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Internal Bremsstrahlung from P^{32}†

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The spectral distribution of the internal bremsstrahlung associated with the beta decay of P^{32} has been measured with a NaI scintillation spectrometer from 80 to 900 kev. The shape of the experimental spectrum is compared with the theoretical distribution, corrected for detector response, for three different beta interactions: (1) allowed; (2) first-forbidden; scalar; (3) first-forbidden; tensor; $\Delta J=2$, yes. The results show that of these interactions, only the allowed case gives a theoretical curve within the estimated error (10 percent) of the experimental points over the entire range of energy.

I. INTRODUCTION

THE theory of the energy distribution and intensity of the internal bremsstrahlung (I.B.) accompanying beta decay, given independently by Bloch[1] and Knipp and Uhlenbeck,[2] and extended by Chang and Falkoff[3] to forbidden beta transitions has proved, within the limitations of experiments to date, to be essentially correct. The calculations of Chang and Falkoff as well as those of Bolgiano, Madansky, and Rasetti[4] indicate that the shape of the I.B. spectrum depends only slightly on the degree of forbiddenness of the beta transition. In general this dependence is negligible at the low energies, increases to a maximum at intermediate energies and decreases again as the transition energy is approached, as we show later.

Thus far the measurements on the I.B. spectrum have been made at the low-energy end where the dependence on forbiddenness is small. Consequently, it has been difficult to determine unambiguously whether the spectrum actually follows the theoretical curves for the appropriate degree of forbiddenness as determined from beta-ray and related measurements. In the case of P^{32}, (beta-ray end point 1.7 Mev) which is known to have an allowed shape for the beta spectrum and is designated an L-forbidden decay,[5] the I.B. spectrum has been carefully examined from 3 kev to 250 kev by Bolgiano, Madansky, and Rasetti,[4] by Renard[6] and by Novey.[7] Within the accuracy of the experiments, the I.B. spectrum fits the allowed case.

In the present paper the authors report measurements of the I.B. spectrum of P^{32} out to 900 kev and compare the shape of the curve with calculations for the allowed and first-forbidden cases out to these energies where the difference in the two theoretical curves should be experimentally measurable.

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[1] F. Bloch, Phys. Rev. **50**, 272 (1936).
[2] J. K. Knipp and G. E. Uhlenbeck, Physica **3**, 425 (1936).
[3] C. S. Wang Chang and D. L. Falkoff, Phys. Rev. **76**, 365 (1949).
[4] Bolgiano, Madansky, and Rasetti, Phys. Rev. **89**, 679 (1953).
[5] L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).
[6] G. A. Renard, J. phys. radium **14**, 361 (1953).
[7] T. B. Novey, Phys. Rev. **89**, 672 (1953).

II. EXPERIMENTAL ARRANGEMENT

The spectrum was measured with the same scintillation spectrometer used in our previous work on P^{32}.[8] It is of the Jordan and Bell[9] type and employs a $1\frac{1}{2}$ in. diameter by 1 in. long NaI(Tl) crystal with a Dumont K1186 photomultiplier. The pulses, after amplification in a linear amplifier, are analyzed with a single-channel pulse-height analyzer. Gamma rays from Cs^{137} (661 kev) and Ba^{131} (122 kev, 369 kev, and 496 kev) were used to calibrate the linear energy scale.

The high specific activity source used ($\sim$0.025 milligram phosphorous per millicurie) was obtained from the Oak Ridge National Laboratory where it was produced by $S^{32}(n,p)P^{32}$, and chemically processed. It was received in the form of phosphate in weak HCl. About 10 mC was placed within a 0.5 cm diameter circle on polystyrene tape of 2.2 mg/cm^2 thickness and the liquids evaporated. This gave a source thickness of the order of 5 mg/cm^2. Any trace of continuous radiation from an impurity would have only a small effect on the measured continuum. No evidence of nuclear gamma rays could be observed during the measurements. For these reasons, the source was deemed to be of sufficient purity for the measurements desired. In order to reduce the ratio of external (E.B.) to internal bremsstrahlung, the source was mounted 20 cm above the face of the detector with a beta absorber about half-way between source and detector. This arrangement is similar to that used by others.[4,7] The detector crystal was shielded from light and stray fields by an aluminum can with an aluminum foil cover. Resting on this can was a wooden support holding a lead collimator with a conical hole. The collimator was 5 cm thick, and its top surface was 10 cm above the face of the crystal. On the top surface of the collimator was a $\frac{1}{4}$-in. sheet of Lucite which completely shielded the collimator from the beta rays of the source. The entire assembly was placed on a tall stool in the center of the laboratory so that the source was not less than $3\frac{1}{2}$ feet from any structure. The collimator and its Lucite cover were large enough to shield the stool from

[8] Goodrich, Levinger, and Payne, Phys. Rev. **91**, 1225 (1953).
[9] W. H. Jordan and P. R. Bell, Nucleonics **5**, No. 4, 30 (1949); W. H. Jordan, Ann. Rev. Nuclear Sci. **1**, 207 (1952).

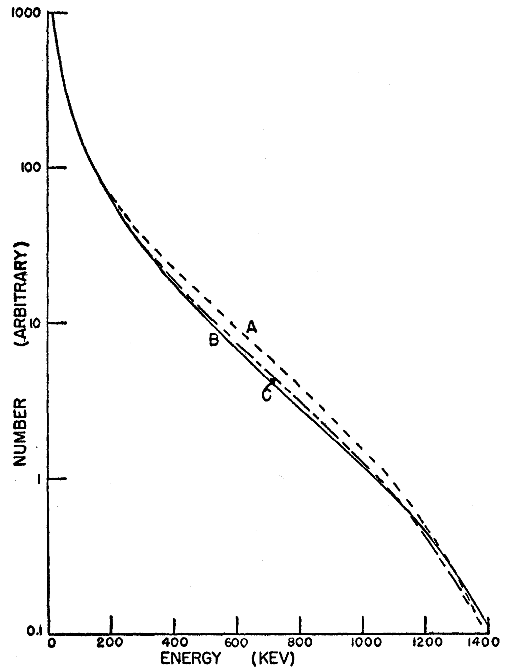

FIG. 1. Calculated energy distributions of internal bremsstrahlung resulting from three beta-interactions (A) allowed; (B) first-forbidden; scalar; (C) first-forbidden; tensor; $\Delta J=2$, yes. The ordinates are normalized to 100 at 150 kev. The calculations are made from equations given in reference 4.

direct rays from the source. The mounting of the source was such that the only betas stopped in a position to see the crystal were those stopped in the Lucite above the collimator hole and a negligible number which moved off at right angles to the collimator axis and were stopped in the polystyrene tape or in the source material. Measurements of the spectrum made with Al foils immediately above the source showed that the contribution due to E.B. produced in the source was negligible.

The contribution of external bremsstrahlung (produced in the beta stopper) to the observed spectrum was determined by obtaining the photon spectrum with an aluminum beta stopper and a copper beta stopper as well as with the Lucite. Extrapolation to $Z=0$ of the number of photons detected as a function of the Z of the beta absorber for various energies, showed that, with the Lucite beta stopper, roughly seven percent of the spectrum was contributed by the external bremsstrahlung. In the calculations this contribution was neglected. This is all the more acceptable since the I.B. and E.B. have a somewhat similar shape.[8]

TABLE I. Calculated relative intensity of internal bremsstrahlung as a function of photon energy for various beta interactions.

k(Mev)	Allowed	First-forbidden scalar	First-forbidden tensor
0.026	7540	7790	7770
0.077	2250	2270	2270
0.179	776	745	749
0.281	397	360	368
0.485	146.7	118.9	126.1
0.690	62.5	46.6	50.9
0.843	32.8	24.1	26.3
1.05	12.33	9.76	10.12
1.20	4.94	4.42	4.27
1.354	1.451	1.51	1.36
1.507	0.591	0.827	0.790

III. DATA AND CALCULATIONS

We show in Table I our calculated I.B. spectrum for: (a) allowed beta transitions, (b) first-forbidden beta transitions; scalar interaction (c) first-forbidden beta transitions; tensor interaction; special case of selection rule ($\Delta J=2$; yes). These calculations are made from the equations given by Bolgiano *et al.*[4] and have been normalized to 1000 at 150 kev. They are also shown

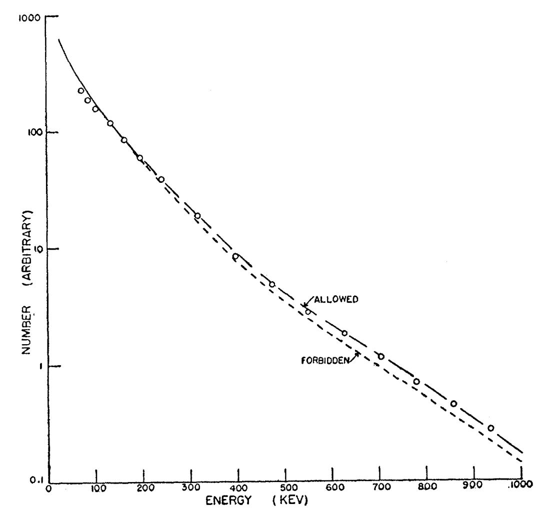

FIG. 2. Energy distribution of internal bremsstrahlung from P^{32}. The dashed curves are the calculated spectra for allowed and first-forbidden (tensor) beta interactions shown in Fig. 1 corrected for detector response. The circles are the experimental points. Standard error from counting statistics is less than the size of the points. Calculated curves and experimental data have been normalized to 100 at 150 kev.

graphically in Fig. 1. In the region below 150 kev, the three I.B. spectra are so nearly the same shape that they have been drawn as one line. Above this energy the spectrum for allowed transitions becomes relatively greater than the spectra for the first-forbidden transitions until in the neighborhood of 800 kev, the curves again approach each other and actually cross at about 1400 kev. At 800 kev the separation of the curves reaches almost 30 percent. It will be noted that of the first-forbidden transitions whose I.B. spectra were computed, the tensor interaction spectrum is the more like the spectrum for allowed transitions.

In Fig. 2 we compare the experimental data with the theory. Here the circles are the experimental data, the long dashed curve and the short dashed curve are the theory for the allowed and first-forbidden tensor interaction cases, respectively, all normalized to 100 to 150 kev. The effect of the detector response has been applied to the theory in this figure. This was done as discussed in our earlier paper[8] except that in the present case, degradation of the photons caused by their passage through the low-Z Lucite absorber was neglected. The uncertainty in the detector response is about 10 percent and forms the principle uncertainty. The standard error from counting statistics is about 3 percent.

The fit of the experimental data to the theory curve for the allowed transition case is much better than 10 percent. We have chosen to show the tensor interaction case for the spectrum from first-forbidden transitions since of the two calculated, it lies nearer the spectrum for allowed transitions. It is, *a fortiori*, evident that the P^{32} I.B. spectrum does not agree with the first-forbidden scalar.

No measurements were made on the ratio of I.B. photons to beta particles. Other experimenters[4,6,7] have found satisfactory agreement working in the region below 250 kev.

We can improve our earlier figures on the upper limit of the possible number of nuclear gammas per beta particle by a factor of 5. If nuclear gammas were present to the extent of 10^{-4} at 200 kev, 4×10^{-5} at 500 kev, or 2×10^{-6} at 900 kev per beta particle, they would have been observed as humps in the spectrum above the smooth curve actually found.

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Radiative Electron Capture in Fe^{55}†

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The internal bremsstrahlung emitted in electron capture by Fe^{55} was studied from 14 kev to the upper energy limit at 220 kev. Fair agreement with the formula of Morrison and Schiff is observed at high energies, whereas a strong rise of the intensity occurs at low energies. The discrepancy may be due to failure of the theory to take into account the effects of nuclear charge, capture of p electrons, and forbiddenness of the transition.

THE internal bremsstrahlung emitted in electron capture by Fe^{55} was studied by Maeder and Preiswerk,[1] and by Bell, Jauch, and Cassidy.[2] The high-energy part of the spectrum was shown to agree at least approximately with the formula calculated by Morrison and Schiff[3] for s-electron capture in allowed transitions, assuming a decay energy slightly above 200 kev. The low-energy portion was not investigated in detail owing either to poor resolution of the spectrometer or to presence of impurities.

We therefore undertook careful measurements of the entire spectrum. The Fe^{55} source was over two years old, hence all the Fe^{59} originally present had decayed. Sodium iodide crystals 10 to 12 mm thick were used in combination with DuMont 6292 photomultipliers. The resolution attained corresponds to full widths at half-maximum of 34-36 percent for a 22-kev line and 18-20 percent for an 87.5-kev line. Spectra were recorded under various geometries and with different crystals and photomultipliers, yielding consistent results.

To obtain the spectral distribution of the gamma radiation from the recorded pulse-size spectrum, one must correct for: (1) Percentage of pulses in photoelectric peak; however, up to 200 kev this correction is small at the crystal thicknesses employed. (2) Incomplete efficiency of the crystal at the higher energies. (3) Absorption by materials between source and crystal. (4) Escape of the K radiation of iodine. (5) Gaussian spread of the pulses. Furthermore, at very low energies, one must be certain that none of the pulses observed are due to the K x-rays of Mn at 5.9 kev, at least 10^4 times stronger than the integrated continuum. The curve due to the x-rays, measured by using a thin Fe^{55} source in immediate contact with an NaI crystal, showed that under our experimental conditions the effect of the x-rays was certainly negligible above 14 kev. Hence the bremsstrahlung was investigated only above this energy. Corrections for absorption at low energies in 0.188 g/cm^2 Lucite and 0.015 g/cm^2 Al interposed between source and detector were made by means of tabulated absorption coefficients and checked by taking spectra with additional absorbers. Corrections for lack of efficiency at high

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[1] D. Maeder and P. Preiswerk, Phys. Rev. **84**, 595 (1951).
[2] Bell, Jauch, and Cassidy, Science **115**, 12 (1952).
[3] P. Morrison and L. I. Schiff, Phys. Rev. **58**, 24 (1940).