tinuum state would require, as indicated earlier, the nonorthogonality of the $^3S_1$ continuum and the $^3S_1$ deuteron ground state. Formation of the P wave would appear to require significant departure from the present theory of direct interactions. In any case, possible experimental verification of all the neutron capture occurring via the continuum singlet state should clearly demonstrate that the mechanism leading to the so-called interaction effect must be sorted out in detail or, failing that, a fresh approach may be needed to deal with the electromagnetic phenomenon associated with the two-body nuclear problem.

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Summing-Energy Spectrum of the Beta Particles Plus Emitted K Electrons in the K-Shell Internal Ionization Accompanying the Beta Decay of ^{63}Ni

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Through a new type of experiment to obtain information on the K-shell internal ionization in β decay, the summing-energy spectrum of electrons (β particles plus emitted K-shell electrons) in coincidence with emitted K x rays in the β decay of ^{63}Ni has been observed directly using two proportional counters. The procedure and results are discussed.

This brief note on the direct observation of the spectrum of electrons emitted in the K-shell internal ionization during β decay of ^{63}Ni is an addendum to a recent work by the present authors.[1] In the previous work, the K x rays from the β source mounted inside the electron counter were measured in coincidence with emitted electrons, for seven segments of the β spectrum. From the coincidence x-ray counts, the energy-dependent K-shell internal-ionization probability per β decay, $P_K(E_\beta^0)$, could be obtained as a function of E_β^0, which is defined as the sum of kinetic energies of the β particle, E_β, and the emitted K electron, E_K, plus the K-shell binding energy of the daughter atom, B_K. In the present work, a summing-energy spectrum of $E_\beta+E_K$ has been measured directly in order to obtain more-refined data on the energy-dependent probability $P_K(E_\beta^0)$.

The technique used to prepare the source mounted inside the electron counter is described in the previous paper.[1] The source solution (^{63}NiCl$_2$ in HCl obtained from the Oak Ridge National Laboratory) was purified using a cation-exchange resin column to remove unfavorable trace ions completely, which make the source hygroscopic. Prior to the experiment, a series of sources with various intensities was prepared. These sources were used to examine features of distortion of the β spectrum due to self-scattering and self-absorption of low-energy electrons. A source with intensity 0.12 μCi and average thickness 1 $\mu g/cm^2$ was used in the final measurement. Its Kurie plot agreed well with that obtained by previous workers[2,3] in the energy region above 8 keV.

Detailed descriptions of the two proportional counters for detecting x rays and electrons, the coincidence unit, other electronic devices, and the experimental techniques associated with their use are also given in Ref. 1. In order to measure the electron spectrum in coincidence with Cu K x rays, only signals corresponding to energies of these rays were selected by a single-channel analyzer in the x-ray channel. The selected x-ray signals and all signals from the electron channel were fed to the coincidence unit, the output pulses of which were used to trigger a multichannel pulse-height analyzer to record the electron spectrum.

Prior to the measurement, delayed-coincidence curves were measured for various energy segments of the β spectrum to examine the dependence of the coincidence efficiency on electron energy. All of these curves were found to be flat-topped at the same delay time, when the coincidence resolving time was set at >1.2 μsec. In the final measurements the coincidence resolving time was ~1.5 μsec, which was sufficient to keep the efficiency 100% over the whole range of electron energy.

In Fig. 1, the photon spectrum in coincidence with all electrons with energies 0–70 keV is shown. The Cu K x-ray peak is superimposed on the continuous background, which is due to internal bremsstrahlung accompanying β decay and external bremsstrahlung caused by the interaction of β particles with the counter gas and surrounding materials near the source. When we observe the electron spectrum in coincidence with Cu K x rays only, viz., only with photons in the region labeled T in Fig. 1, the window of the photon channel includes the x-ray peak, but we must eliminate the contribution from false coincidences due to the bremsstrahlung photons in the shaded region A in the figure.[4] The interpolated borderline dividing the regions T and A was estimated by taking the general appearance of the bremsstrahlung spectrum into account. The contribution from false coincidences due to bremsstrahlung photons of the region A can be deduced from two electron spectra, $W_B(E)$ and $W_C(E)$, observed in coincidence with photons in the neighboring regions B and C, provided that the ratio of number of the observed electron counts in $W_B(E)$ to that in $W_C(E)$ is constant for any electron energy E. This condition was verified experimentally in the whole region except above 50 keV; the ratio was found to be given by a value nearly equal to the ratio of number of photon counts in the region B to that in the region C.

We can therefore derive the summing-energy spectrum of electrons (β particles and emitted K electrons) in coincidence with Cu K x rays only from the expression

$$W_K(E) = W_{A+T}(E) - \left[\frac{S_A - S_C}{S_B - S_C} W_B(E) + \frac{S_B - S_A}{S_B - S_C} W_C(E)\right], \tag{1}$$

where S_A, S_B, and S_C are the numbers of photon counts in the regions A, B, and C, respectively, and $W_{A+T}(E)$ is the electron spectrum in coincidence with photons corresponding to the region A + T; we have $E = E_\beta + E_K$. In this expression, the terms in square brackets represent the electron spectrum in coincidence with photons in the region A, i.e., the contribution from false coincidences with photons of the background bremsstrahlung. From observations of the three electron spectra $W_{A+T}(E)$, $W_B(E)$, and $W_C(E)$, and estimated values of S_A, S_B, and S_C, we could obtain the electron spectrum to be studied, $W_K(E)$. The result is shown in Fig. 2. The errors shown are mainly due to the statistical counting errors of $W_{A+T}(E)$, $W_B(E)$, and $W_C(E)$ and to the uncertainty

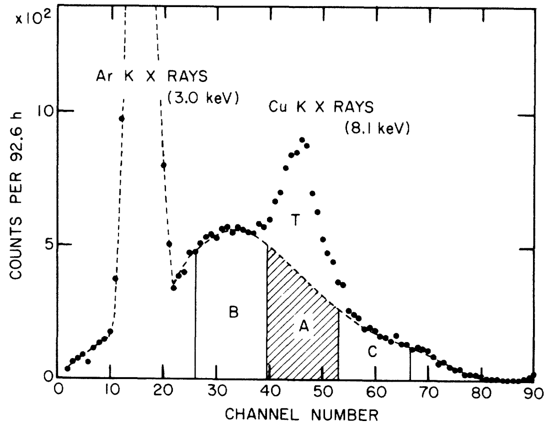

FIG. 1. Photon spectrum from the ^{63}Ni source observed by the x-ray proportional counter in coincidence with all electrons emitted from the source with energies less than 70 keV. The 8.1-keV Cu K x rays resulting from the K-shell internal ionization are superimposed on the bremsstrahlung spectrum. A peak evident at 3.0 keV is due to the Ar K x rays from ionization of the counter gas by β particles.

in the borderline between the Cu K x-ray peak and the background continuum.

Utilizing the spectrum $W_K(E)$ thus obtained, we can easily derive the experimental energy-dependent probability per β decay, $P_K(E_\beta^0)$, from the following equation:

$$P_K(E_\beta^0) = \frac{W_K(E_\beta^0)}{W_\beta(E_\beta = E_\beta^0)} \frac{1}{D\omega_K}. \tag{2}$$

Here, $W_K(E_\beta^0)$ is the absolute internal-ionization transition probability as a function of $E_\beta^0 = E + B_K$, and $W_\beta(E_\beta)$ is the ordinary β-decay probability. The quantity D is the effective detection efficiency of the photon counter, and ω_K is the K-shell fluorescence yield of the daughter atom, Cu; for these values, we adopted $D = (1.56 \pm 0.15) \times 10^{-2}$ and $\omega_K = 0.45$, as in our previous work.[1] $W_K(E_\beta^0)$ can be obtained by shifting the measured spectrum $W_K(E = E_\beta + E_K)$ by the K-shell binding energy of the daughter atom, Cu, $B_K = 9.0$ keV, because $E_\beta^0 = E + B_K$. For $W_\beta(E_\beta = E_\beta^0)$ we used the ordinary β-ray spectrum observed by the present electron counter having the source in it. In the observation of both $W_K(E = E_\beta + E_K)$ and $W_\beta(E_\beta = E_\beta^0)$, rigorous energy calibration for signals from the electron channel should be required. Since a slight decrease (~5%) of the amplitude of the output signals due to distortion of the electric field in the electron counter by the inserted source-supporting device was found, the calibration was performed with and without this inserted system, using nuclides emitting x rays and/or conversion electrons. The measured values of $P_K(E_\beta^0)$ are shown in Fig. 3. The errors are due to those in $W_K(E)$ and in the detection efficiency D.

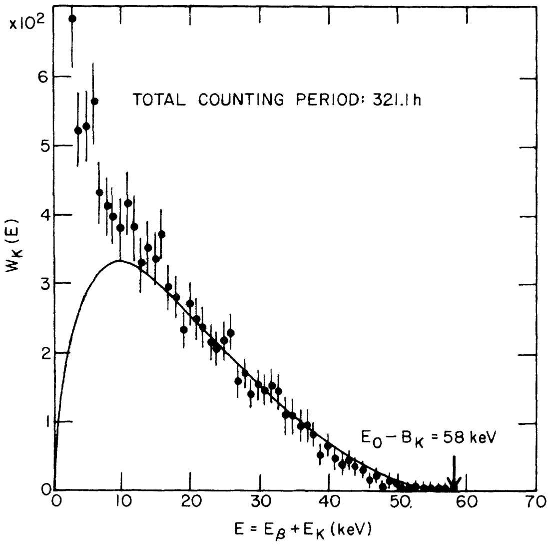

FIG. 2. Measured summing-energy spectrum of β particles plus K electrons emitted in the K-shell internal ionization of ^{63}Ni. The solid curve represents the theoretical curve calculated from Eq. (3).

Our experimental results were compared with the calculated values, which are shown by solid curves in Figs. 2 and 3. On the basis of the one-step theory by Stephas and Crasemann,[5,6] the shape of the summing-energy spectrum $W_K(E = E_\beta + E_K)$ can be expressed as

$$W_K(E = E_\beta + E_K) \propto \int_0^E S(E_\beta, E_0 - E_\beta^0) F(Z+1, E_\beta) \times |M_A|^2 p_\beta (E_\beta + 1)(E_0 - E_\beta^0)^2 dE_K. \tag{3}$$

Here, all symbols are defined as in our previous paper.[1] The values of $P_K(E_\beta^0)$ were calculated by Eq. (13) in Ref. 1. In these calculations, we assumed an allowed-type spectrum for ^{63}Ni, i.e., $S(E_\beta, E_0 - E_\beta^0) = 1$ and $\epsilon = \frac{1}{2}$. For the squared matrix element $|M_A|^2$, we used the result of the calculation by Stephas and Crasemann[6] using relativistic hydrogenic wave functions [see Eq. (5) in Ref. 6]. However, because of a singularity arising from a term $p_K^{2(1+\gamma-\gamma')}$ in this $|M_A|^2$, integrals in $W_K(E)$ and $P_K(E_\beta^0)$ always diverge to infinity. In the present calculation, this diverging term was omitted.[7]

As can be seen in Fig. 2, the measured spectrum $W_K(E)$ agrees fairly well with the theoretical curve in the energy region above 15 keV. However, the measured values deviate from the calculated ones in the region below 15 keV; the discrepancy becomes larger with decreasing energy E. This deviation is caused by self-scattering and self-absorption of electrons in the source. Since K-shell electrons are always emitted with rather low kinetic energies (average energy ~9 keV) in this process, it is understandable that the sum-

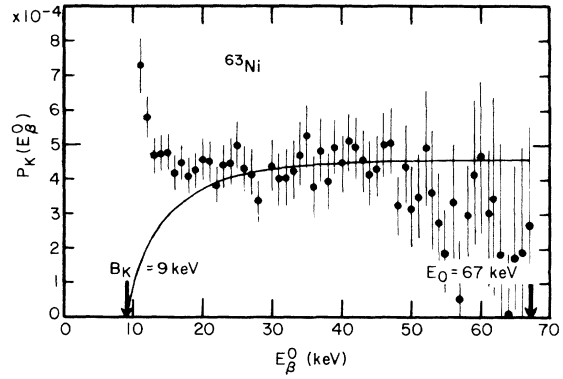

FIG. 3. Measured energy-dependent K-shell internal-ionization probability $P_K(E_\beta^0)$ for ^{63}Ni. Vertical bars indicate standard deviations. The solid curve represents the theoretical curve calculated according to Eq. (13) in Ref. 1.

ming-energy spectrum in the low-energy region is distorted more conspicuously than the single β spectrum. The effect of distortion due to low emitted K-electron energies is remarkably apparent in the E_β^0-dependent probability $P_K(E_\beta^0)$, as shown in Fig. 3. The measured values deviate from the theoretical curve in the low-energy region below 25 keV as well as in the high-energy region above 50 keV. The tendency toward low measured values in the higher-energy region is also caused by the effect of source thickness on the low-energy emitted K electrons. It should be added here that the lowest datum of $P_K(E_\beta^0)$ for ^{63}Ni obtained in our previous work[1] is less trustworthy and its deviation from the theory can be explained by this effect (see Fig. 9 in Ref. 1).

The present experiment for the direct observation of the summing-electron spectrum in coincidence with K x rays illustrates a useful method for studying K-shell internal ionization in β decay. However, some improvements could be made in this method. Thinner sources prepared by vacuum evaporation, or gaseous sources, are desirable. The use of a Si(Li) detector with higher energy resolution as the x-ray detector would reduce the error due to bremsstrahlung.

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[7] This difficulty in $|M_A|^2$ is caused by an approximation made in the calculation by Stephas and Crasemann. They set $1+\gamma-\gamma'=1$ in the contour integral of Eq. (8) in Ref. 5. We have successfully derived the atomic matrix element M_A without any approximation. Calculations of the summing-energy spectrum $W_K(E)$ and the energy-dependent probability $P_K(E_\beta^0)$ using our exact matrix element are now in progress.