Gamma Transitions Following the Decay of Nickel-65

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The gamma transitions following the decay of 2.6-hour Ni^{65}, have been studied by coincidence scintillation spectrometry. Gamma rays of energies 0.37, 0.51, 0.61, 0.77, 0.85, 0.95, 1.11, 1.48, 1.62, and 1.72 Mev having the intensity of 55, 1.5, 0.6, ~1, ~0.6, ~0.3, 140, 290, 10, and 6 per thousand disintegrations, respectively, are emitted in this decay. The gamma-gamma coincidence study is consistent with energy levels of Cu^{65} at 0.77, 1.11, 1.48, 1.62, and 1.72 Mev. The angular correlation of 0.37- and 1.11-Mev gamma rays suggests the spin assignment of $\frac{5}{2}$ for the 1.11-Mev level and $\frac{7}{2}$ or $\frac{3}{2}$ for the 1.48-Mev level. Both the gamma transitions are mixtures of $E2$ and $M1$.

INTRODUCTION

THE energy levels of Cu^{65} have been studied by inelastic scattering of protons[1,2] and by Coulomb excitation.[3] The levels below 2 Mev, observed by (p,p') reactions and located at 0.770, 1.114, 1.482, 1.623, and 1.725 Mev, are shown in Fig. 1. By Coulomb excitation only two levels at 0.815 and 1.150 Mev are reported.[3] Considering the possible errors in the measurements of the energies of the gamma rays emitted after Coulomb excitation, it seems reasonable to conclude that the 0.815- and 1.150-Mev levels are the same as the 0.770- and 1.114-Mev levels observed in (p,p') reaction.

Siegbahn and Ghosh[4] have reported three beta groups of end-point energies 2.1, 1.01, and 0.62 Mev, feeding to the ground, 1.11- and 1.48-Mev levels, respectively. The 1.48-Mev level is reported to decay through a 0.37−1.11 Mev gamma-ray cascade and a crossover transition. Using anthracene crystals as gamma detectors, Wiedling and Carlsson[5] reported an asymmetry of 19% in the angular correlation of the 0.37- and 1.11-Mev gamma rays and suggested a spin assignment of $\frac{5}{2}$ and $\frac{7}{2}$ for the 1.11- and 1.48-Mev levels. Recently the angular correlation of this gamma-ray cascade has been studied by Hartmann and Asplund,[6] and they suggest the spin value of $\frac{7}{2}$ for both the levels. Lawson and Uretsky[7] have presented a theoretical treatment of the levels of Cu^{65} and predicted the spin sequence of $\frac{1}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{3}{2}$ for the 0.77-, 1.11-, 1.48-, and 1.62-Mev levels.

In view of the large decay energy of 2.1 Mev, the 2.6-hour Ni^{65} has been sudied to determine the extent to which the levels reported by (p,p') reaction and Coulomb excitation are excited in its decay. The angular correlation measurements were made to determine the possibility of $M1$ and $E2$ admixture in the gamma transitions and to establish, if possible, the spin sequence of the two levels involved.

[1] M. Mazari, W. W. Buechner, and R. P. de Figueiredo, Phys. Rev. **108**, 373 (1957).
[2] R. R. Spencer, G. C. Phillips, and T. E. Young, Phys. Rev. **108**, 69 (1957).
[3] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[4] K. Siegbahn and A. Ghosh, Phys. Rev. **76**, 307 (1949).
[5] T. Wiedling and A. Carlsson, Phys. Rev. **83**, 181 (1951).
[6] B. Hartmann and I. Asplund, Arkiv Fysik **13**, 339 (1958).
[7] R. D. Lawson and J. L. Uretsky, Phys. Rev. **108**, 1300 (1957).

EXPERIMENTAL PROCEDURE

Various samples of 99.9% purity of nickel, in the form of metallic powder, oxide, and sulphate, were irradiated for a period of four to five hours in the Apsara reactor (Trombay). The active material was then chemically purified to remove the traces of Mn^{56} and also Co^{58} formed by the (n,p) reaction on Ni^{58}.

The gamma-ray spectrum from a purified sample of Ni^{65} as observed by a 4-in. diameter×4-in. thick NaI(Tl) crystal scintillation spectrometer, is shown in Fig. 2. In addition to the prominent full energy peaks at 0.37, 1.11, and 1.48 Mev, there are indications for the presence of 0.51-, 0.61-, 1.62-, and 1.72-Mev gamma-ray peaks. The high-energy tail beyond 1.48-Mev peak is shown to be composed of the last two gamma rays. These energy values are taken from (p,p') measurements. The small peak at 0.51 Mev persists with almost the same relative intensity with respect to 0.37-Mev gamma ray when the source to crystal distance is changed. The probability of pair production by the intense 1.48-Mev gamma ray in the aluminum which is a part of the crystal assembly is about 10^{-5}. If the 1.48-Mev gamma ray is absorbed in the crystal through a pair production process and both the annihilation quanta escape through the crystal, it will produce pulses corresponding to 0.46 Mev but the probability for such a process is less than 10^{-3}. These observations rule out

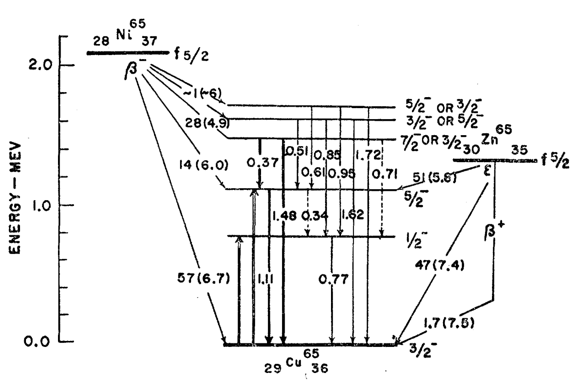

FIG. 1. Level scheme for the excited states of Cu^{65} nucleus. The percentage of beta groups are followed by log ft values given in parenthesis. Intense gamma transitions are shown by thick lines and unobserved transitions are shown by dotted lines.

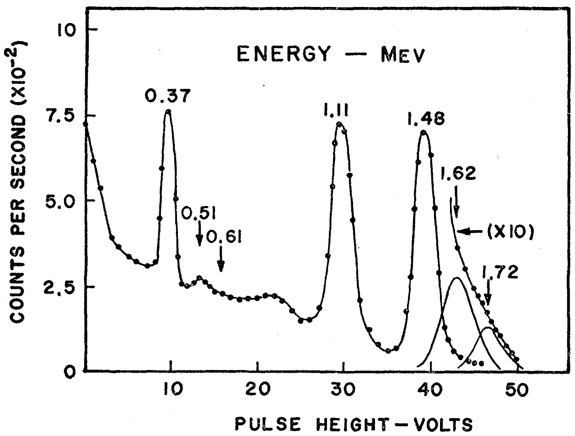

FIG. 2. Gamma spectrum of Ni^{65}, viewed by 4-in. diameter ×4-in. thick NaI(Tl) crystal from a distance of 10 cm along its axis.

the possibility of 0.51-Mev peak originating from such secondary processes, including the coincidence pile-up of 0.37-Mev gamma ray and the back-scattered quanta of 1.11-Mev gamma ray. The presence of 0.51-Mev gamma ray is further confirmed in coincidence measurements. The spectrum shown in the figure was recorded keeping the source at a distance of 10 cm from the crystal surface, corresponding to a coincidence pile-up factor of 1.5% for the detection of 1.11-Mev gamma ray with its full energy peak, and in coincidence with any of the gamma ray feeding that level. The pulses at 1.62 and 1.72 Mev could arise, in principle, due to the simultaneous detection of 0.51- and 0.61-Mev gamma rays along with the 1.11-Mev gamma which, as will be seen later, is in coincidence with both. However, the intensities of the 1.62- and 1.72-Mev radiations are even larger than the 0.51- and 0.61-Mev gamma radiations, and hence could not arise due to such a piling-up process alone.

GAMMA-GAMMA COINCIDENCE STUDY

The coincidence measurements were made with two scintillation spectrometers, having 1.75-in. diameter×2-in. thick NaI(Tl) crystals as gamma detectors. They were operated with the standard fast slow coincidence technique having a resolving time $2\tau = 4\times10^{-8}$ second. The full energy peak of a gamma ray was selected in one detector with a single-channel pulse-height analyzer, and the gamma-ray spectrum in coincidence with it, in the other detector, was observed on a Getti type[8] twenty-channel analyzer built here.

From energy considerations of the various gamma rays and the suggested level scheme,[1] shown in Fig. 1, it is expected that in addition to the 0.37-Mev gamma ray originating from 1.48-Mev level, the 0.51- and 0.61-Mev gamma rays originating from the 1.62- and 1.72-Mev levels may also feed the 1.11-Mev level. To establish this, the gamma-ray spectrum in coincidence with 1.11-Mev gamma ray was studied. The two NaI(Tl) crystal detectors viewed the source at right angle to each other and a shield of one-centimeter thick lead was interposed in between the two crystals to avoid any scattered photons from one crystal entering the other. The coincidence spectrum thus observed is shown in Fig. 3. It shows that 0.51- and 0.61-Mev gamma rays are in coincidence with 1.11-Mev gamma ray; and they are presumably emitted from 1.62- and 1.72-Mev levels, respectively. It may be mentioned that inner and external bremsstrahlung associated with the 1-Mev beta group feeding the 1.11-Mev level is also contributing a continuous low intensity coincidence background to the obsrevations shown in Fig. 3.

The gamma-ray spectrum shown in Fig. 2, does not indicate an obvious presence of 0.77-Mev gamma ray corresponding to the de-excitation of 0.77-Mev level. The peak would not show up if the population of the level is less than a percent. To look for any weak gamma transitions feeding that level, one channel of the coincidence spectrometer was fixed to accept pulses corresponding to 0.77-Mev gamma energy and the pulse-height spectrum observed in coincidence, in the other channel, was recorded. Since the expected gamma transistors are likely to be very weak, the two detectors were kept in head on position to improve the coincidence counting efficiency. The detectors looked at the source through a wide-angle cone of lead, having a half angle of 80° and the apex had an opening of one-centimeter diameter. The observations showed the presence of 0.85- and 0.95-Mev gamma rays. These could originate from the 1.62- and 1.72-Mev levels and feeding the 0.77-Mev level. The coincidence spectrum below 800 kev was rendered complex due to the presence of various pile-up pulses for which the above arrangement is rather favorable. Unfortunately, due to low intensity of the expected gamma transitions, it was not possible to use right-angle geometry or to do absorption experiments.

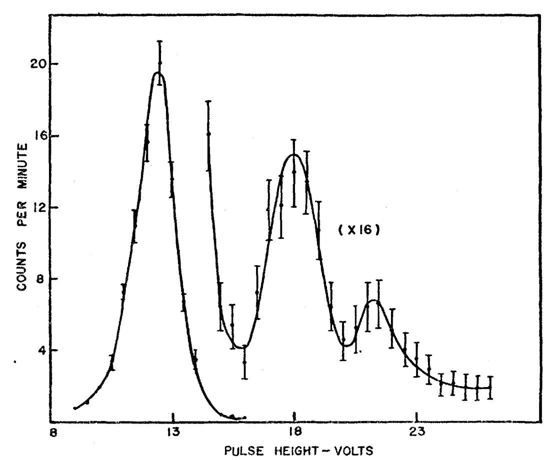

FIG. 3. Pulse-height distribution of gamma spectrum in coincidence with 1.11-Mev gamma ray.

[8] E. Gatti, Nuovo cimento 5, 748 (1957).

TABLE I. Intensities of beta and gamma transitions in the decay of Ni^{65}.

Max. energies of beta groups Mev	Intensities beta groups per thousand disintegrations	Log ft	Energies of associated gamma rays Mev	Photons per thousand disintegrations
0.38	7	~6	1.72 0.95 0.61	6 ~0.2 0.6
0.48	13	~6	1.62 0.85 0.51	11 ~0.5 1.5
0.62	340	4.9	1.48 0.71 0.37	280 ≪0.2 60
1.01	70	6.3	1.11 0.34	130 ≪0.1
2.1 ···	570 ···	6.5 ···	··· 0.77	··· ~0.7

Thus, it has not been possible to conclude about the presence of 0.71-Mev gamma ray expected to be emitted from the 1.48-Mev level. However, there seems to be little doubt about the presence of 0.85- and 0.95-Mev gamma transitions, since no combination of coincidence pile-up could explain the peaks in this energy region. An attempt was made to look for the transition from 1.11-Mev level to the 0.77-Mev level in the decay of Zn^{65}. Here the presence of annihilation radiation was giving coincidences between pulses corresponding to 0.68- and 0.34-Mev energy through back-scattering process. On the basis of these observations, it has been estimated that the transitions to the 0.77-Mev state from the 1.11- and 1.48-Mev levels could have a branching less than 10^{-3} of that of the transitions to the ground state. The intensities of the various beta and gamma transitions obtained from the above measurements are shown in Table I. The intensity of the beta transition going to the ground state is taken from the measurements of Siegbahn and Ghosh.[4]

GAMMA-GAMMA ANGULAR CORRELATION

The angular correlation apparatus is the same used in coincidence measurements. The NaI(Tl) crystals, used as gamma detectors, were surrounded with lead cones having conical apertures of half-angle of 8°. The coincidence circuit had single-channel pulse-height analyzers looking into the detector pulses. The coincidence rate was recorded at every angle for five minutes, each observation being preceded by a similar one at 90°. After subtracting the chance coincidences, the asymmetry $W(\theta)/W(90°)$ was determined at six angles at an interval of 15°. This ratio was suitably corrected for the decay of the source during the time of each set of observations. The ratio of true to random coincidences was generally better than ten. The values of the asymmetry ratio at various angles are shown in Fig. 4 along with its least-squares fit curve. The correlation function is found to be,

$$W(\theta)=1+(0.185\pm0.055)P_2(\cos\theta)+(0.028\pm0.015)P_4(\cos\theta),$$

which when corrected for the angular resolution of the detectors, gives

$$W(\theta)=1+(0.190\pm0.055)P_2(\cos\theta)+(0.031\pm0.015)P_4(\cos\theta).$$

DISCUSSION OF RESULTS

The level scheme for Cu^{65} obtained from (p,p') reaction is in full agreement with the present gamma-gamma coincidence study. The ground-state spin of Cu^{65} is measured[9] to be $\frac{3}{2}$. On the basis of shell-model considerations, the spin of Ni^{65} is presumably $\frac{5}{2}$ and odd parity. The log ft values of the beta transitions to the 1.11- and 1.48-Mev levels, are 4.9 and 6.3, respectively. Hence, they are of allowed nature. The possible spin values of the two states could be $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ with odd parity. Thus, there are nine spin sequences possible for the two excited states involved in the present correlation study. It is not possible to obtain the measured correlation function with pure multipole gamma transitions, in any of the above nine spin sequences. The data were therefore analyzed considering mixtures of $E2$ and $M1$ in both the transitions. It is found that with suitable $E2-M1$ admixtures in both the transitions only two spin sequences, namely $\frac{7}{2}-\frac{5}{2}-\frac{3}{2}$ and $\frac{3}{2}-\frac{5}{2}-\frac{3}{2}$, can give the observed correlation function. The possible admixtures are shown in Table II.

The spin sequence of $\frac{7}{2}-\frac{7}{2}-\frac{3}{2}$ for the 1.48, 1.11 Mev and ground state, as suggested by Hartmann and Asplund[6] does not fit in with these measurements. With this spin sequence, 1.11-Mev transition is pure $E2$ and the 0.37-Mev transition could be a mixture of $E2$ and $M1$. For this spin sequence to be compatible with the observed experimental value of the coefficient of $P_2(\cos\theta)$ in the angular correlation function, the value of the coefficient of $P_4(\cos\theta)$ term should lie between 0 to 0.007 or between 0.07 to 0.12. These values are very much outside the limits of experimentally measured value of 0.031 ± 0.015 for the coefficient of $P_4(\cos\theta)$.

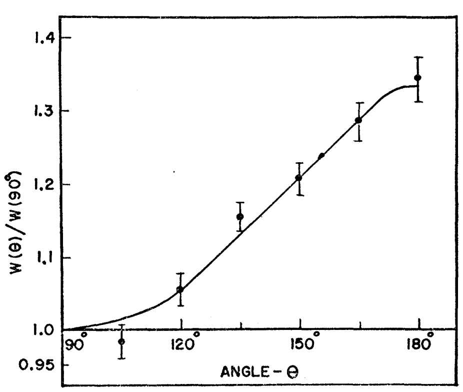

FIG. 4. The asymmetry parameter $W(\theta)/W(90°)$ at various angles and the least-squares fit curve of the form, $W(\theta)=1+0.195\cos^2\theta+0.130\cos^4\theta$.

[9] J. E. Meck, Revs. Modern Phys. 22, 64 (1950).

TABLE II. Nature of the 0.37- and 1.11-Mev gamma transitions, with the probable spin values for the 1.48- and 1.11-Mev levels, obtained from the angular correlation study.

Spins of the levels at 1.48 Mev	1.11 Mev	0 Mev	Nature of the 0.37-Mev transition limits of $E2/M1$	Nature of the 1.11-Mev transition limits of $E2/M1$
$\frac{7}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	10 to 39	0.1 to 1.2
			0.3 to 1.4	∞ to 50
			28 to ∞	0.2 to 1.2
			0.3 to 1.5	2 to 7.5
$\frac{3}{2}$	$\frac{5}{2}$	$\frac{3}{2}$	12 to 27	0.02 to 0.11
			0.02 to 0.11	12 to 27
			0.3 to 33	0.1 to 0.3
			0.1 to 0.3	0.3 to 33

The Coulomb excitation of 0.77-Mev level is only five times faster than the estimates for single-particle excitation[3] and also that the shell model predicts a $P_{\frac{1}{2}}$ state for the 29th proton in Cu^{65} above the ground of $P_{\frac{3}{2}}$, it is probable that the 0.77-Mev level is of $P_{\frac{1}{2}}$ configuration. The spin value $\frac{1}{2}^-$ is also supported by the absence of any observed beta transition from Ni^{65} or Zn^{65}, both of them having probable spin values of $\frac{5}{2}^-$. The spin $\frac{1}{2}$ is expected from Lawson and Uretsky's calculations.[7]

The values of the K-conversion coefficients for the 0.37-, 1.11-, and 1.48-Mev transitions are rather insensitive to the admixture of $M1$ and $E2$ and therefore incapable of discriminating[10] between the two possible spin sequences given in Table II. The character of the 0.71-Mev transition from the 1.48-Mev state to the 0.77-Mev level, would be $M3$ or $M1$, depending upon the spin assignment of $\frac{7}{2}$ or $\frac{3}{2}$ for the 1.48-Mev state, as suggested by the angular correlation measurements. On the basis of Weisskopf's lifetime formula, the intensity ratio for the 0.71- and 1.48-Mev gamma rays should be of the order of 10^{-8} or 10^{-1} depending upon the two spin values. Unfortunately no conclusive results could be obtained about the intensity of 0.71-Mev gamma ray. However, the spin sequence predicted by Lawson and Uretsky[7] would favor the spin value $\frac{7}{2}$ for the 1.48-Mev state. The transition from 1.11- to 0.77-Mev level would be $E2$ for the proposed spin values. On the basis of Weisskopf's lifetime formula, the intensity of 0.34-Mev gamma ray should be about 0.3% of that of 1.11-Mev transition. Since the Coulomb excitation of 1.11-Mev level is 40 times faster than the estimates for single-particle excitation, the level could have a different configuration than the $P_{\frac{1}{2}}$ level at 0.77 Mev. This would retard the 0.34-Mev transition and the upper limit of intensity, shown in Table I, would not be inconsistent with the proposed spin values. The observed transition of 0.85-Mev gamma ray from the 1.62-Mev level is also consistent with the spin $\frac{3}{2}$ for the 1.62-Mev level proposed by Lawson and Uretsky.[7]

[10] A. Ajzenberg-Selove, Suppl. Nuovo cimento 4, 2 (1956).

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