FIG. 2. Resonant scattering distribution from a scatterer of $\sim$1850 g of Sm_2O_3.

first approximation. The resonant scattered gamma-ray distribution is shown in Fig. 2 for a source strength of $\sim$20 millicuries. The ratio of the 837-kev to 961-kev photopeaks is 1.8 which is in agreement with the ratio of the γ rays before scattering, 1.4, corrected for detection efficiencies and for the different angular distributions of the scattered gamma rays at 100°—the mean angle of scattering. The cross section measured with the solid source is $(5\pm1)\times10^{-26}$ cm^2, the major uncertainties being in the geometry and source strength determinations. The liquid source gave a 20% higher cross section; the difference may be due to a slowing down of the recoiling nucleus in the solid or a change in its effective mass.

In order to calculate the lifetime of the transition one should take into account the natural width of the emitting level, the Doppler broadening of the emitted gamma ray due to the neutrino recoil, the possible slowing down of the recoiling nucleus, the effective mass, and the temperature broadening of the emission and absorption lines. If the recoil and temperature effects are neglected, a lower limit on the mean life can be set as 1.7×10^{-14} sec. An upper limit is certainly the slowing-down time in the solid, approximately 2×10^{-13} sec,[7] since a stationary nucleus with a level of this mean life will give a cross section less than 1/100 that observed. Conversely, therefore, the gamma ray is emitted in general before the recoil slows down so that the Doppler broadening due to the neutrino emission must be taken into account, and the resonance scatter-

ing becomes a sensitive detector of the direction of neutrino emission. Taking into account the width of the emitting line and the Doppler shift due to the recoiling nucleus, assumed to have an effective mass number equal to 152, the mean life of the 1^- level becomes $\tau=(3\pm1)\times10^{-14}$ sec. The effect of the temperature of the source and scatterer has been neglected. The measured lifetime is thus approximately 150 times longer than the single proton estimate. This mean life corresponds, according to the formulation of Bohr and Mottelson,[8] to an octupole deformation parameter, $\beta_3\simeq0.07$, for the 1^- state of Sm^{152}.

I would like to thank M. Goldhaber, A. W. Sunyar, and J. Weneser for many valuable discussions.

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] L. Grodzins and H. Kendall, Bull. Am. Phys. Soc. Ser. II, 1, 163 (1956).
[2] O. Nathan and M. A. Waggoner, Nuclear Phys. 2, 548 (1957).
[3] L. Grodzins, Bull. Am. Phys. Soc. Ser. II, 1, 329 (1956); Nuclear Data Card 57-1-90 (National Research Council, Washington, D. C., 1957).
[4] A. de-Shalit and M. Goldhaber, Phys. Rev. 92, 1211 (1953); Krisyouk, Sergeyer, Latyshev, and Vorobyou, Nuclear Phys. 4, 579 (1957).
[5] K. G. Malfors, in Beta- and Gamma-Ray Spectroscopy, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955), p. 494; F. R. Metzger, Phys. Rev. 101, 286 (1956).
[6] Goldhaber, Grodzins, and Sunyar [Phys. Rev. 109, 1015 (1958)], following Letter.
[7] K. Iakovac, Proc. Phys. Soc. (London) A67, 601 (1954).
[8] A. Bohr and B. Mottelson, Nuclear Phys. 4, 529 (1957).

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\sigma_\nu\cdot\hat{p}_\nu=-1$ (negative helicity).

Our method may be illustrated by the following simple example: take a nucleus A (spin $I=0$) which decays by allowed orbital electron capture, to an excited state of a nucleus $B(I=1)$, from which a γ ray is emitted to the ground state of $B(I=0)$. The conditions necessary for resonant scattering are best fulfilled for those γ rays which are emitted opposite to the neutrino, which have an energy comparable to that of the neutrino, and which are emitted before the recoil energy is lost. Since the orbital electrons captured by a nucleus are almost entirely s electrons (K, L_I, $\cdots$ electrons of spin $S=\frac{1}{2}$), the substates of the daughter nucleus
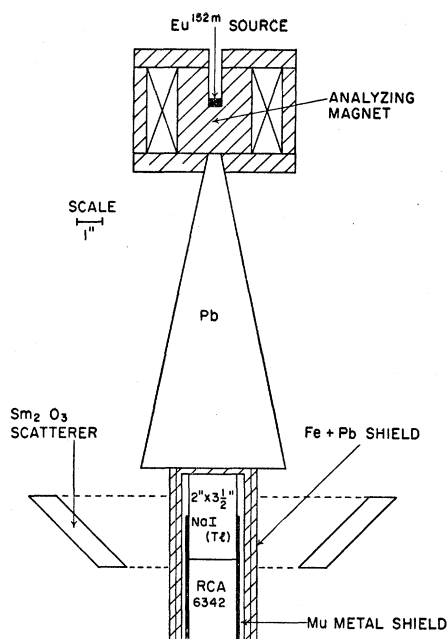
FIG. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm_2O_3 scatterer: 1850 grams.

B, formed when a neutrino is emitted in the Z direction, are $m = -1, 0$ if the neutrino has positive helicity, and $m = +1, 0$ if the neutrino has negative helicity. In either case, the helicity of the γ ray emitted in the $(-Z)$ direction is the same as that of the neutrino. Thus, a measurement of the circular polarization of the γ rays which are resonant-scattered by the nucleus B, yields directly the helicity of the neutrino, if one assumes only the well-established conservation laws of momentum and angular momentum.

To carry out this measurement we have used a nucleus which appears to have the properties postulated in the example given: $_{63}Eu^{152m}$(9.3 hr). It probably has spin 0 and odd parity.[1] It decays to an excited state of $_{62}Sm^{152}$(1 −) with emission of neutrinos which have an energy of 840 kev in the most prominent case of K-electron capture. This is followed by an $E1$ γ-ray transition of 960 kev to the ground state (0+). The excited state has a mean life of $(3\pm1)\times10^{-14}$ sec, as determined by Grodzins.[1] Thus, even in a solid source most of the γ-ray emission takes place before the momentum of the recoil nucleus has changed appreciably.

The experimental arrangement used is shown in Fig. 1. The Eu^{152m} source is inserted inside an electromagnet which is alternately (every three minutes) magnetized in the up or down direction. The γ rays which pass through the magnet are resonant-scattered from a Sm_2O_3 scatterer (26.8% Sm^{152}), and detected in a 2-in.$\times$3$\frac{1}{2}$-in. cylindrical NaI(Tl) scintillation counter. The photomultiplier (RCA 6342) is magnetically shielded by an iron cylinder and a mu-metal shield.

The effectiveness of this magnetic shield was demonstrated by check experiments with a Cs^{137} γ-ray source in a manner similar to that described previously.[2] No significant effect of magnetic field reversal on the photomultiplier output was noticed when two narrow acceptance channels were set on the steeply sloping low- and high-energy wings of the 661-kev photopeak, respectively.

The source was produced by bombarding $\sim$10 mg of Eu_2O_3 in the Brookhaven reactor. In typical runs the intensity varied from 50–100 mC. Nine runs varying in length from 3 to 9 hours were carried out. The scattered radiation is shown in Fig. 2. It contains both γ rays emitted from the 960-kev state (960 and 840 kev). Counts were accumulated simultaneously in 3 channels A, B, and C as shown in Fig. 2. A cycle of field reversals was used such that the decay corrections were negligible. No effects of field reversal or decay were noticed in channel C. Channel A exhibited a possible small magnetic field effect which was less than one-tenth of that observed in channel B. In channel B, which bracketed the photopeaks, a total of $\sim$3$\times$10^6 counts were accumulated. In 6 runs carried out in the arrangement shown in Fig. 1, an effect $\delta = (N_- - N_+)/\frac{1}{2}(N_- + N_+) = +0.017\pm0.003$ was found in channel B after the nonresonant background had been subtracted. Here N_+ is defined as the counting rate with the magnetic field pointing up, and N_- as the counting rate with the field pointing down.
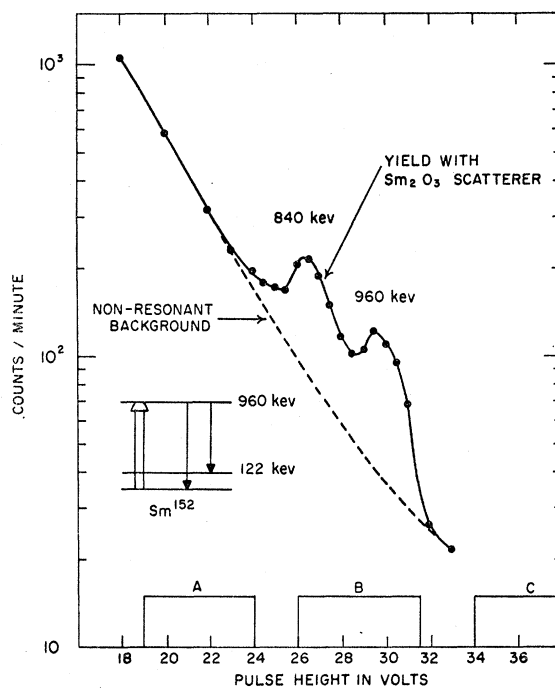

FIG. 2. Resonant-scattered γ rays of Eu^{152m}. Upper curve is taken with arrangement shown in Fig. 1 with unmagnetized iron. Lower curve shows nonresonant background (including natural background).

The magnet response was tested with the bremsstrahlung from a $Sr^{90}+Y^{90}$ source, for which the helicity is negative,[2] $\sigma_\gamma \cdot \hat{p}_\gamma = -1$. Eu^{152m} runs were made with both solid and dissolved sources (HCl solution), and both gave similar results. The effective path length of the 960-kev γ ray in the magnet was somewhat uncertain, partly because of the extent of the source and partly because of a lack of knowledge of the field distribution in the return path. We estimate that the average path is equivalent to 3 ± 0.3 mean free paths in fully magnetized iron. From this we expect an effect of $\delta = \pm0.025$ with an accuracy of 10%, if the 960-kev γ rays are 100% circularly polarized, with the $-$ sign corresponding to positive helicity (spin parallel to their direction of propagation) and the $+$ sign to negative helicity. Thus we find that in our case the γ rays are $(68\pm14\%)$ circularly polarized, and that their helicity is negative. As a further check, 3 runs were carried out with a shorter magnet of length $3\frac{1}{2}$ in. with the source on top of the magnet. In this case also a negative helicity was found, the circular polarization being $(66\pm15\%)$.

From the energy of the neutrinos emitted, the width of the γ-ray line, and the fact that the circular polarization varies with the direction of emission of the γ ray relative to the neutrino as $\cos\theta$, we calculate that a circular polarization, which in the ideal case discussed above would be 100%, would be reduced to $\sim75\%$. This should be further reduced to a slight extent because of the effect of thermal motion and because some γ rays are emitted after the recoil has changed momentum. Thus our result seems compatible with spin $0-$ for Eu^{152m}, and 100% negative helicity of the neutrinos emitted in orbital electron capture.[3]

In all formulations of β-decay theory no distinction is made between the neutrino emitted in orbital electron capture and that emitted in β^+ decay. Taken together with the fact that the helicity of the positrons in a Gamow-Teller transition is positive[4] or with the fact that positrons are emitted from oriented nuclei in the direction in which the nuclear spin is pointing,[5] our result indicates that the Gamow-Teller interaction is axial vector (A) for positron emitters, in agreement with the conclusions of Hermannsfeldt et al.[6] These authors show that all recoil experiments with β^+ emitters are compatible with AV, but not with TS interactions which have been reported for β^- emitters (largely based on He^6 recoil experiments).[7] The AV combination may be compatible with lepton conservation and a universal Fermi interaction as pointed out by Sudarshan and Marshak[8] and by Feynman and Gell-Mann.[9] This view is strengthened by the recent results showing positive helicity for the positrons from μ^+ decay.[10] It would therefore seem desirable to apply the method described here to a β^- emitter in order to determine the helicity of the antineutrino. Although the analysis of such an experiment is considerably more complicated, it may prove possible to reach a decision between A and T,

which is independent of the "classical" recoil experiments.

We wish to thank J. Weneser for many valuable discussions.†

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] L. Grodzins, Phys. Rev. 109, 1015 (1958), preceding Letter.
[2] Goldhaber, Grodzins, and Sunyar, Phys. Rev. 106, 826 (1957).
[3] It is worthwhile to inquire how our conclusions are affected if the less plausible spin-parity assignments of $1\mp$ are assumed for Eu^{152m}. For the case of a $1^- \overset{\epsilon}{\to} 1^- \overset{\gamma}{\to} 0^+$ transition, J. Weneser (unpublished) finds

$$\sigma_\gamma \cdot \hat{p}_\gamma = \frac{(\sigma_\nu \cdot \hat{p}_\nu)[\frac{1}{2}|G_{GT}|^2 \pm \sqrt{2}|G_{GT}| \cdot |G_F|]}{|G_{GT}|^2 + |G_F|^2},$$

where $G_{GT} = M_{GT}C_{GT}$ and $G_F = M_F C_F$. This has been calculated on the simplifying assumption that the two-component neutrino theory and time-reversal invariance hold [see T. D. Lee and C. N. Yang, Phys. Rev. 105, 1671 (1957)]. For a neutrino helicity of -1 the photon helicity varies from $+0.5$ to -1.0, and for a neutrino helicity of $+1$ the photon helicity varies from -0.5 to $+1.0$. Considering the reduction factors discussed above, the experimentally found helicity of the γ rays is in agreement with the assumption of neutrinos of negative helicity, even if Eu^{152m} has spin-parity $1-$. In the other very unlikely case of a $1+$ assignment to Eu^{152m}, we could not at present draw a definite conclusion concerning the neutrino helicity. The theory for first forbidden transitions is being investigated by A. M. Bincer.
[4] L. A. Page and M. Heinberg, Phys. Rev. 106, 1220 (1957).
[5] Ambler, Hayward, Hoppes, Hudson, and Wu, Phys. Rev. 106, 1361 (1957); Postma, Huiskamp, Miedema, Steenland, Tolhoek, and Gorter, Physica 23, 259 (1957).
[6] Hermannsfeldt, Maxson, Stähelin, and Allen, Phys. Rev. 107, 641 (1957).
[7] B. M. Rustad and S. L. Ruby, Phys. Rev. 97, 991 (1955).
[8] E. C. G. Sudarshan and R. Marshak, Phys. Rev. (to be published).
[9] R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).
[10] Culligan, Frank, Holt, Kluyver, and Massam, Nature 180, 751 (1957).
† Note added in proof.—According to a private communication from Professor V. L. Telegdi, a refinement of the experiment of Burgy, Epstein, Krohn, Novey, Raboy, Ringo, and Telegdi, [Phys. Rev. 107, 1731 (1957)] favors $V-A$ for the β interaction.

Axial Symmetry of Nuclear Wave Functions

R. K. NESBET

Department of Physics, Boston University, Boston, Massachusetts
(Received November 25, 1957)

IN connection with recent work deriving the principal results of the Bohr-Mottelson theory from the nuclear shell model with axially symmetrical (spheroidal) potential,[1] it should be pointed out that there is a simple theorem which relates the spheroidal potential to the *a priori* Hartree-Fock method. This theorem follows trivially from results given in a somewhat different context in earlier papers.[2,3]

The Hartree-Fock method, for the present purpose, is to be thought of as a variational calculation which attempts to find the single Slater determinant (a normalized many-particle wave function constructed as an antisymmetrized product of single-particle wave functions) for which the mean value of the total energy is a