to the question of the identity of neutrinos and antineutrinos.[2] We have accordingly re-evaluated the expected and extreme mean lives for comparison with the experimental results with the conclusion that the previous inference as to the inapplicability of the Majorana hypothesis (neutrino identical with antineutrino) stands. The quantitative argument follows: the available kinetic energy of the emitted neutrino, assuming no net neutrino emission in accordance with the Majorana hypothesis, is given by Johnson and Nier as 3.65±0.10 Mev. (We previously used the more favorable value 4.4±0.8 Mev). For this new energy figure a reasonable value for the mean life is 4×10^{15} years, an extreme value is 1.9×10^{18} years.[3] These lifetimes are to be compared with the experimental result of $>4.4\times10^{18}$ years, a limit derived by considering the count rate associated with one standard deviation from a smoothed curve of count rate *versus* energy.[2]

As pointed out by Tiomno,[4] it is possible to build a "mixed" theory in which double beta decay is unaccompanied by neutrino emission, and yet have the neutrino obey the Dirac equation. In this case an observably short lifetime for β decay could have an ambiguous interpretation. Such a theory is restricted independently of the phenomenon of double beta decay by the negative experiment of Davis[5] in which an appreciable amount of such an admixture of neutrinos and antineutrinos from the decay of neutron-rich isotopes would have produced a positive result.

* Work done under the auspices of the U. S. Atomic Energy Commission.

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Evidence for Circular Polarization of Bremsstrahlung Produced by Beta Rays

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York*
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We have investigated the degree and sense of circular polarization of bremsstrahlung produced by β^- rays. Near the high-energy end of the spectrum we find that the photons are almost completely circularly polarized, with their spin antiparallel to their direction of propagation.

The question of parity conservation in weak interactions, raised by Lee and Yang,[1] has been partially answered by recent experiments which show that parity

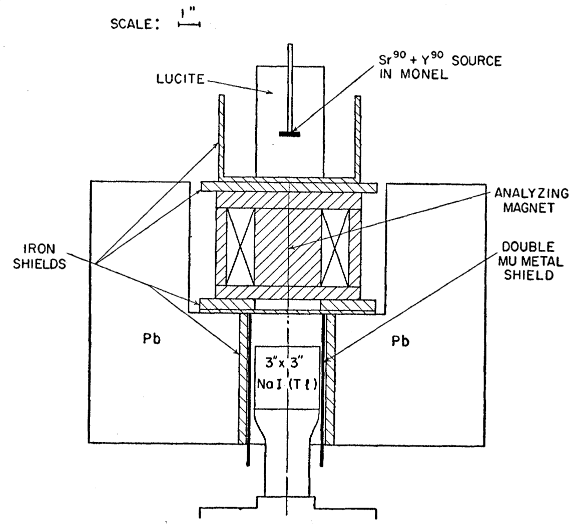

Fig. 1. Arrangement for analyzing degree and sense of circular polarization of bremsstrahlung from β^- source.

is not conserved in interactions involving neutrino emission.[2-4] The two-component neutrino theory[5-7] can account for these results in a natural manner. From this theory it follows that β rays are polarized longitudinally, and if time-reversal invariance is assumed the polarization is found to be $\pm v/c$, where the plus sign is expected for positrons and the minus sign for negative electrons.[7-9] The existence of a polarization compatible with these ideas has recently been demonstrated for both electrons[10] and positrons.[11]

It appeared to us worthwhile to investigate whether the longitudinal polarization of the β rays will in turn give rise to a circular polarization of the bremsstrahlung which they produce. To search for such an effect, we used a source of $Sr^{90}+Y^{90}$ in equilibrium. The decay scheme of this source is well known.[12] High-energy β^- rays are emitted from the decay of Y^{90} (maximum energy = 2.24 Mev, $(v/c)_{max}=0.98$; no γ rays have been reported). The source, kindly lent to us by the Medical Research Department of this Laboratory, had an intensity of 120 mC; it was enclosed in Monel, $\sim$100 mg/cm^2, and contained in a thick Lucite cylinder which absorbed all β rays. For such a source assembly, most of the high-energy bremsstrahlung originates in the Monel which has $Z_{eff}\approx 28$ (60% Ni, 33% Cu, 6.5% Fe). Only a small fraction consists of internal bremsstrahlung from the source and of external bremsstrahlung produced in the Lucite.[13]

The principle of the analysis of the circular polarization of x-rays is based on the existence of a spin-dependent part of the Compton cross section, as is described in detail by Gunst and Page.[14] The analyzer consisted of a cylindrical electromagnet, which could be magnetized to saturation either parallel or antiparallel to the photon direction (see Fig. 1), thus polarizing 2 out of the 26 electrons of the iron atoms.

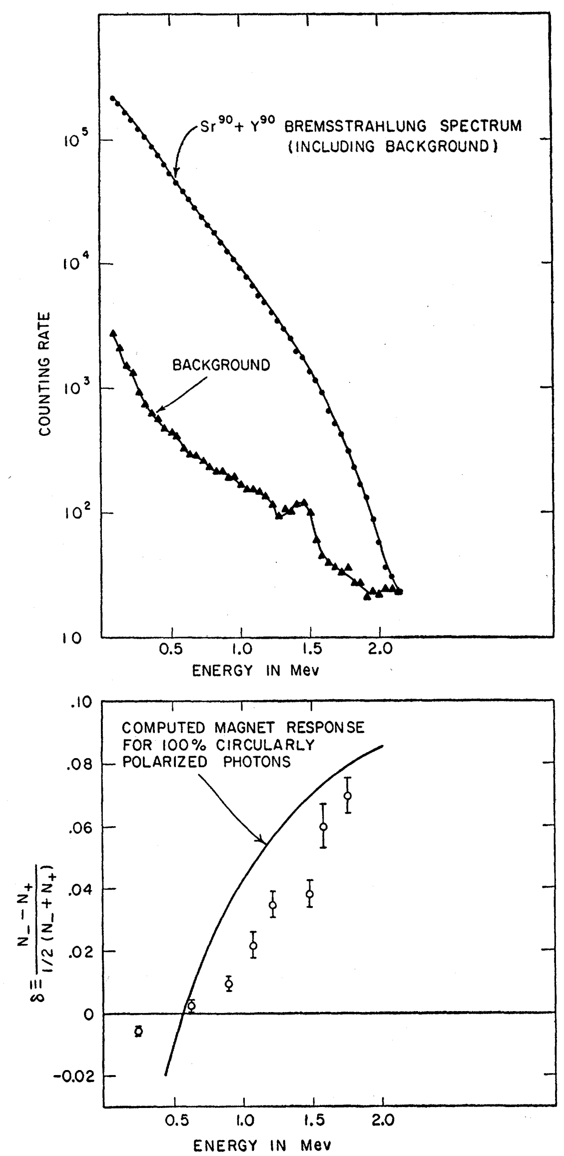

FIG. 2. Upper part: background count and bremsstrahlung spectrum (filtered through iron of magnet) from Sr^{90} ($E_0=0.535$ Mev) and Y^{90} ($E_0=2.24$ Mev). The peak in the background spectrum is presumably due to the 1.46-Mev γ rays of K^{40} present as an impurity in the scintillation counter. Lower part: experimental values for δ, and computed magnet response curve as a function of energy for 100% circularly polarized photons with spin antiparallel to direction of propagation.

The analyzer was built previously for another experiment by deBenedetti, Grodzins, Madey, and Sunyar.[15]

Figure 2 (upper part) shows the distribution of pulses obtained with the 3 in. $\times$ 3 in. NaI(Tl) scintillation counter for the bremsstrahlung spectrum from the $Sr^{90}+Y^{90}$ source filtered by the iron (mean of both field directions). The degree and sense of circular polarization was measured as a function of energy up to the highest energy for which we obtained a reasonable counting rate (1.8 Mev). During the measurements, the direction of the magnetic field was reversed every ten minutes. If we define N_+ as the counting rate with the field pointing up (toward the source), N_- as the counting rate with the field pointing down, and the polarization effect as $\delta \equiv (N_- - N_+)/[\frac{1}{2}(N_- + N_+)]$, we find $\delta = 0.07 \pm 0.005$ at 1.8 Mev with a channel width of $\sim$70 kev.

To check the possible influence of a reversal of the magnetic field on the pulse height from the photomultiplier, we performed an experiment with the 1.77-Mev γ rays of Bi^{207} as a source, which should not be expected to show any circular polarization. To exaggerate any possible effect of field reversal, we set the acceptance channel on the steeply sloping high-energy wing of the 1.77-Mev photopeak. We found a small effect, $\delta = 0.02 \pm 0.002$, in the same direction as for the x-rays. However, because of the approximately 10 times larger slope of the comparison line, this indicates a small correction, -0.002 to the x-ray data.

If only the core ($3\frac{1}{2}$ in. long) of our magnet were saturated, we would expect $\delta = 0.065$ for completely circularly polarized photons of 1.8 Mev.[14] If the iron in the return path of the magnet were also saturated in the same direction as the core, the path length would be 5 in. and we would expect $\delta = 0.095$. A reasonable estimate for the effective path length of saturated iron is $4\frac{1}{4}$ in., for which one would expect $\delta = 0.08$. The effect found is thus indicative of a high degree of circular polarization ($\sim$90%) of the high energy bremsstrahlung.

The lower part of Fig. 2 shows the experimental points for a number of selected energies, as well as the effect computed[14] for completely circularly polarized photons of a given energy, traversing $4\frac{1}{4}$ in. of saturated iron ("computed magnet response"). The experimental points cannot be interpreted immediately as representing the degree of circular polarization of the bremsstrahlung as a function of energy, except near the high energy end. To obtain the actual polarization as a function of x-ray energy a number of corrections would have to be made, some of which require separate investigations. These include an investigation of the angular distribution of the bremsstrahlung and the production of low-energy photons through the scattering of high-energy photons in the magnet.

From the dependence of the transmitted intensity on the direction of the magnetic field, it follows that the spin of the photons points opposite to their direction of motion, i.e., in the same direction as the intrinsic spin of the β^- rays. This is in agreement with theoretical expectations for high-energy bremsstrahlung emitted in the forward direction.[16] Because bremsstrahlung from fast electrons is mainly emitted in the forward direction, our arrangement has a "self-collimating" quality. Any depolarization due to scattering of the electrons before they radiate should be small at the high-energy end of the β-ray spectrum. The longitudinal polarization of β rays is thus established for a first forbidden β-ray transition of unique shape ($\Delta J = 2$, yes).

Experiments with other sources which should permit separation of effects due to internal and external bremsstrahlung are being prepared.

The bremsstrahlung method of analyzing the longitudinal polarization of β rays may prove of special value for high-energy β rays, and might be applicable to electrons from μ-meson decay.

Dr. K. W. McVoy of this Laboratory gives a partial theoretical interpretation of the effect reported here in an accompanying Letter. Dr. R. E. Cutkosky of the Carnegie Institute of Technology has kindly informed us of calculations based on the two-component neutrino theory which indicate that circular polarization should also exist for internal bremsstrahlung.

* Work done under the auspices of the U. S. Atomic Energy Commission.

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Circular Polarization of Bremsstrahlung from Polarized Electrons in Born Approximation*

KIRK W. McVOY

Brookhaven National Laboratory, Upton, New York

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THE Bethe-Heitler bremsstrahlung cross section has been re-derived for transitions from specific initial to specific final electron spin states, in order to compare the calculated circular polarization with the experimental results obtained by Goldhaber, Grodzins, and Sunyar.[1] Although the matrix elements are simple to derive, the cross section for bremsstrahlung produced in an arbitrary direction appears to be very complicated, and only the cross section in the directly forward direction is presented in detail here.

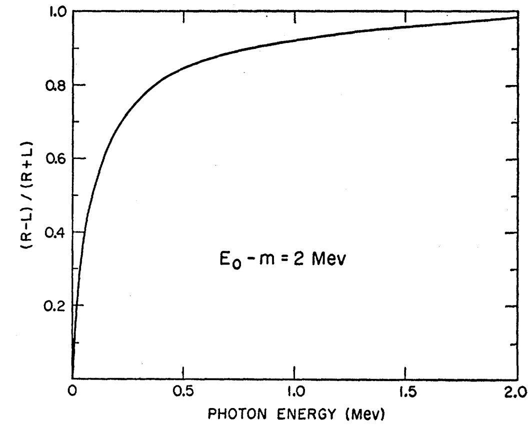

FIG. 1. Circular polarization of the forward bremsstrahlung from 2-Mev "spin-forward" electrons.

In Heitler's notation,[2] the matrix element for the process, after summing over intermediate states, is

$$M=\frac{1}{q^2}\left\{\frac{(u_0^*,(\boldsymbol{\alpha}\cdot\mathbf{e})(E+H_{p'})u)}{2(E_0k-\mathbf{p}_0\cdot\mathbf{k})}-\frac{(u_0^*,(E_0+H_{p''})(\boldsymbol{\alpha}\cdot\mathbf{e})u)}{2(Ek-\mathbf{p}\cdot\mathbf{k})}\right\}, \quad (1)$$

with $\mathbf{p}'=\mathbf{p}_0-\mathbf{k}$, $\mathbf{p}''=\mathbf{p}+\mathbf{k}$, and $\mathbf{q}=\mathbf{p}_0-\mathbf{p}-\mathbf{k}$; $\mathbf{e}$ is the polarization vector of the photon. We shall choose the z axis along the $\mathbf{k}$ direction throughout and write $\mathbf{e}=(\mathbf{e}_x+i\delta\mathbf{e}_y)/\sqrt{2}$ for circularly-polarized light. The state, $\delta=+1$, corresponding to one positive unit of angular momentum being carried in the propagation direction, we shall call "right-circularly-polarized," and $\delta=-1$ "left-circularly-polarized." The recoil energy of the nucleus will be neglected throughout.

The Dirac-matrix commutation rules permit us to write

$$\begin{aligned}(u_0^*,\ (\boldsymbol{\alpha}\cdot\mathbf{e})(E+H_{p'})u)&=(u_0^*,\ [2(\mathbf{e}\cdot\mathbf{p}_0)-k(\boldsymbol{\alpha}\cdot\mathbf{e})+\delta k(\boldsymbol{\sigma}\cdot\mathbf{e})]u),\\ (u_0^*,\ (E_0+H_{p''})(\boldsymbol{\alpha}\cdot\mathbf{e})u)&=(u_0^*,\ [2(\mathbf{e}\cdot\mathbf{p})+k(\boldsymbol{\alpha}\cdot\mathbf{e})+\delta k(\boldsymbol{\sigma}\cdot\mathbf{e})]u).\end{aligned} \quad (2)$$

In order to evaluate the matrix elements between specific spin states, we shall choose u's which simultaneously satisfy

$$\begin{aligned}(\boldsymbol{\alpha}\cdot\mathbf{p}+\beta m)u&=Eu,\\ (\boldsymbol{\sigma}\cdot\mathbf{p})u&=\epsilon pu,\end{aligned} \quad (3)$$

which is possible since the operators commute. $\epsilon=+1$ defines the state in which the electron's spin is parallel to its momentum; $\epsilon=-1$, the state in which it is antiparallel. We shall use ϵ_f for the final electron spin state and ϵ_0 for the initial electron state. If we use the usual "low-energy" representation for the Dirac matrices, the