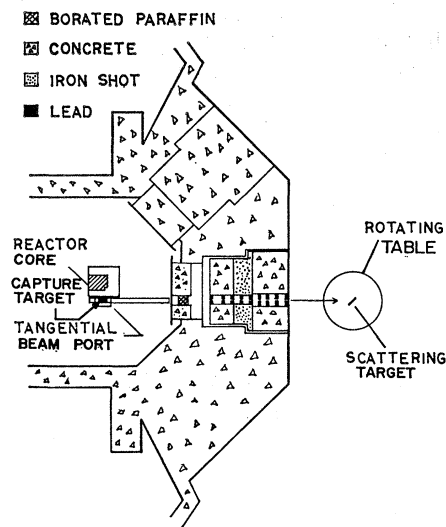
BORATED PARAFFIN
CONCRETE
IRON SHOT
LEAD

FIG. 1. Experimental arrangements.

studied by several investigators.[5-8] By studying the spectrum of low-energy cascade photons in coincidence with the resonantly scattered photons, the resonant isotopes were identified to be Cd^{112} and Ni^{62}.[6,7] The spin[5-8] and parity[8] of the 7.64-MeV resonance levels in both nuclei were determined to be 1^+. In the present work, we restudied the nuclear fluorescence of the 7.64-MeV iron capture γ rays in Cd^{112} and Ni^{62} using a 20-cc Ge(Li) spectrometer. The high energy resolution available with the Ge(Li) detector and its compact geometry made it possible to identify 11 γ transitions in Cd^{112} and three in Ni^{62} without recourse to the coincidence measurements. Angular distribution measurements were carried out for four strong lines in Cd^{112} and two in Ni^{62}. The spin assignments and the determination of the multipolarity of the involved γ transitions will be discussed.

II. EXPERIMENTAL PROCEDURE

The experimental arrangements are shown in Fig. 1. The γ-ray sources consisted of 0.5 kg of natural iron placed near the core of the University of Virginia 1-MW reactor. The capture γ-ray beam pipe was directed tangential to the reactor core to provide an effective shielding of the detector against the fission γ rays produced in the core. A series of lead rings collimated the γ-ray beam to 2 in. in diameter at the scattering target position. The beam was monitored during each run using a thimble-type ionization chamber placed in the beam at its exit point from the reactor shielding wall.

[5] M. Giannini et al., Nuovo Cimento 34, 1116 (1964).
[6] K. Min, Phys. Rev. 152, 1062 (1966).
[7] G. P. Estes and K. Min, Phys. Rev. 154, 1104 (1967).
[8] R. Moreh and M. Friedman, Phys. Letters 26B, 579 (1968).

With the reactor operating at 1 MW, the γ dose was typically about 7 R/h. The dose registered during each run was used to normalize the data to a set target irradiation.
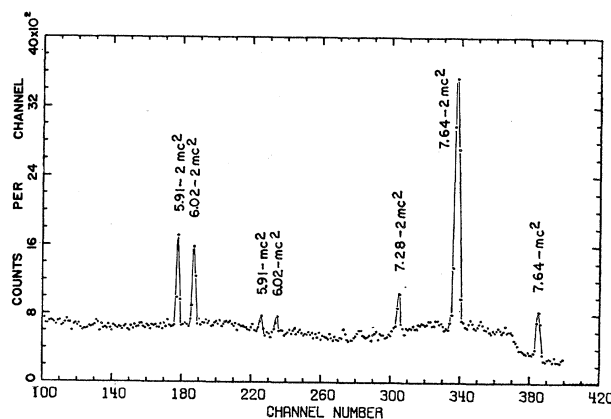
The scattering targets were natural cadmium and nickel plates of thickness 3.8 cm. They were placed in the beam 2 m from the reactor shielding wall. The scattered photons were detected with a 20-cc Ge(Li) spectrometer mounted on a rotating table with its axis of rotation fixed at the center of the scattering target position. The target-to-detector distance was 12 cm giving an angular resolution of 12°. The spectra of the resonantly scattered photons were measured at six angles in 10° intervals ranging from 100° to 150° with respect to the incident beam direction.

The resonant scattering at angles less than 100° was obscured by the strong forward peaking of nonresonant background mainly due to the high-energy Compton scattered photons.

III. RESULTS

A. Spectrum of Capture γ Rays from Iron

Preceding the scattering runs, the spectrum of the incident iron capture γ rays was measured with the Ge(Li) detector facing the beam directly at a reduced reactor power of 100 W. The direct spectrum is shown in Fig. 2. The dominant double escape peaks of the 7.64-, 7.28-, 6.02-, and 5.91-MeV lines are clearly identified. The prominent 7.64-MeV line is actually a doublet consisting of 7.633- and 7.647-MeV lines.[9] This doublet is shown partially resolved in Fig. 3 which was obtained using a high biased-amplifier gain to expand the scale. Since the present experiment was unable to determine which of the doublet excites the Cd^{112} and

FIG. 2. Direct spectrum of iron capture γ radiation, $Fe^{56}(n, \gamma)$. The resonant line is the dominant 7.64-MeV transition.

[9] G. T. Ewan and A. J. Tavendale, Nucl. Instr. Methods 26, 182 (1964).

FIG. 3. The partially resolved 7.64-MeV doublet.

FIG. 5. The spectrum of photons resonantly scattered from the nickel sample.

Ni[62] resonances, this doublet will be hereafter referred to simply as the 7.64-MeV line.

The direct spectrum shown in Fig. 2 was used to calibrate the spectrometer for the scattering data.

B. Spectrum of Resonantly Scattered Photons

The spectra of the photons scattered from the cadmium and nickel samples at 140° are shown in Figs. 4 and Fig. 5, respectively. At the same scattering angle, the background scattering runs were also made using two comparison targets of tin and copper, with their thicknesses matched in electronic absorption to the cadmium and nickel samples, respectively. By comparing with the background spectra, the peaks observed in Fig. 4 and Fig. 5 were identified with the resonant scattering from Cd[112] and Ni[62].

1. Cd[112] Spectra

In Fig. 4, four strong lines at 7.64, 7.02, 6.41, and 5.76 MeV are observed. On the assumption that these lines result from the primary transitions from the 7.64-
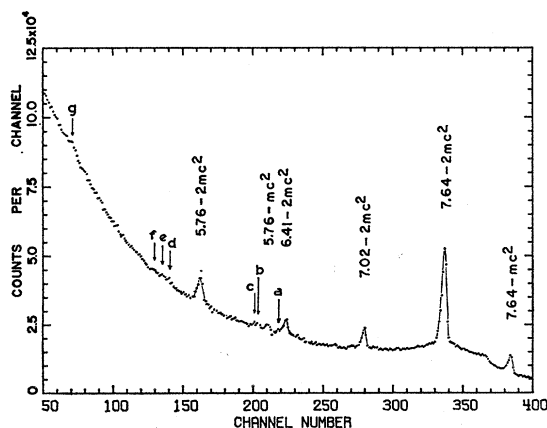
MeV resonance level, the final states populated by these transitions are the ground state and the 0.62-, 1.23-, and 1.88-MeV excited states. In addition to these strong lines, seven weaker lines (labeled in Fig. 4 by a–g) at 6.35, 6.20, 6.17, 5.52, 5.46, 5.40, and 4.79 MeV are observed.

2. Ni[62] Spectra

Figure 5 shows three strong lines at 7.64, 6.46, and 5.58 MeV corresponding to the transition from the 7.64-MeV resonance level to the ground state, 1.18-, and 2.06-MeV excited states.

The energy levels and the photon transitions in Cd[112]

FIG. 4. The spectrum of photons resonantly scattered from the cadmium sample. The energies of the weak lines labeled a–f are given in Fig. 6.
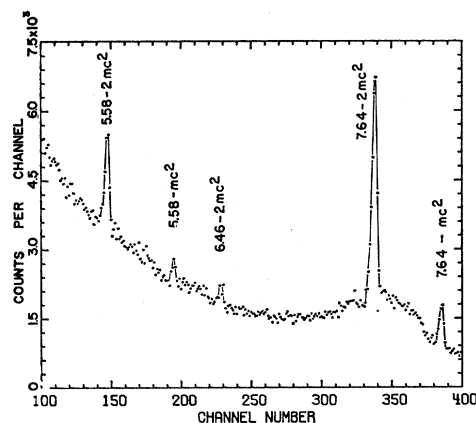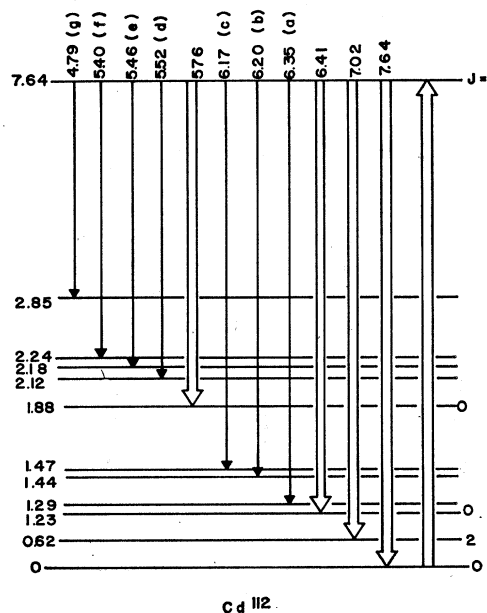

FIG. 6. Decay scheme of Cd[112] excited by iron capture γ rays.

TABLE I. Summary of angular distribution measurements in Cd^{112}. The first column gives the energies of the scattered γ rays; the second column gives the energies of the final states, $E-7.64$. The theoretical distributions given in the column 4 are those which give best agreement to the experimental distributions given in the column 3, assuming only pure transitions. The fifth column gives the spin assignment. The $J=2$ assignment to the 0.62-MeV level is not affected by $M1-E2$ admixture (see Sec. III C 1 b).

E (MeV)	Final state (MeV)	$W(\theta)$ (Experimental)	$W(\theta)$ (Theoretical)		J
7.64	0	$1+(0.98\pm0.13)\cos^2\theta$	$1+\cos^2\theta$	$(0\to1\to0)$	1
7.02	0.62	$1+(0.34\pm0.07)\cos^2\theta$	$1+0.43\cos^2\theta$	$(0\to1\overset{2}{\to}2)$	2
6.41	1.23	$1+(1.16\pm0.17)\cos^2\theta$	$1+\cos^2\theta$	$(0\to1\to0)$	0
5.76	1.88	$1+(1.11\pm0.20)\cos^2\theta$	$1+\cos^2\theta$	$(0\to1\to0)$	0

and Ni^{62} observed in the present experiment are summarized in Figs. 6 and 7. The level scheme of Cd^{112} (Fig. 6) is essentially the same with our earlier results[6] obtained using two NaI coincidence spectrometers. The energies of the levels agree within 10 keV. The present data, however, show evidences for the weaker transitions a–f which were either absent or not resolved from the adjacent line in the earlier measurements. The level scheme of Ni^{62} (Fig. 7) is identical with the previous results.

The spin assignments shown in Figs. 6 and 7 are discussed below.

C. Angular Distribution of Resonantly Scattered Photons

Angular distributions of the four strong photon groups in Cd^{112} (7.64-, 7.02-, 6.41-, and 5.76-MeV lines in Fig. 4), and two in Ni^{62} (7.64- and 5.58-MeV lines in
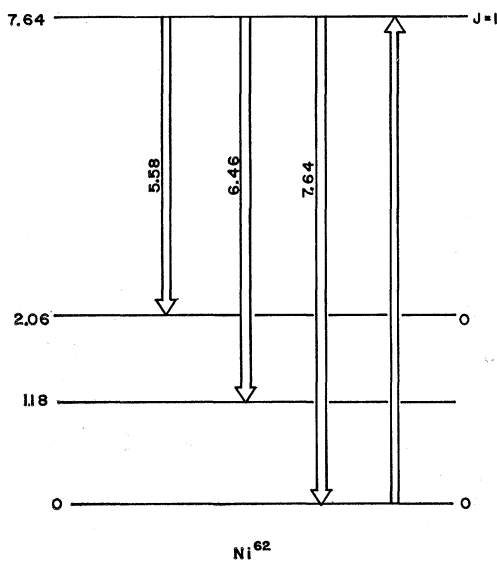
Fig. 5) were measured at 10° intervals from 100° to 150° with respect to the incident beam direction. Since the spectra of the scattered photons from the comparison targets of tin and copper were found to be smooth in the region of these resonances, the background counts for each peak were determined by using the following least-squares-fitting procedure. For a given peak, a total of ten data points in the nonresonance region adjacent to it were chosen (five on each side) and a linear background through these points was obtained by the least-square fitting. The net counts for the resonant scattering were taken as the difference between the sum of the five highest channels in the spectra and the sum of the linear background counts for the cor-
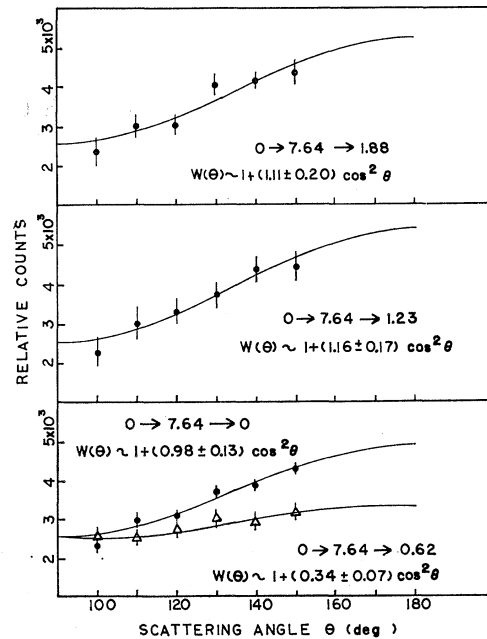

FIG. 7. Decay scheme of Ni^{62} excited by iron capture γ rays.

FIG. 8. Angular distributions of resonantly scattered photons in Cd^{112}. The solid lines are the least-square fits through the data points.

TABLE II. Summary of angular distribution measurements in Ni^{62}.

E (MeV)	Final state (MeV)	$W(\theta)$ (Experimental)	$W(\theta)$ (Theoretical)	J
7.64	0	$1+(1.06\pm0.09)\cos^2\theta$	$1+\cos^2\theta$ $(0\rightarrow1\rightarrow0)$	1
5.58	2.06	$1+(1.15\pm0.22)\cos^2\theta$	$1+\cos^2\theta$ $(0\rightarrow1\rightarrow0)$	0

responding channels. The net counts were then nor-malized to the same incident γ dosage and corrected for the different target orientations. The final results for Cd^{112} and Ni^{62} are shown in Figs. 8 and 9. The solid lines through the data points are the least-square fits of the form $W(\theta)\sim1+A\cos^2\theta$. The angular distribution measurements and the spin assignments based on these results are summarized in Tables I and II.

1. Cd^{112} (Fig. 8 and Table I)

a. 0→7.64→0. Since the ground state is 0$^+$, the transitions are of the form $0(J)J(J)0$. The observed angular distribution $W(\theta)\sim1+(0.98\pm0.13)\cos^2\theta$ agrees well with the theoretical distribution $W(\theta)\sim1+\cos^2\theta$ for the sequence $0(1)1(1)0$. Therefore, the spin of the 7.64-MeV scattering level is assigned to be unity in agreement with our previous assignment.[6] The parity of the 7.64-MeV level in Cd^{112} was previously reported by Moreh and Friedman[8] to be even. Therefore, the photon absorption and the subsequent reemission by the 7.64-MeV level to the 0$^+$ ground state are by pure M1 transition. The spin assignment to the scattering

level insures that only terms through $\cos^2\theta$ will appear in the angular distributions of all the photon groups resonantly scattered from this level. This fact justifies the fitting of the form $W(\theta)\sim1+A\cos^2\theta$ to the observed angular distribution.

b. 0→7.64→0.62. The transition to the 0.62-MeV level shows a distribution $W(\theta)\sim1+(0.34\pm0.07)\cos^2\theta$. If it is assumed that the 7.64→0.62 transition is pure, the theoretical distribution which gives the best agreement to the experiment is $W(\theta)\sim1+0.43\cos^2\theta$ appropriate for the sequence $0(1)1(2)2$, thus assigning spin 2 to the 0.62-MeV level. This is in agreement with the well-established 2$^+$ assignment to the 0.62-MeV level which is interpreted to be the one-quadrupole phonon state. However, since the theoretical angular distribution for the sequence $0(1)1(2)2$ lies outside of the un-certainties of the observed distribution, the present experiment does not exclude the possibility of a M1−E2 admixture in the 7.64→0.62 transition. In order to examine the possibility of admixture in more detail, we define the anisotropy A by $A\equiv[W(150°)-W(100°)]/W(100°)$. The theoretical values of A for the sequence $0(1)1(\frac{1}{2})2$ are plotted in Fig. 10 as a function of the mixing ratio δ. Here, δ is defined to be the ratio of the reduced matrix element for E2 transition to that for M1. Figure 10 also shows the experi-mental value of anisotropy, $A=0.24\pm0.05$. From Fig. 10, one obtains two solutions for δ: $\delta=+(0.23\pm0.06)$ or $\delta=-(15_{-7}^{+55})$. The positive solution corresponds to

$0 \rightarrow 7.64 \rightarrow 2.06$

$W(\theta)\sim1+(1.15\pm0.22)\cos^2\theta$

$0 \rightarrow 7.64 \rightarrow 0$

$W(\theta)\sim1+(1.06\pm0.09)\cos^2\theta$

SCATTERING ANGLE θ (deg)
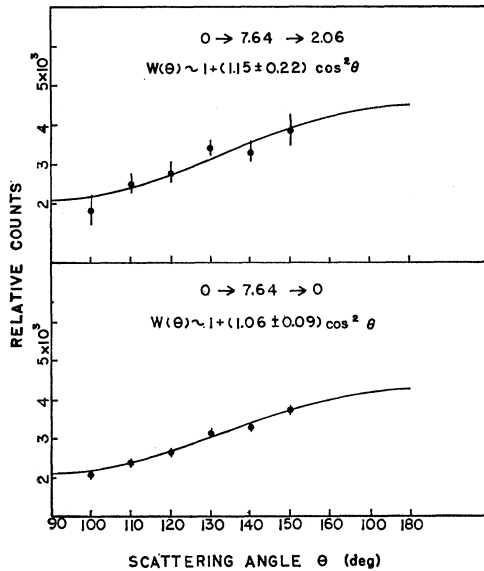
FIG. 9. Angular distributions of resonantly scattered photons in Ni^{62}. The solid lines are the least-squares fit through the data points.

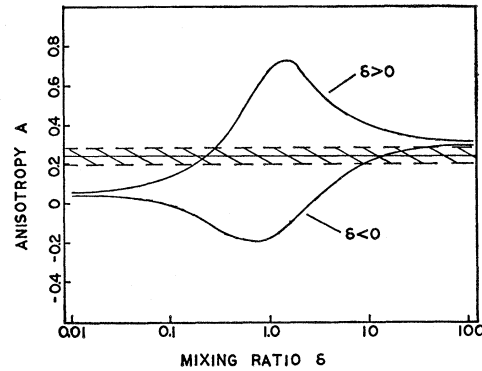MIXING RATIO δ

FIG. 10. Anisotropy $A\equiv[W(150°)-W(100°)]/W(100°)$ as a function of the mixing ratio δ for the sequence $0(1)1(\frac{1}{2})2$. The experimental value $A=0.24\pm0.05$ is shown by the shaded area.

an $E2$ admixture (in intensity) of about 5% to the dominant $M1$ transition. The negative solution corresponds to an almost pure $E2$ transition with a $M1$ admixture of about 0.5%. Even though this experiment cannot determine which of the two solutions is the correct one, the negative solution is considered rather unlikely because for a 7-MeV γ-ray transition in this region of the Periodic Table, $M1$ is expected to be at least competitive with $E2$. An almost pure $E2$ transition from a 1^+ level to a 2^+ level would require a special selection rule to explain the blocking of $M1$ transition.

c. $0{\rightarrow}7.64{\rightarrow}1.23$. The observed angular distribution $W(\theta){\sim}1+(1.16{\pm}0.17)$ $\cos^2\theta$ is in fair agreement with the distribution $1+\cos^2\theta$ expected for the sequence $0(1)1(1)0$. Therefore, the spin value 0 is assigned to the 1.23 MeV. We identify this level with the 1.228-MeV level[10] observed in the $Cd^{111}(d,p)Cd^{112}$ reaction which is interpreted as the 0^+ member of the two-quadrupole phonon triplet. It is concluded that the inelastic scattering $0{\rightarrow}7.64{\rightarrow}1.23$ involves pure $M1$ transitions.

d. $0{\rightarrow}7.63{\rightarrow}1.88$. The observed distribution $W(\theta){\sim}1+(1.11+0.20)$ $\cos^2\theta$ agrees within the experimental uncertainties with $1+\cos^2\theta$ for $0{\rightarrow}1{\rightarrow}0$ sequence. Therefore, the spin of the 1.88-MeV level is determined to be 0. We identify the 1.88-MeV level observed in this experiment with the 1.876-MeV level in Ref. 10, and the 1.84-MeV level in Ref. 11, both observed in $Cd^{111}(d,p)$ reactions. In both references, the values of the orbital angular momentum l_n and the parity were determined to be 0^+ so that J^π for this level is either 1^+ or 0^+. Our result is consistent only with $J^\pi = 0^+$ assignment to this level.

2. Ni^{62} (Fig. 9 and Table II)

a. $0{\rightarrow}7.64{\rightarrow}0$. $W(\theta){\sim}1+(1.06{\pm}0.09)$ $\cos^2\theta$ agrees with the $1+\cos^2\theta$ distribution for the sequence $0(1)1(1)0$. The parity of the 7.64-MeV resonance level in Ni^{62} has been determined to be even.[8] Combining this result, it is concluded that the 7.64-MeV level has $J^\pi = 1^+$.

b. $0{\rightarrow}7.64{\rightarrow}2.06$. The experimental distribution $W(\theta){\sim}1+(1.15{\pm}0.22)$ $\cos^2\theta$ once again assigns $J=0$ to the 2.06-MeV level. We identify this level with the known 0^+ two-phonon vibrational level at 2.048 MeV.[12]

IV. CONCLUSION

By inelastic scattering of the 7.64-MeV iron capture γ rays, 11 energy levels in Cd^{112} and three in Ni^{62} were studied. Many of the energy levels observed in the present experiment can be identified with the energy levels excited in (d,p) reaction, the energy assignments in the two experiments agreeing within 10 keV. For four levels in Cd^{112} and two in Ni^{62}, spin assignments were made by measuring the angular distributions of the resonantly scattered γ rays. With the exception of the 0.62-MeV 2^+ level in Cd^{112}, all of these levels are strongly excited by pure $M1$ transitions. For the 0.62-MeV level of Cd^{112}, the angular distribution is consistent with a 5% $E2$ admixture to the dominant $M1$ transition leading to this level.

Cd^{112} and Ni^{62} are both examples of the so-called vibrational nuclei. In this connection, it is interesting to note that the 1.23-MeV level in Cd^{112} and the 2.06-MeV level in Ni^{62}, both strongly excited in this experiment, are the 0^+ members of the two-quadrupole phonon triplet (0^+, 2^+, 4^+). Of the three possible transitions from the 1^+ resonance level to these triplets, the transition to the 4^+ members can be ruled out in this experiment; it would be difficult to observe $M3$ transition in competition with the $M1$ transitions. From the viewpoint of a simple vibrational model, the transition probabilities from the 1^+ resonance level to the 0^+ and 2^+ members of the triplet are expected to be about equal. However, only the transitions to the 0^+ members were observed in the present experiment. This fact indicates that in Cd^{112} and Ni^{62} the wave functions of the 0^+ and 2^+ members of the two-phonon triplet have very different components. A similar situation in another vibrational nucleus Zn^{66} has been reported by Shikazono and Kawasaki.[13]

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