an fragment-gamma correlations are in progress for gamma rays of various average energies to investigate further details of the process.

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Study of the Radiations Emitted in the Decay of Ni^{65}*

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Radiations emitted in the decay of Ni^{65} have been studied using scintillation spectrometry and absolute beta counting. The half-life of this nuclide has been measured to be 2.553 ± 0.008 h. A decay scheme is presented which contains some weak transitions observed to depopulate the higher energy states. Intensities are presented for these transitions and upper limits are placed on intensities of previously reported transitions which were not observed in this work.

I. INTRODUCTION

PROPERTIES of the decay of 2.55-h Ni^{65} have been studied by several experimenters. Swarthout *et al.*[1] and Conn *et al.*[2] performed early studies of the β^- radiation emitted by this nuclide. Siegbahn and Grosh[3] reported energies and coincidence relationships for the prominent transitions. More recently, Jambunathan *et al.*[4] have reported six additional transitions which followed beta branching to higher energy levels. The existence of these levels had previously been established in (p,p') scattering experiments,[5] but they had not been observed to be excited in the beta decay of Ni^{65}.

Three measurements of the directional correlation of the 0.37–1.114-MeV cascade appear in the literature.[4,6,7] As a result of these measurements, three distinct spin sequences were proposed for the levels in Cu^{65} at 1480 and 1114 keV. Recent Coulomb excitation measurements[8] have indicated that the spins and parities of the first three known excited levels of Cu^{65} are $\frac{1}{2}-$, $\frac{5}{2}-$, and $\frac{7}{2}-$, respectively. In view of recent interest in core-excitation models of nuclear structure,[9–12] it is felt that a more complete knowledge of the decay scheme of Ni^{65} and particularly of the intensities of the weaker gamma-ray transitions observed in this decay would aid in the application of these models to this nuclide.

II. EXPERIMENTAL TECHNIQUES AND DATA

1. Source Preparation

Samples of Ni^{65} were produced by irradiation of Ni_2O_3 in a thermal flux facility of the Materials Testing Reactor ($\approx 1.5\times10^{13} n/cm^2$ sec). Following irradiation, material was purified using standard Ni chemistry. Sources 3 mm in diameter were prepared for the gamma-ray studies by evaporating Ni in HCl solution, onto 10-mg/cm² plastic films. Liquid sources for the directional-correlation measurement were contained in thin-walled Lucite holders, $\frac{1}{16}$ in. in diameter. Special sources for $4\pi\beta$ counting were prepared from solutions of irradiated Ni, enriched to 99.92% in the Ni^{65} isotope, by deposition on 5 μg/cm² films of VYNS.

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2. Gamma-Ray Measurements

The gamma radiation emitted in the decay of Ni^{65} was observed with 3-in.-diam by 3-in.-cylindrical NaI(Tl) detectors. Sources were measured at a distance of 10 cm along the axis of the detector. With this source-detector distance, coincidence-summing effects in the detector were negligible in this experiment. A beryllium absorber was interposed between the source and detector to absorb the beta radiation. A polystyrene cap 360 mg/cm^2 thick, placed over the scintillation crystal, served to shield the counter from the effects of air-scattered beta radiation scattered into the sides of the crystal. The effects of this cap as well as the other procedures used at this laboratory for quantitative gamma-ray spectroscopy have been discussed previously.[13,14]

Energy calibration of the scintillation spectrometers was accomplished by the method of internal comparison using the 1114-keV gamma ray from the decay of Ni^{65}. The procedure for energy determinations for the major gamma rays in the Ni^{65} spectrum was as follows. Full-energy peaks of the spectrum were each fit by a method of least-squares to Gaussian functions. Using the results of this analysis, a normalization of the spectrum to a standard pulse-height scale was made. The positions of the peaks in this standard scale were then compared to a pulse-height-vs-energy curve obtained for this particular spectrometer. Such a comparison corrects for the nonlinear energy response of NaI(Tl).

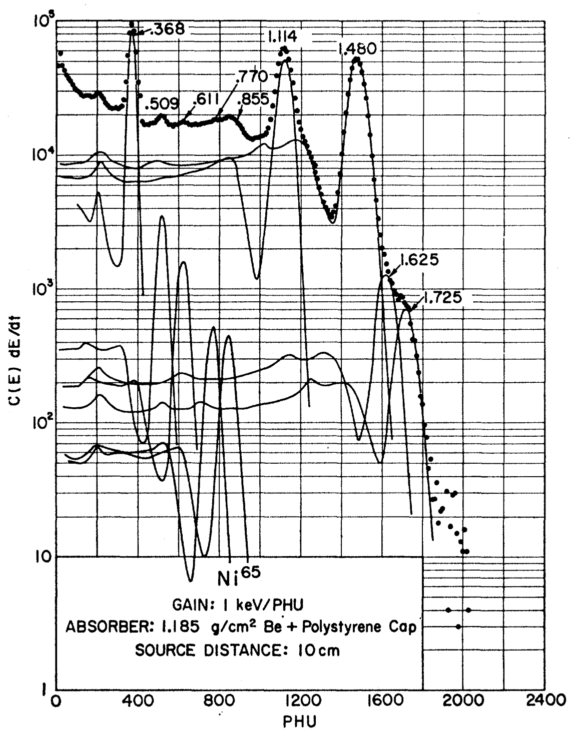

FIG. 1. Gamma-ray spectrum of 2.55-h Ni^{65}.

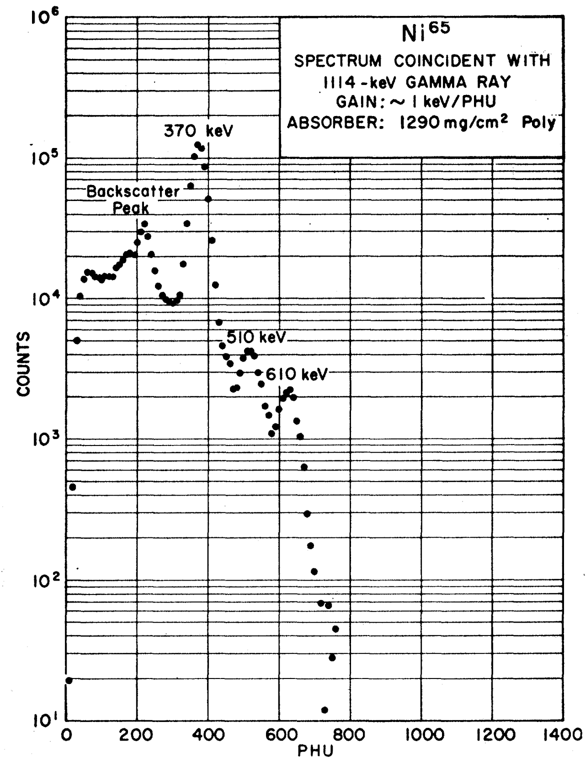

FIG. 2. Gamma-ray spectrum coincident with 1114-keV transition.

A typical pulse-height spectrum obtained from a Ni^{65} sample is shown in Fig. 1. All gamma rays were found to decay with a half-life characteristic of Ni^{65}. A least-squares analysis was made of the data shown in the figure. The analysis used response functions for monoenergetic gamma rays calculated[14] for the particular detector and geometry used in this experiment. Also included in the fit was a bremsstrahlung shape taken using a source of Y^{90} and normalized in energy to correspond to the end-point energy of the Ni^{65} ground-state beta transition. The accuracy of such analyses in simple cases (such as this) has been demonstrated previously.[14] A determination of the intensities of the 509- and 610-keV gamma rays, relative to the intensity of the 368-keV transition, was aided by the coincidence data described below. Intensities of the 770- and 855-keV transitions and upper limits for the intensities of the 710- and 960-keV transitions were obtained entirely from analyses of the coincidence data. Gamma-ray energies, relative intensities, and absolute intensities are listed in Table I. The values for absolute intensities were obtained by comparison of gamma-ray intensities with absolute disintegration rates determined from 4π β-γ coincidence measurements.

Gamma-gamma coincidence measurements were performed using a pair of 3-in.$\times$3-in. NaI(Tl) detectors.

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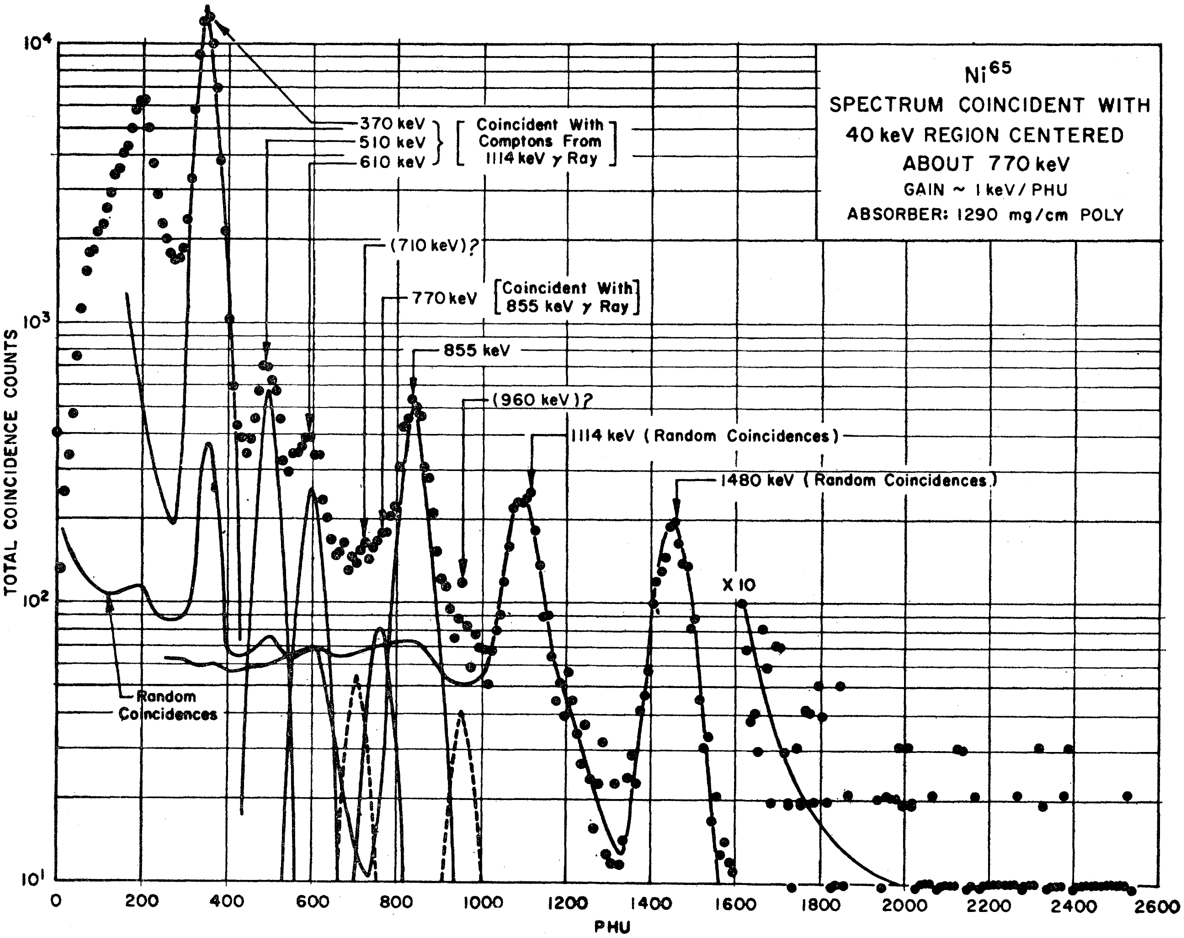

FIG. 3. Gamma-ray spectrum coincident with 770-keV transition.

Graded back-scatter shields were used and all measurements were made at 90° geometry to reduce the effect of coincidences resulting from the scattering of photons between the crystals. The coincidence spectrometer used a single-channel pulse-height analyzer operated in conjunction with a 256-channel analyzer of conventional design. Double-differentiated amplifiers were used on both channels to allow the use of the zero cross-over point to derive timing signals for the fast inputs to a fast-slow coincidence system. With this system, 100% coincidence efficiency for all pulses from 2 to 90 V in amplitude was achieved with a fast resolving time of 8×10^{-8} sec. A typical spectrum taken in coincidence with an energy region centered about 1114 keV is presented in Fig. 2. Intensities of the 509- and 611-keV transitions, relative to the intensity of the 368-keV transition were obtained from these data. Figures 3 and 4 show spectra taken in coincidence with 40-keV energy regions centered about 770 and 855 keV, respectively. The 770- and 855-keV transitions observed in these spectra presumably represent a cascade from the level at 1623 keV through the level at 770 keV. If a 955-keV transition to the 770-keV state from the level at 1725 keV is present with an intensity comparable to that of the 855-keV transition, as was reported by Jambunathan *et al.*,[4] spectra taken in coincidence with the 770-keV transition (Fig. 3) should show its presence. An upper limit for the intensity of the 955-keV transition as well as an upper limit for the intensity of a 710-

TABLE I. Energies, relative intensities, and absolute intensities for gamma rays from Ni^{65} decay.

E_γ(keV)	I_γ(relative)	I_t(absolute)
368±5	0.18 ±0.01	4.50±0.30%
509±7	0.015±0.002[a]	0.38±0.08%
611±7	0.010±0.002[a]	0.25±0.06%
710	···	<0.006%
770±10	0.003±0.001[a]	0.08±0.03%
855±10	0.003±0.001[a]	0.08±0.03%
960	···	<0.006%
1114±3	0.63 ±0.03	15.8 ±0.8%
1480±5	1.000	25.0 ±2.0%
1625±10	0.028±0.004	0.70±0.12%
1725±10	0.018±0.002	0.45±0.06%

[a] Determined from coincidence data.

keV gamma ray representing a transition from the 1480-keV level to the 770-keV level may be obtained from the data shown in Fig. 3. Intensities of the 770- and 855-keV gamma rays, relative to that of the 368-keV transition, were obtained by analysis of the data in Figs. 3 and 4. In this analysis it was necessary to determine the fractions of the single channel counting rate which were due to events in the Compton distribution of the 1114-keV transition and to the photopeak of the 770- or 855-keV gamma ray. Intensities for the 770- and 855-keV transitions and upper limits for the intensities of the 710- and 955-keV transitions are given in Table I. No coincidences were observed between the 368-, 509-, or 610-keV transitions.

Directional-correlation measurements were made on the 368–1114-keV cascade. The apparatus used for these measurements was similar to the coincidence system described above. Data were taken with source-detector distances of 10 cm at angles of 90°, 135°, and 180°. A discussion of the reasons for the use of only three angles and for the choice of angles is given by Reich *et al.*[15] A graded back-scatter shield was used in taking these data to reduce the effects of Compton scattering of the 1480-keV gamma ray between the crystals. The spectrum of the 368-keV gamma ray, coincident with the 1114-keV photopeak, was recorded in the multichannel analyzer. The effects of scattering on the spectra could thus be noted and taken into account. Nineteen measurements were made at each angle, each containing approximately 4000 events in the 368-keV photopeak. Determinations of the random coincidence counting rate were made several times during the experiment. At no time was the random rate found to be more than 5% of the total coincidence counting rate. Appropriate corrections were made to the data to account for this effect.

3. Half-Life Determination

The half-life of the Ni^{65} activity was obtained by observing the decay of the beta spectrum using a 4π β flow proportional counter. Least-squares analysis of these data indicates the presence of one component with a half-life of 2.553±0.008 h.

III. RESULTS AND DISCUSSION

1. Results

Figure 5 presents a decay scheme for Ni^{65} which is consistent with the data. The spin and parity of the ground state of Cu^{65} are[4] $\frac{3}{2}-$. The spins and parities of the levels at 770, 1114, and 1480 keV have been reported[8] to be $\frac{1}{2}-$, $\frac{7}{2}-$, and $\frac{5}{2}-$, respectively. The level at 1623 keV must have a spin of either $\frac{3}{2}$ or $\frac{5}{2}$ to be consistent with the intensity of the observed gamma transitions to the levels at 770 and 1114 keV. Similarly, the

[15] C. W. Reich, J. A. Merrill, and E. D. Klema (to be published).

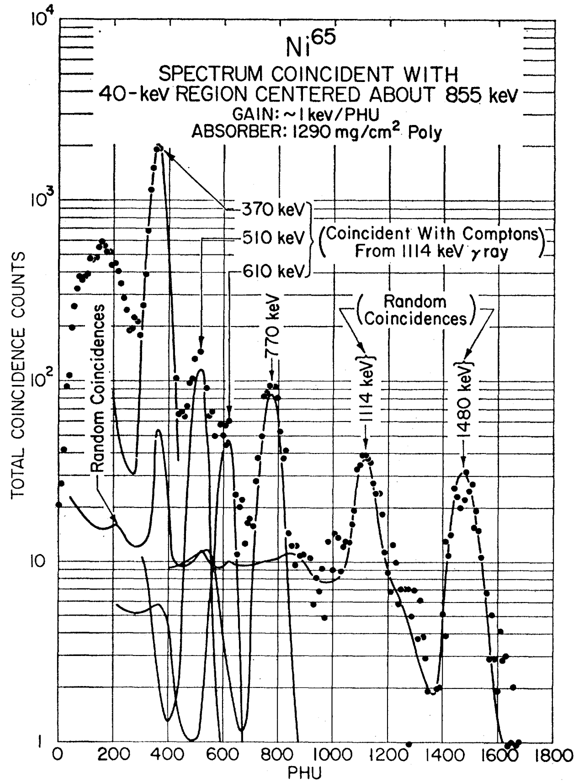

FIG. 4. Gamma-ray spectrum coincident with 855-keV transition.

1725-keV level may have a spin of either $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$. The parity of both the 1623- and 1725-keV levels must be negative to be consistent with observed log *ft* values for the beta groups feeding these levels.

A fit of the directional-correlation data for the 368–1114-keV gamma cascade to a function of the form $W(\theta)=A_0+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ yielded values for A_2/A_0 and A_4/A_0 of (0.189±0.005) and (0.013±0.008), respectively. These values have been corrected for finite solid angle effects. As was pointed out in reference 15, the use of only the three angles, 90°, 135°, and 180° in making the measurements yields more precise values for the coefficients A_2 and A_4 than the use of many angles for a comparable number of observations. However, systematic errors may be introduced through uncertainties in the angle positions. It is felt that, in the present experiment, these systematic uncertainties are smaller than the statistical uncertainties. Since the spin sequence $\frac{7}{2}(1,2)\frac{5}{2}(1,2)\frac{3}{2}$ allows mixing in either or both of the transitions, the values obtained for the coefficients are consistent with the spins given by Gove[8] over a large range of the mixing parameters δ_1 and δ_2 for the two gamma rays. It is impossible to determine a unique value for the mixing in either transition. However, it is highly unlikely that either transition is pure (either $M1$ or $E2$).

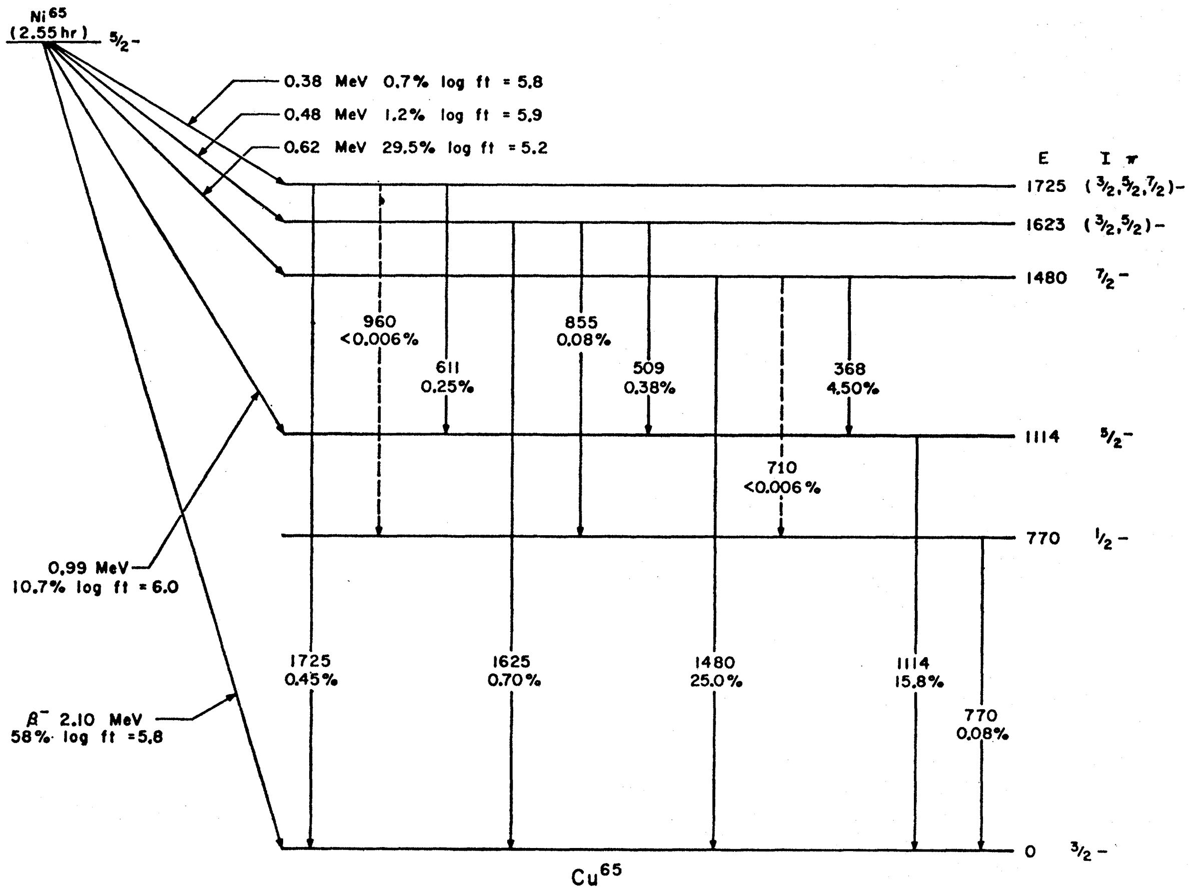

FIG. 5. Decay scheme for Ni^{65}. The dashed lines represent transitions which were not observed but where upper limits may be placed on their intensities.

2. Discussion of Results

If the shell model is applicable to the nuclides Ni^{65} and Cu^{65}, the $\frac{5}{2}-$ ground state of Ni^{65} presumably arises from an unpaired $f_{5/2}$ neutron in this odd-A nucleus. Similarly, the $\frac{3}{2}-$ ground state of Cu^{65} most probably arises from an uncoupled $p_{3/2}$ proton. Hence, one would expect the allowed β^- branch to the ground state of Cu^{65} to be "l" forbidden. A $\log ft$ of 5.8 for this transition supports this argument. The values of $\log ft$ for the β^- transitions to the states at 1114, 1623, and 1725 keV are also of this same order, while the $\log ft$ for the beta group to the level at 1480 keV is 5.2. The indication is, therefore, that the transition to this latter level is for some reason unhindered. If, indeed, this state is part of the core excitation, it is difficult to explain the small value for the $\log ft$.