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Decay of A^{35}†

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The positron decay of A^{35} has been investigated with a magnetic lens beta-ray spectrometer and a NaI(Tl) scintillation spectrometer. A maximum beta-ray energy of 4.96±0.04 Mev was found, which is 0.5 Mev higher than the previous values determined by cloud-chamber measurements. The new value is in good agreement with the end point predicted from Coulomb energy considerations. Two weak gamma rays were found with energies of 1.19±0.04 and 1.73±0.04 Mev; both are in good agreement with reported levels in Cl^{35}. Analysis of the complex beta spectrum shows that approximately 7% of the A^{35} decays to two excited states in Cl^{35}. The ft value of the ground-state, mirror transition is 6200±400 seconds. From this ft value and the ft value of O^{14}, the $|\int\sigma|^2$ for this transition was estimated to be less than 0.13; the e-ν angular correlation coefficients were calculated to be $+0.96\pm0.04$ and -0.93 ± 0.09 for the V, T and S, T beta interactions, respectively. These coefficients are indistinguishable from those expected in the case of a pure Fermi transition, indicating that A^{35} would be very suitable for identifying the Fermi invariant in the beta-decay interaction by an angular correlation experiment.

INTRODUCTION

The monatomic gas, A^{35}, has been considered suitable for electron-neutrino (e-ν) angular correlation experiments[1] for the purpose of identifying the form of the Fermi invariant in the beta-decay interaction.[2] Its maximum recoil energy is high, and the decay to the ground state is a $\frac{3}{2}$-$\frac{3}{2}$ mirror transition for which the Fermi matrix element can be calculated. No investigation, however, of the shape of the beta spectrum or search for gamma rays to determine whether the decay is simple or complex has been reported.

The maximum beta energy has been previously measured by cloud-chamber techniques as 4.4 Mev.[3,4] This value, together with the half-life of 1.88±0.04 seconds,[3] gives a comparative half-life of approximately 3400 seconds. The beta end-point energy predicted by the semiempirical, Coulomb energy formula of Peaslee[5] is 0.5 Mev higher than the cloud chamber values. This disagreement is well outside of the errors assigned to either determination. The investigations of the comparative half-life systematics for mirror image transitions by Trigg[6] and the B-x diagrams of Winther and Kofoed-Hansen[7] both indicate that the comparative half-life of A^{35} is too small.

It was desirable for these reasons to investigate the decay scheme of A^{35} and to redetermine the maximum beta energy with greater precision. The beta spectrum was measured with a magnetic thin-lens spectrometer, and the gamma spectrum was observed with a NaI(Tl) scintillation spectrometer. With the new ft value obtained for the A^{35} mirror transition, an estimate was made of the upper limit of the Gamow-Teller matrix element, and the e-ν angular correlation coefficients were calculated for the V,T and S,T forms of the beta decay interaction.

PRODUCTION OF A^{35}

The A^{35} was produced for this experiment by the reaction $Cl^{35}(p,n)A^{35}$. Liquid carbon tetrachloride was bombarded with 10-Mev protons from the Brookhaven 60-inch cyclotron. No significant competing reactions were expected at this energy. Because the half-life of A^{35} is relatively short, the gas had to be produced and delivered to the experimental apparatus continuously during the measurements. Figure 1 is a schematic diagram of the target chamber and gas delivery system. The external proton beam from the cyclotron, which had an average intensity of 60 microamperes, entered the brass target vessel through a 0.0015-inch, tempered Duralumin window. The escape of the radioactive gas from the carbon tetrachloride was aided by localized boiling resulting from the power dissipated by the 600-watt proton beam in the immediate vicinity of A^{35} production. The vapor from the liquid target swept the

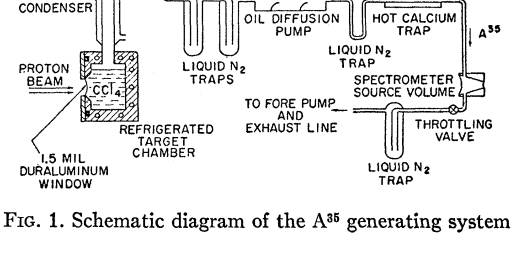

Fig. 1. Schematic diagram of the A^{35} generating system.

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† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] D. C. Peaslee, Phys. Rev. **89**, 1148 (1953).

[2] Electron-neutrino angular correlation experiments with Ne^{19} by Maxon, Allen, and Jentschke [Phys. Rev. **97**, 109 (1955)] and W. P. Alford and D. R. Hamilton [Phys. Rev. **94**, 779 (1954)], and with the neutron by J. M. Robson [Phys. Rev. **100**, 933 (1955)] indicate that the Fermi invariant is probably scalar.

[3] D. R. Elliott and L. D. P. King, Phys. Rev. **59**, 403 (1941).

[4] M. G. White *et al.*, Phys. Rev. **59**, 63 (1941).

[5] D. C. Peaslee, Phys. Rev. **95**, 717 (1954).

[6] George L. Trigg, Phys. Rev. **86**, 506 (1952).

[7] A. Winther and O. Kofoed-Hansen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 27, No. 14 (1953).

A^{35} from the target chamber and through 50 feet of $\frac{1}{4}$-inch copper tubing leading from the cyclotron vault to the experimental area. The temperature of the target vessel and associated reflux condenser was maintained at -5°C to control the rate of evaporation of the carbon tetrachloride.

Because a pure source of A^{35} was desired at low pressure, the carbon tetrachloride vapor and other condensable impurities were removed from the gas stream by a pair of liquid nitrogen traps. The remaining gas was compressed with an oil diffusion pump and passed through a smaller liquid nitrogen trap and a hot calcium trap for further purification before going to the source volume. The transit time of the gas through the entire system was approximately 3 to 4 seconds, or about two half-lives of the activity.

HALF-LIFE

The source volume for the half-life and gamma-spectrum measurements consisted of a cylindrical 15 cc plastic volume with 8-mg/cm² Duralumin end windows. The radioactive gas could be isolated in the volume by means of a pair of solenoid-actuated toggle valves. For the half-life determination the activity was detected with a plastifluor scintillation counter, and the output of the scaler was recorded with a fast pen oscillograph. The half-life obtained by averaging the results of 24 decay curves is 1.83 ± 0.03 seconds, which is in good agreement with the previously reported value.[3] The logarithmic decay curve is linear for at least five half-lives, showing no indication of other activities.

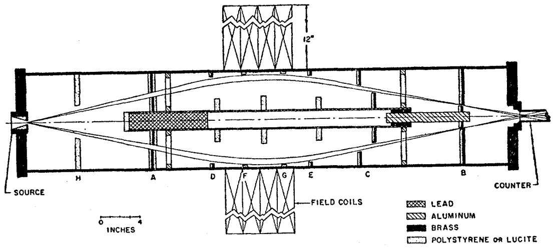

FIG. 2. Schematic diagram of the baffle system for the thin-lens spectrometer.

BETA-RAY SPECTRUM

A conventional thin-lens, iron-free, magnetic spectrometer of the type described by Hornyak, Lauritsen, and Rasmussen,[8] was used to measure the beta spectrum. The baffle system was revised so as to reduce low-energy scattering, and a gaseous source volume was constructed. Figure 2 shows a schematic diagram of the baffle system. Baffles *A-E* consisted of $\frac{1}{8}$-inch brass covered with $\frac{1}{4}$-inch polystyrene, as shown in the diagram. Baffles *F-H* were made of $\frac{1}{2}$-inch Lucite. The beam through the spectrometer was defined by the entrance aperture *A*, and the ring focus slit, *B*. The edges of all other baffles were outside of the beam trajectory. Baffles *D-G* prevented electrons scattered at small angles from the brass walls of the spectrometer tube from entering the beam. The central shaft of the baffle system was made of aluminum tubing filled with lead at the source end.

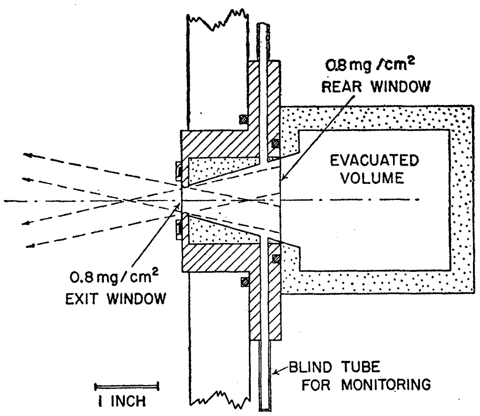

FIG. 3. Gaseous source volume for the thin-lens spectrometer.

A scale drawing of the gaseous source volume for the spectrometer is shown in Fig. 3. Particular care was taken to minimize source scattering effects. The walls of the volume were constructed of polystyrene and tapered so that scattered electrons could not enter the spectrometer beam, which is indicated in the figure by the broken lines. The exit window and rear surface consisted of 0.8-mg/cm² aluminized Mylar film. The exit aperture was made of brass which was thick enough to stop 5.5-Mev beta rays. A blind tube leading out of the volume provided a source for monitoring the gaseous activity in the volume. The known beta spectra of A^{41}, He^6, and P^{32} have been measured with this source volume and baffle arrangement, and the Kurie plots were linear down to less than 300 kev. The agreement of the end points of these beta emitters with the known values showed that the calibration of the spectrometer for gaseous sources is the same as for extended, thin, solid sources placed at the median plane of the source volume.

The beta spectrum of A^{35} was measured with a resolution of approximately 3%. The spectrometer was calibrated with 975.9-kev conversion electrons[9] from an extended source of Bi^{207} placed at the median plane of the source volume. The source, which was electroplated onto a thin copper foil, was kindly prepared for us by D. Alburger. The Kurie plot of the beta spectrum is shown in Fig. 4. The deviation from linearity at about 3.5 Mev indicates the presence of lower-energy groups.

GAMMA-RAY SPECTRUM

The gamma activity was measured with a $1\frac{3}{4}$- by 2-inch NaI(Tl) crystal scintillation counter, and the

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[8] Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).

[9] D. E. Alburger, Phys. Rev. **92**, 1257 (1953).

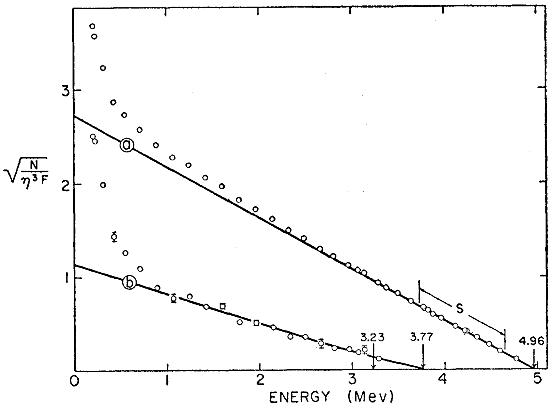

FIG. 4. Kurie analysis of the complex positron spectrum of A^{35}. Curve (a) is a weighted least-squares fit to the points in the region *S*. Curve (b) is the theoretical Kurie plot of a complex spectrum containing 2% and 5% of the 3.23-Mev and 3.77-Mev beta groups, respectively.

pulse-height distribution was analyzed and recorded on a 20-channel pulse-height analyzer. The spectrometer was calibrated with the 1.277-Mev gamma ray from Na^{22} and the 1.368- and 2.754-Mev gamma rays from Na^{24}. Peaks were found in the gamma spectrum, shown in Fig. 5, at 1.19±0.04 and 1.73±0.04 Mev in addition to the 0.51-Mev annihilation peak and the 0.70-Mev annihilation pair coincidence peak. Two tests were made to establish that the two higher energy peaks were due to real gamma rays from A^{35}. The spectrum was remeasured with lead absorbers placed between the source and detector. The resulting relative attenuation of the peaks agreed with that expected for the assigned energies showing that they were not due to coincidences between an annihilation quantum and a lower energy gamma ray. A time-delayed spectrum was taken by isolating the source volume and allowing the A^{35} to decay for 10 seconds before counting was started. The spectrum obtained from several such runs did not show the presence of the above peaks, thereby eliminating the possibility that they were due to a long-lived contaminant which escaped detection in the half-life curves.

The peak at about 0.7 Mev is attributed to a coincidence between a pair of annihilation quanta, one entering the crystal directly and the other Compton-scattered through 180° by the shielding around the source volume. As was expected, this peak disappeared when lead absorbers were used. A similar peak was also observed in the gamma spectrum of positron active Cu^{64} when measured under similar geometric conditions.

The 1.19-Mev gamma ray was estimated to be two to four times as intense as the 1.73-Mev gamma ray. More accurate measurements of the absolute gamma-ray intensities from the scintillation spectrum were not attempted because of the intense bremsstrahlung background and the difficulty in duplicating the source geometry when calibrating the efficiency of the crystal.

DECAY SCHEME AND COMPARATIVE HALF-LIFE

The energies of the gamma rays observed from the decay of A ^{5} are in agreement, within the experimental errors, with levels reported in Cl^{35} at 1.22 and 1.76 Mev from inelastic proton scattering experiments.[10,11] This indicates that both gamma rays represent transitions to the ground state and are not in cascade. The beta spectrum may therefore be expected to contain, in addition to the ground-state transition group, a 3.23-Mev group and a 3.77-Mev group.

A weighted least-squares fit to the portion of the Kurie plot extending above 3.77 Mev over the region indicated in Fig. 3, gives an end point of 4.96±0.04 Mev for the ground state transition. After the subtraction of this group, the Kurie plot of the remaining spectrum fits a straight line which intersects the abscissa between the end points of the two possible lower groups predicted by the gamma-ray energies, which indicates that both groups are probably present. This composite Kurie plot of the lower groups represents 7±2.5% of the total number of A^{35} decays, where the error is a conservative estimate based on the statistical errors in the background correction and the least-squares fit. The fit of the data is not very sensitive to the relative ratio of these two groups as long as the total percentage is kept constant. Consideration of the probabilities of the possible multipole transitions, consistent with the ratio of the gamma-ray intensities and the total percentage of the lower beta groups, shows that a 0.54-Mev gamma ray in cascade with the 1.19-Mev gamma ray could not account for a significant fraction of the observed relative intensity of the latter. The ratio of the intensities of the two lower beta groups are, therefore, given directly by

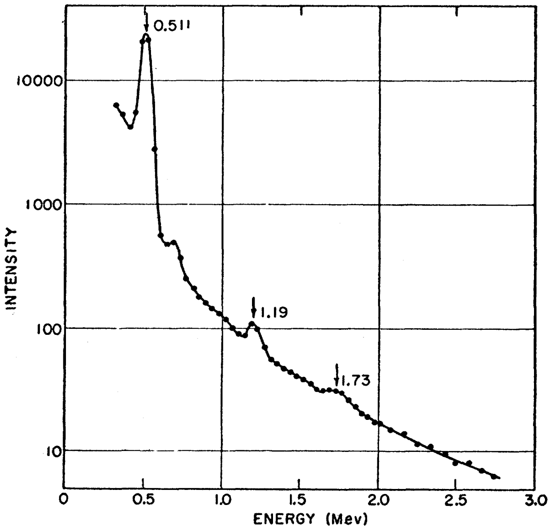

FIG. 5. Gamma spectrum of A^{35}.

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[10] Van Patter, Swann, Porter, and Mandeville, Bull. Am. Phys. Soc. Ser. II, 1, 39 (1956).

[11] Endt, Paris, Sperduto, and Buechner, Bull. Am. Phys. Soc. Ser. II, 1, 223 (1956).

the observed ratio of the intensities of the gamma rays. The resulting intensities are 2±1% and 5±2% for the 3.23-Mev and 3.77-Mev beta groups, respectively.

The upward deviation below 0.9 Mev is larger than can be accounted for by additional transitions to higher levels reported in Cl^{35} by Endt *et al.*[11] and is attributed to scattering processes occurring in the source and baffles. It should be noted that there may be a slight contribution from this low-energy scattering to the beta spectra of the lower groups which would favor the negative error in the above percentages.

From these data, the ft value of the ground state transition is 6200±400 seconds. The $\log ft$ values of the 3.23-Mev and 3.77-Mev beta groups are 4.7±0.3 and 4.5±0.2, respectively, which are consistent with those found for unfavored allowed transitions. A proposed decay scheme for A^{35} is shown in Fig. 6.

DISCUSSION

The observed end point of 4.96±0.04 Mev for A^{35} is in excellent agreement with the value, 5.02±0.17 Mev, predicted by Peaslee's semiempirical Coulomb energy relation for light $(4n+3)$ nuclei,[5] where the error is the root-mean-square deviation of the experimental decay energies for other nuclei of this series. The ft value of 6200 seconds calculated from this new end-point energy is nearly twice the previous value of 3400 seconds.

An upper limit of the Gamow-Teller matrix element for the ground state transition of A^{35} can be calculated from its ft value, the ft value of the $0\rightarrow 0$ transition of O^{14} (3275±75 seconds),[12] and an upper limit for the ratio of the Fermi and Gamow-Teller coupling constants, C_F^2/C_{GT}^2. The ft value for a given allowed beta transition, ξ, is related to the matrix elements and coupling constants by the expression

$$\text{const}=(ft)_\xi\left[C_F^2\left|\int 1\right|_\xi^2+C_{GT}^2\left|\int\sigma\right|_\xi^2\right]. \tag{1}$$

The squares of the Fermi matrix element, $|\int 1|^2$, are 2 and 1 for the O^{14} and A^{35} transitions, respectively[6,7]; the Gamow-Teller component, $|\int\sigma|^2$, is zero for the O^{14} transition. Solution of the two resulting equations yields

$$\left|\int\sigma\right|_{A^{35}}^2=\frac{C_F^2}{C_{GT}^2}(0.06_{-0.06}^{+0.07}). \tag{2}$$

Recent evaluations of the ratio of the coupling constants indicate that its value is probably less than one.[12,13] With this as an upper limit, $|\int\sigma|^2$ for A^{35} is less than 0.13.

This upper limit of $|\int\sigma|^2$ for A^{35} is considerably smaller than the theoretical values of 0.32 and 0.60 predicted by the single-particle models for jj and LS coupling, respectively.[14] It is, however, consistent with the values[6,7] of 0.1 and 0.15 calculated from models where the odd particle shares its angular momentum to some extent with the rest of the nucleus, as determined by the deviation of the magnetic moment from the Schmidt limits.

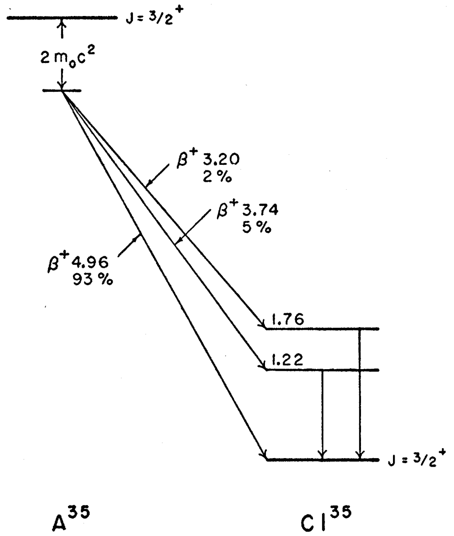

FIG. 6. Decay scheme of A^{35}. The energies assigned to the levels in Cl^{35} are the more accurate values reported from inelastic proton scattering experiments.

The relatively small amount of Gamow-Teller component present in the decay of A^{35} will have very little effect on the results of an e-ν angular correlation experiment for determining the Fermi invariant. The Gamow-Teller interaction has been shown to be predominantly tensor by e-ν experiments on He^6.[15,16] On the assumption that there is no intermixing of the Fermi invariants,[17] the angular correlation coefficient[18] for a simple allowed transition is

$$\lambda=\frac{\left(\frac{1}{3}C_T^2\left|\int\sigma\right|^2\mp C_F^2\left|\int 1\right|^2\right)}{\left(C_T^2\left|\int\sigma\right|^2+C_F^2\left|\int 1\right|^2\right)}, \tag{3}$$

where the minus and plus signs apply to the cases of scalar and polar-vector for the Fermi interaction, respectively. This coefficient can be evaluated for the A^{35} ground state transition in terms of the Fermi matrix elements and ft values for O^{14} and A^{35} by use of

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[12] J. B. Gerhart, Phys. Rev. **95**, 288 (1954).

[13] J. M. Blatt, Phys. Rev. **89**, 83 (1953).

[14] M. Goeppert-Mayer, in *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 450.

[15] B. M. Rustad and S. L. Ruby, Phys. Rev. **97**, 991 (1955).

[16] J. S. Allen and W. K. Jentschke, Phys. Rev. **89**, 902 (1953).

[17] Pohm, Waddell, and Jensen, Phys. Rev. **101**, 1315 (1956).

[18] S. R. deGroot and H. A. Tolhoek, Physica **16**, 456 (1950).

expression (1).[19] The resulting values of λ for the S,T and V,T admixtures are

$$\lambda_{S,T}=-0.93\pm0.09,$$
$$\lambda_{V,T}=+0.96\pm0.04.$$

These quantities are indistinguishable from the case of a pure Fermi transition, which would yield values of either -1 for the scalar invariant or $+1$ for the vector invariant. The A^{35} mirror transition is, therefore, considerably more favorable for a recoil experiment than was previously indicated by the values, $\lambda_{S,T}=-0.36$ and $\lambda_{V,T}=0.68$, calculated from the old ft value of 3400 seconds. An experimental measurement of λ for A^{35}, however, would have to be corrected for the weak lower beta groups before the results could be compared with the above predictions.

ACKNOWLEDGMENTS

We are indebted to Dr. David Alburger for his generosity in lending us the thin-lens spectrometer and for the preparation of electroplated Bi^{207} sources. We thank Dr. O. Kofoed-Hansen for his advice and assistance in the experiments. We are grateful to Professor W. W. Havens, Jr., and Professor C. S. Wu for their encouragement and many helpful suggestions. Finally, it is a pleasure to acknowledge the hospitality of Brookhaven National Laboratory, in particular Dr. C. P. Baker and the cyclotron staff for their assistance and cooperation in providing cyclotron bombardments.

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[19] This method of predicting the angular correlation coefficient was suggested by D. C. Peaslee.

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Radiative Capture of Orbital Electrons

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A theory is developed of the continuous radiation spectrum which accompanies nuclear capture of atomic electrons. It is shown that quantitative predictions of the spectrum intensities must take into account the influence of the electrostatic field of the nucleus on the radiation process. This is accomplished by evaluating and making use of a particularly simple form of the Green's function for electron propagation in a Coulomb field. In a first approximation which treats the atomic electrons nonrelativistically, the spectra radiated by electrons captured from S-states are shown at all energies to have the form $x(1-x)^2$, where $x=E/E_{\max}$. Radiative capture of electrons from P-states is shown to produce a spectrum which becomes extremely intense at low energies, where it merges continuously with the characteristic x-ray spectrum. Certain relativistic corrections to the S-state radiative capture probabilities are evaluated and shown to bring about an energy-dependent reduction of the intensities of the corresponding spectra. Functions are tabulated from which the spectra for allowed capture from various orbital states of any element may be determined. The calculated spectra are found to be in satisfactory agreement with those observed experimentally. In particular, the unexpectedly high intensities found at low γ-ray energies are explained by the radiatively induced capture of electrons from P states.

1. INTRODUCTION

ALTHOUGH capture of orbital electrons is one of the more common forms of nuclear decay, the indirect nature of the methods by which it has been detected has limited its usefulness as a source of nuclear data. In particular the usual observation of the process by means of the subsequently emitted x-rays or Auger electrons has contributed only a knowledge of decay lifetimes. The efficient analysis of nuclear γ radiation, which has recently become practicable, makes possible a much more direct means for studying orbital capture. This method takes advantage of the radiation which is emitted in a certain fraction of the decay processes as a result of sudden acceleration of charge and magnetic moment. Although such radiation is weak in intensity, an emitted photon shares the large energy which is released by the capture, an energy which would otherwise be carried off entirely by the neutrino. The continuous γ-ray spectra which result bear an analogy to the electron spectra of β decay. They may be expected to furnish corresponding information on energy releases and changes of spin and parity.

An early calculation of the radiation to be anticipated in K capture was made by Morrison and Schiff.[1] They predicted that the intensity distribution would have the form $x(1-x)^2$, where x is the ratio of the γ-ray energy to the energy released in the reaction. The observed spectra show a considerably larger number of low-energy γ rays than this form predicts. In particular, in every element for which the spectrum is known down to energies approaching the characteristic x-ray region,

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[1] P. Morrison and L. I. Schiff, Phys. Rev. 58, 24 (1940).