TABLE II. Ratios of "poor" geometry to total cross section measured with bismuth fission chambers.

Element	σ_i/σ_t (270 Mev)	σ_i/σ_t (95 Mev)
Carbon	0.505±0.02	0.46±0.015
Copper	0.50 ±0.02	0.39±0.005
Lead	0.51 ±0.01	0.40±0.01
	0.49 ±0.02	

the neighborhood of 270 Mev agree well with each other from beryllium to lead. To obtain a reasonable fit with the data in terms of the transparent model of the nucleus,[2] the potential change experienced by the bombarding neutron when entering a nucleus must be dropped to zero. New measurements, to be published later, indicate the total cross sections for these elements are flat in the vicinity of 270 Mev.

The experimentally measured value of the total $n-p$ cross section for the 270-Mev neutrons is $38\pm1.5\times10^{-27}$ cm². The value predicted[7] by the model proposed by Christian and Hart, in which tensor forces are combined with a Yukawa potential, is 37×10^{-27} cm² at 280 Mev.[8]

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[7] R. S. Christian, private communication.
[8] The value published by R. S. Christian and E. W. Hart, Phys. Rev. 77, 441 (1950), is erroneous.

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Measurement of Absolute Electron Capture Rates with an Application to the Decay of Ni^{57}*

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Observation of radiations from 36-hour Ni^{57} with a proportional counter and pulse-height analyzer shows that cobalt x-rays are emitted. Decay is divided equally between K-capture and emission of 845-kev positrons. The positron spectrum has the allowed shape. Coincidence measurements involving the comparison of Ni^{57} and Na^{22} give the result that both K-capture and positron emission in Ni^{57} are followed by emission of a 1.9-Mev gamma-quantum. In the K branch there are some 120-kev gamma-rays and possibly others of energy less than 0.5 Mev in cascade with the hard gammas.

I. INTRODUCTION

PULSE analyzers and proportional counters suitable for the detection and identification of x-rays[1,2] have recently been developed. With the aid of such an instrument, the quantitative investigation of electron capture processes is being undertaken. The first case studied is that of 36-hour Ni^{57}, which, it has been reported, emits 0.67- to 0.72-Mev positrons, 1.97-Mev gamma-rays, and some softer gamma-rays.[3,4] The observation[5] that the apparent yield of the reaction $Ni^{58}(\gamma, n)Ni^{57}$ as measured by β-counting was lower than expected from (γ, n) yields in neighboring elements led to the suspicion that Ni^{57} might decay by electron capture.

The Ni^{57} was produced by bombardment of iron with 30-Mev alpha-particles in the cyclotron of the Department of Terrestrial Magnetism of the Carnegie Institution. With the aid of carriers the nickel activity was chemically separated from the target and purified from other activities, especially those of cobalt, manganese, and copper, which may have been produced by alpha-particles, deuterons, or neutrons either in the iron or in its supporting materials. The treatment involved dissolution of the iron target in 12N HCl; oxidation of the iron to the ferric state and its removal from the solution by ether extractions; and precipitation then of nickel dimethylglyoxime in the presence of tartrate ion to keep ferric ion in solution and of carriers to "hold back" cobalt, manganese, and copper. The nickel precipitate was dissolved and reprecipitated under the above conditions twice more. The Ni^{57} with its 0.1 to 4 milligrams of nickel carrier was finally converted to NiS and mounted on thin aluminum foil.

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[1] Curran, Cockroft, and Angus, Phil. Mag. 40, 53, 522, 631, 929 (1949).
[2] Bernstein, Brewer, and Rubinson, Nucleonics 6, No. 2, 39 (1950).
[3] G. T. Seaborg, and I. Perlman, Rev. Mod. Phys. 20, 585 (1948).
[4] F. Maienschein and J. L. Meem, Jr., Phys. Rev. 76, 899 (1949).
[5] M. L. Perlman, Phys. Rev. 75, 988 (1949).

II. X-RAY MEASUREMENTS

It was found that cobalt K x-rays are emitted in the decay of Ni^{57}. The counter for measurements of the energy and intensity of the x-rays was made from a four-inch diameter brass tube, 12 inches long, in which was placed a coaxial tungsten wire 0.004 inch in diameter. Gas composition was 90 percent argon and 10 percent methane; the total pressure was one atmosphere. Radiations entered the sensitive space through a beryllium window 20 mg/cm^2 in thickness. This instrument was operated as a proportional counter, and it demonstrated a voltage plateau in total number of pulses above noise level. The sliding channel analyzer used to measure the pulse spectrum from the counter has been described.[2]

If monochromatic x-rays are allowed to enter the counter and if the number of pulses observed in each pulse height interval is plotted *versus* the pulse height, two maxima are observed in the resultant curve; one whose position corresponds in pulse height to the energy of the incident quanta and the other, much less pronounced, to an energy lower by the K x-ray energy of the principal counter gas. The observed peak position for Ni^{57} was compared with the peak positions for K radiations of manganese, copper, and cobalt produced in the decays of Fe^{55}, Zn^{65}, and Ni^{59}, respectively. It is clear (Fig. 1) that cobalt x-rays are emitted in the decay of Ni^{57}.

For one sample the decay of the x-ray peak was followed over a period of 12 days. Day-to-day corrections for rather small drifts of channel width and peak position were made by measurement of an Fe^{55} standard. After subtraction of a long-lived contribution amounting to approximately one percent of the original peak activity, the x-ray half-life was found to be 38 ± 2 hours.

The absolute electron capture rate for a sample was determined in the following manner. The area under the pulse height distribution curve was measured. A background originating probably from Compton electrons in the counter was subtracted. The net area remaining is equal to the K x-ray counting rate multiplied by the size of the pulse-height acceptance interval or channel width. The latter quantity was obtained by two independent methods. One was essentially to put into the analyzer pulses of uniform height from a generator and to see over what range in channel position the pulses were accepted. Figure 2 shows the ratio of the observed channel rate to input rate as a function of channel position. The channel width was taken as the width of a rectangle having the same height and area as the curve. The second method was to set the measured area under a curve for Fe^{55} (no gamma-rays) equal to the total counting rate observed; i.e., all pulses above noise, multiplied by the channel width. The two width measurements agreed within one percent. For the Ni^{57} sample the counting rate thus calculated was converted to an absolute capture rate by corrections for geometrical efficiency, absorption in air and in the beryllium window, fluorescence yield,[6] and counter efficiency. The last quantity, about 0.90 for the counter used, is simply the fraction of the x-rays absorbed by the counter gas in the average path. For quanta in this energy range absorbed in argon, processes other than photoelectric ones may be neglected.

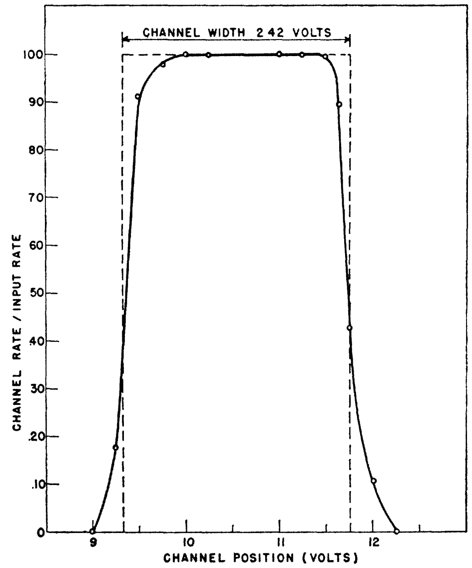

FIG. 2. Measurement of channel width of pulse-height analyzer.

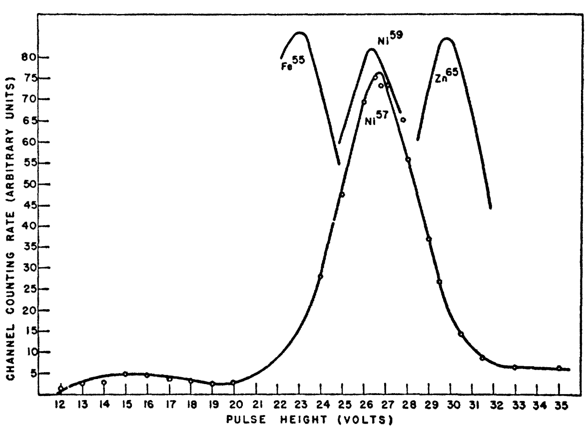

FIG. 1. Observed peak positions for the x-rays emitted by Fe^{55}, Ni^{57}, Ni^{59}, and Zn^{65}.

III. BETA- AND GAMMA-RAY MEASUREMENTS

Absorption of the radiations with detection by end-window and windowless counters demonstrated the presence of a component, probably Auger electrons, completely removed by aluminum 0.2 mg/cm^2 thick. The aluminum end point of the positron activity was at 263 mg/cm^2, equivalent to 0.78 Mev as determined by Feather analysis[7] with Na^{22} (0.55 Mev) as the standard. A small x-ray contribution to the Geiger counting rate was corrected for with the aid of the result of a beryllium absorption experiment. Measurements with a mica-window counter in a magnetic field

[6] Steffen, Huber, and Humbel, Helv. Phys. Acta **22**, 167 (1949).
[7] Macklin, Lidofsky, and Wu, Phys. Rev. **78**, 318A (1950).

gave no evidence for the presence of negative electrons. Examination of the radiations from a source approximately 0.5 mg/cm^2 thick in a lens-type beta-ray spectrometer showed the positron energy to be 0.845±0.010 Mev. A line of electrons, very weak in intensity (less than one percent of the positron activity) was observed at 114 kev; these may be interpreted as K-conversion electrons of a 120-kev gamma-ray. A Fermi-Kurie plot (Fig. 3) shows that the positron spectrum is simple and has an allowed shape.

The source was not sufficiently active to allow detection in the spectrometer of the gamma-rays accompanying the decay of Ni^{57} by means of photo-electrons ejected from a radiator. The energy of some of the Ni^{57} gamma-rays was determined to be between 1.7 and 2.2 Mev by the facts that they produce photo-neutrons in beryllium but not in deuterium. The half-thickness for the absorption of these gamma-rays in lead is 15.7 g/cm^2, which corresponds to an energy of 2.0 Mev. Measurements were made also with a variably biased scintillation counter; by comparison of the bias curves for the hard gamma-rays of Ni^{57}, Pr^{144} (2.19 Mev),[8] Sb^{124} (1.7 Mev),[3] and Co^{60} (1.17 and 1.33 Mev),[3] the energy of the Ni^{57} gamma-rays was determined to be 1.9±0.1 Mev, in agreement with an earlier measurement.[4] Absorption in lead of the Ni^{57} gamma-rays with scintillation counter detection demonstrated that, in addition to the 1.9-Mev gamma-rays and annihilation radiation, softer radiations are also present whose absorption characteristics are compatible with an energy of 120 kev. The presence of still another low energy component cannot be excluded.

The beta- and gamma-activities were followed separately for 10 to 15 days. They decayed with half-lives of 36.2±1 and 36.6±1 hours, respectively. In the spectrometer it was determined that the 114-kev line decays with approximately the same half-life as the positron activity.

For the same Ni^{57} sample for which the electron capture rate was measured, an absolute beta-disintegration rate was determined by correction[9] of the measured Geiger activity for solid angle, absorption in air and counter window, backscattering, coincidence loss, and x- and gamma-activities. The ratio of positron decay rate to the simultaneous K-capture rate is 1.0±0.1.

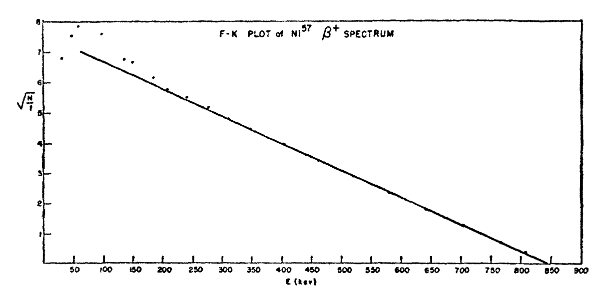

FIG. 3. Fermi-Kurie plot of the positron spectrum of Ni^{57}.

[8] D. E. Alburger *et al.*, Brookhaven National Laboratory Report 39 (AS-3), 17 (1949).
[9] B. P. Burtt, Nucleonics **5**, No. 2, 28 (1949).

IV. COINCIDENCE MEASUREMENTS

Coincidences were observed from Ni^{57} between counts in a mica-window G-M tube and in a scintillation counter biased so as not to register annihilation radiation. These coincidences, corrected for chance events, confirm the observation of Maienschein and Meem[4] that a hard gamma-ray follows positron emission. This is presumably the 1.9-Mev ray previously mentioned. The coincidence rate per hard gamma for Ni^{57}, corrected for a few $X-\gamma_h$-coincidences, was compared in a fixed geometry with the same quantity for Na^{22}, which decays by emission of a positron followed by one 1.3-Mev gamma-quantum.[10] The ratio

$$\left(\frac{\beta-\gamma_h}{\gamma_h}\mathrm{Na}^{22}\right)\Big/\left(\frac{\beta-\gamma_h}{\gamma_h}\mathrm{Ni}^{57}\right)$$

is 1.95. Here γ_h represents the hard gamma-counting rate, and $\beta-\gamma_h$ the positron-hard gamma-coincidence rate. The result indicates that in the decay of Ni^{57} there is a hard gamma-quantum following both the positron emission and the electron capture processes.

Coincidences were measured between a scintillation counter biased as above and one whose bias was set close to noise level. The ratio

$$\left(\frac{\gamma-\gamma_h}{\gamma_h}\mathrm{Na}^{22}\right)\Big/\left(\frac{\gamma-\gamma_h}{\gamma_h}\mathrm{Ni}^{57}\right)$$

was found to be 1.2; it should have been approximately 2.0 if the only gammas other than the hard ones were from the annihilation of the positrons. This observation of gammas in cascade is in agreement with the work previously cited.[4] The number of gamma-rays in cascade was not determined because the efficiency of the scintillation counter for the softer gammas was not known. An increase in the bias of the lower biased counter made it possible to cut off the softer nuclear gamma-rays, although sensitivity to annihilation radiation remained. Under this condition the ratio

$$\left(\frac{\gamma-\gamma_h}{\gamma_h}\mathrm{Na}^{22}\right)\Big/\left(\frac{\gamma-\gamma_h}{\gamma_h}\mathrm{Ni}^{57}\right)$$

was found to be 2.0 in good agreement with the $(\beta-\gamma_h)/\gamma_h$ experiment. It is thus established that the softer gamma-rays have an energy less than 0.5 Mev, as Maienschein and Meem suggested. The results of the $(\gamma-\gamma_h)/\gamma_h$ experiments with the two different counter biases show that approximately equal numbers of soft gamma-hard gamma- and annihilation quantum-hard gamma-coincidences were observed from the Ni^{57}

[10] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).

sample at the lower bias. Thus, since the counting efficiency for the soft nuclear gammas certainly does not exceed that for annihilation radiation, it may be concluded that Ni^{57} emits at least as many soft gamma-quanta as it does positrons. Some of these soft gamma-rays observed may be the 120-kev gammas whose conversion electrons were observed in the beta-ray spectrometer.

In an attempt to ascertain whether gamma-rays are in cascade in the positron branch of the Ni^{57} decay, coincidences were measured for Ni^{57} and for Na^{22} between a G-M tube and a scintillation counter biased just above noise level. The counters were shielded from each other by a one-inch thickness of lead. Measurements were made both with and without a beryllium absorber for the positrons in front of the mica window of the G-M tube, so that it was possible to correct for gamma- and x-ray counts in the G-M tube and for $X-\gamma$-coincidences. The ratio

$$\left(\frac{\beta-\gamma}{\beta}\mathrm{Ni}^{57}\right)\Big/\left(\frac{\beta-\gamma}{\beta}\mathrm{Na}^{22}\right)$$

was found to be 1.1. The $(\gamma-\gamma_h)/\gamma_h$ result shows that the annihilation quanta and softer gammas of Ni^{57} contribute about equally to the $\gamma-\gamma_h$ coincidence rate and therefore equally to the single rate in the low biased counter. It would thus appear from the value 1.1 for the ratio

$$\left(\frac{\beta-\gamma}{\beta}\mathrm{Ni}^{57}\right)\Big/\left(\frac{\beta-\gamma}{\beta}\mathrm{Na}^{22}\right)$$

that relatively few of the soft gammas of Ni^{57} are in the positron branch of the decay. In fact, because the 1.9-Mev Ni^{57} quanta are counted approximately 5 percent more efficiently than the 1.3-Mev Na^{22} quanta, the ratio should be greater than 1.0 even if no gammas are in cascade in the positron branch of the Ni^{57} decay. Thus it may be concluded that very few, if any, of the positrons are followed by a gamma-ray cascade; this result agrees with the simple shape of the Fermi-Kurie plot for the positrons.

IV. DISCUSSION

For a beta-transition of total energy $m_0c^2+0.84$ Mev the ratio of K-capture to positron emission processes should be 0.8 according to the Fermi theory.[6,11] The experimental value for the over-all ratio of K-capture to positron emission is 1.0. This difference, which we believe to be significant, together with the observation of gamma-gamma-coincidences outside of the main positron branch in the Ni^{57} decay, points to the existence of a low energy transition occurring principally by electron capture. This transition would need to account for approximately one-sixth of all the transitions in order to bring theory and experiment into agreement. From the fact that the number of gamma-hard gamma-coincidences approximately equals the number of annihilation quantum-hard gamma-coincidences it may be inferred that several soft gamma-quanta are in cascade following the low energy K-capture transition.

[11] C. Møller, Physik. Zeits. Sowjetunion **11**, 9 (1937).

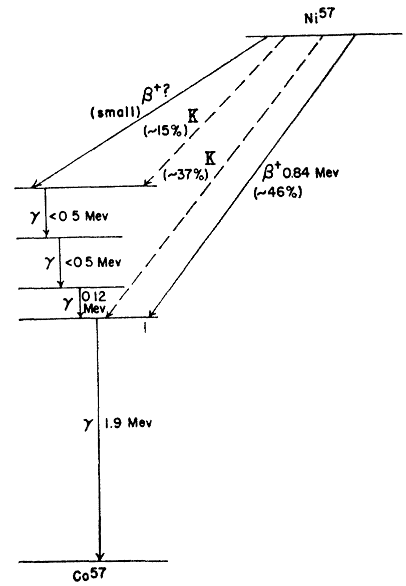

FIG. 4. Partial decay scheme of Ni^{57}. In the cascade, the relative position of the 0.12-Mev gamma-ray is not fixed and the number of low energy gamma-rays may be greater than three.

The data are in agreement with the partial decay scheme given in Fig. 4. This scheme, however, does not seem to be compatible with the assignment of spins and parities in accordance with the selection rules. Additional work on details of the Ni^{57} decay is needed for the determination of a complete scheme.

We are indebted for the cyclotron irradiations to Dr. D. Cowie and Dr. P. Abelson. The gamma-ray energy determinations by the photo-neutron and the biased scintillation counter methods were carried out by Mr. E. der Mateosian. Miss Elizabeth Wilson gave valuable assistance in making some of the measurements.