shading.[3] Corrections were applied both for Coulomb repulsion of the K^+ by the nucleus, and for the effect of the exclusion principle inside the nucleus.[4] From the best-fit curve of Fig. 1 we have obtained the solid curve of Fig. 2, and in this same way the cross sections from our experimental points.[5] The dashed curve shown in the same figure is the result of a further correction to include the effect of reflection at the nuclear boundary by a spherically symmetrical repulsive potential of 15 Mev. One notes an increasing K-nucleon cross section with increasing energy; the most rapid rise in the cross section occurs in our energy interval.

More detailed analyses are currently in progress, as regards both the elastic and inelastic nuclear interactions.

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

[1] The kinetic energy in the lab and center-of-mass angle for each of these K–H events are: 181 Mev, 104°; 187 Mev, 92°; 163 Mev, 85°; 167 Mev, 98°; 181 Mev, 146°; 198 Mev, 95°.

[2] Biswas, Ceccarelli-Fabbrichesi, Ceccarelli, Gottstain, Varshneya, and Valoschek, Nuovo cimento **5**, 123 (1957); Cocconi, Puppi, Quareni, and Stangellini, Nuovo cimento **5**, 172 (1957), and G. Puppi (private communication); Bhowmik, Evans, Nilsson, Prowse, Anderson, Keefe, Kernan, and Losty, Nuovo cimento (to be published); Widgoff, Pevsner, Davis, Ritson, Schluter, and Henri, Phys. Rev. **107**, 1430 (1957); Baldo-Ceolin, Cresti, Dallaporta, Grilli, Guerriero, Merlin, Salandin, and Zago, Nuovo cimento **5**, 402, 1957; Lanutti, Chupp, Goldhaber, Goldhaber, Puppi, and Quareni (private communication); Hoang, Kaplon, and Cester, Phys. Rev. **107**, 1698 (1957).

[3] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), p. 359; ($r_0 = 1.38\times10^{-13}$ cm).

[4] The calculation of this correction has been made by R. Sternheimer, Phys. Rev. **106**, 1027 (1957) and refers to a K-nucleon scattering process which is isotropic in the center-of-mass system. The correction has been made under the assumption that the K^+ energy is reduced by 25 Mev on entering the nucleus.

[5] In making these calculations no allowance was made for those inelastic events with $\Delta E/E \lesssim 10\%$ which escaped detection. The effect of their inclusion, however, has been estimated. By using the model described by Sternheimer (reference 4), it is found that on the average in our energy interval λ_i would be decreased by $\sim$6% and σ_{K-N} increased by $\sim$1.5 mb. An estimate can also be made by using the observed energy-loss distribution for inelastic events and extrapolating it to zero. In this way we find that λ_i should be decreased by $\sim$4% and σ_{K-N} increased by $\sim$1 mb.

Detection of Ga^{66} Positron Polarization by the Annihilation-in-Flight Rate in Polarized Matter

S. Frankel,* P. G. Hansen,† O. Nathan, and G. M. Temmer‡

Institute for Theoretical Physics, University of Copenhagen Copenhagen, Denmark

(Received September 23, 1957)

Various schemes have recently been employed for the detection of longitudinal electron polarization.[1–4] We wish to report here yet another method appropriate for positrons only. Both electrostatic deflection followed by Mott scattering,[1] and Møller scattering in magnetized foils,[2] are methods with better analyzing power for negatrons than for positrons. We therefore thought it worthwhile to explore the method of positron annihilation-in-flight in magnetized media.

Our method is based on the difference which exists in the annihilation-in-flight rates for the $M=0$ and $M=1$ magnetic substates formed by the incident, longitudinally polarized positron and the polarized electron partner in magnetized material. One may easily see from the conservation laws that in two-quantum annihilation-in-flight, where one of the quanta is emitted in the forward direction, only the $M=0$ state can contribute. Even if we accept annihilation quanta over a large solid angle in the forward direction, the $M=0$ annihilation rate may still predominate over the $M=1$ rate.[5,6] We make use of this discrimination to investigate the longitudinal polarization of positrons from Ga^{66}. We have, in fact, observed a consistent counting-rate difference for two antiparallel magnetization directions in a magnetized foil bombarded with monochromatic positrons from a source of Ga^{66}. The energetic positron branch to the ground state of Zn^{66} most probably represents a beta transition of the pure Fermi type ($0^+\rightarrow0^+$). Recent measurements[4,7] have yielded conflicting evidence concerning the state of polarization of these positrons.

Figure 1 shows the experimental arrangement. The final beam spot at I_2 has a diameter of 14 mm and strikes the central member of a stack of high-permeability iron-nickel transformer laminations[8] inclined at 45° to the beam. The magnetic foil is thick enough to stop 2-Mev positrons and carries a measured saturation flux density of 15 000 gauss. Because of multiple scattering of the positrons[9] the advantage of the intrinsic forward peaking of the annihilation-in-flight cross section is almost entirely lost, and we find it necessary to move our detector as close as possible to the annihilator to obtain sufficient counting rates.

Figure 2 shows typical gamma-ray spectra for 2-Mev and 1.5-Mev positrons annihilating in iron, along with background checks at zero lens current. Maximum gamma-ray energies for foward emission are indicated by arrows. The exact shape of these curves is governed by the details of the slowing-down process and multiple scattering of the positrons in iron, as well as the gamma-ray response function of the crystal, but their main features display the expected behavior. The background curve is seen to coalesce with the spectra just above the calculated maximum values of 2.78-Mev and 2.27-Mev for 2-Mev and 1.5-Mev positrons, respectively.

A large peak at 511 kev, not shown in the figure, measures the number of positrons annihilating at rest ($\simeq$90% of all incident positrons) and serves as a valuable monitor for possible systematic differences introduced upon reversing the magnetizing current of the foil (other than gain changes in the photomultiplier, which we found to be completely absent). We find less than 0.8% difference (in a direction *opposite* to the observed polarization effect) in the counting rates on

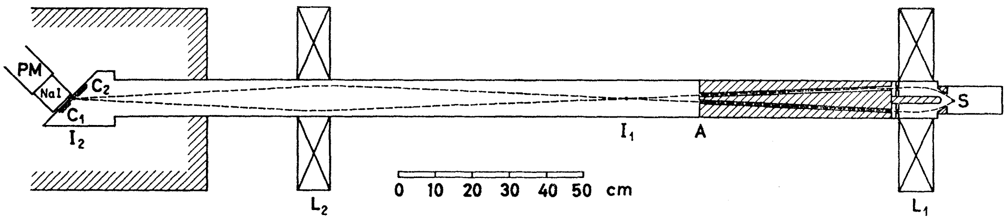

FIG. 1. Schematic drawing of experimental arrangement for the detection of positron annihilation-in-flight in magnetized material. S— radioactive source; L_1 — primary thin lens forming image of source S at I_1; L_2 — secondary thin lens forming final positron beam spot at I_2; C_1 and C_2—energizing coils for magnetized annihilator foil; PM—photomultiplier with 3 n.×3 in. NaI crystal. Cross-hatched regions represent lead shielding. No shielding inside vacuum tube beyond point A.

this peak where our statistical accuracy is rather high ($\simeq$0.2%). About 0.3% of this difference can be accounted for by the change in the annihilation-in-flight rates. Another check run with a copper foil (thick enough to stop the positrons) covering the magnetized iron gave a difference in the annihilation-in-flight rates of up to 1±0.3% between the two directions of magnetization, the difference being *opposite* to that observed with magnetized material. Part of this effect ($\simeq$0.3%) is believed due to the relative absorption of the circularly polarized quanta by the magnetized iron and is of the proper sign.[4] We made no attempt to correct our actual runs for the remaining unexplained ($\simeq$0.7%) effect and therefore believe that the differences obtained with iron may represent *lower* limits.

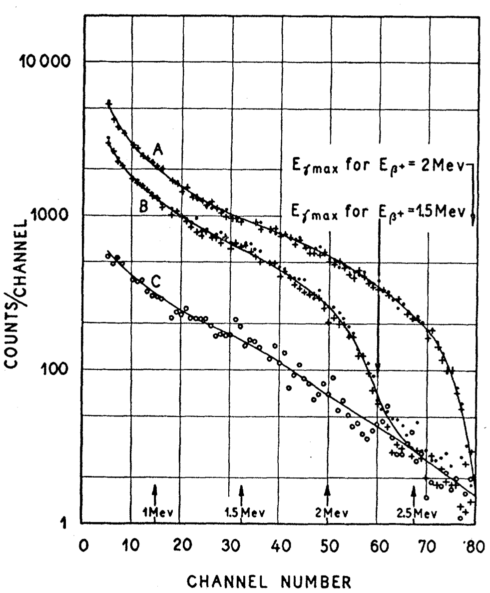

FIG. 2. Typical annihilation-in-flight spectra obtained with positrons from Ga^{66}. (A) Energy distribution of gamma rays produced by 2-Mev positrons incident on iron. Calculated upper energy limit at 2.78 Mev is indicated by arrow. (B) Energy distribution of gamma rays produced by 1.5-Mev positrons incident on iron. Calculated upper energy limit at 2.27 Mev is indicated by arrow. (C) Background spectrum of gamma rays obtained with zero current in L_1 and L_2. Crosses and dots refer to runs taken with opposite directions of magnetization in the annihilator foil. Curves are shown only to illustrate general behavior and *not* to display polarization effects.

A 300-millicurie source of Ga^{66} was produced by the $Cu^{63}(\alpha,n)Ga^{66}$ reaction with 20-Mev alpha particles from the Institute's cyclotron. We were able to obtain a 100-millicurie source of about 1 mg/cm^2 thickness and 2 mm diameter by ion-exchange techniques. We observed a consistent excess of $M=0$ over $M=1$ counting rates, the average over many runs being tabulated in Table I. The total annihilation-in-flight counting rate at the beginning of the run was of the order of 200 cps. We show the results for both 2.0- and 1.5-Mev positrons, along with the uncertainties due to counting statistics alone. In all cases we have summed the results of ten adjacent channels, corresponding to gamma-ray energy intervals of about 280 kev. We checked the gain stability of the system periodically with 2.62-Mev gamma rays from a thorium source. The background in the 2-Mev runs never exceeded 15%, but contributed up to 30% in the 1.5-Mev measurements, making the latter less reliable. It may be seen from Table I that the size of the effect decreases as we go to lower gamma-energy channels; this we believe to be due to the multiple scattering in the foil and the consequent decrease in the anisotropy δ to be expected,[10] and also to some depolarization by magnetic scattering in the foil.

From the fact that the observed effect near the upper energy limit lies close to the theoretically expected maximum value, we conclude that the positrons leading to the ground-state of Ga^{66} are highly polarized in the direction of motion. This conclusion is in agreement with the measurements on the circular polarization of annihilation quanta.[4]

TABLE I. Percent counting rate differences for opposite directions of the magnetization current. The indicated errors are from counting statistics only.

γ-ray energy interval (Mev)	Percent counting rate differences. $E_{\beta^+}=1.5$ Mev	$E_{\beta^+}=2.0$ Mev
0.85–1.13	1.6±0.4	−0.1±0.2
1.13–1.42	1.7±0.6	1.1±0.3
1.42–1.70	2.9±0.7	1.6±0.4
1.70–1.99	0.5±0.8	0.1±0.5
1.99–2.27	3.5±1.5	1.2±0.5
2.27–2.55		1.5±0.7
2.55–2.84		3.4±1.2

We are indebted to Dr. R. M. Sinclair for drawing our attention to the positron problem. We wish to record our gratitude to Dr. N. O. Lassen and his co-workers for providing the strong radioactivity essential to this research. Two of us (S. F. and G. M. T.) further deem it a pleasant duty to acknowledge the generous hospitality extended to us by Professor Niels Bohr at his Institute, as well as the support derived from grants of the John Simon Guggenheim Memorial Foundation.

* John Simon Guggenheim Memorial Fellow. Permanent address: Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania.

† Permanent address: A. E. K., Risø, Roskilde, Denmark.

‡ John Simon Guggenheim Memorial Fellow. Permanent address: Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.

[1] Frauenfelder, Bobone, von Goeler, Levine, Lewis, Peacock, Rossi, and DePasquali, Phys. Rev. **106**, 386 (1957); H. de Waard and O. J. Poppema, Physica **23**, 597 (1957); M. E. Vishnevsky *et al.*, Nuclear Phys. 4, 271 (1957).

[2] Frauenfelder, Hanson, Levine, Rossi, and DePasquali, Phys. Rev. **107**, 643 (1957).

[3] Goldhaber, Grodzins, and Sunyar, Phys. Rev. **106**, 826 (1957).

[4] Deutsch, Gittelmann, Bauer, Grodzins, and Sunyar, Phys. Rev. **107**, 1733 (1957).

[5] We are indebted to A. Bohr for working out for us the separate $M=0$ and $M=1$ annihilation-in-flight cross sections.

[6] L. A. Page, Phys. Rev. **106**, 394 (1957).

[7] Frauenfelder, Hanson, Levine, Rossi, and DePasquali, Phys. Rev. **107**, 910 (1957).

[8] H.C.R. alloy (50% Fe, 50% Ni).

[9] H. W. Kendall and M. Deutsch, Phys. Rev. **101**, 20 (1956).

[10] Let us define the polarization P of the positron beam as $P=(N^+-N^-)/(N^++N^-)$. (N^+, N^- represents number of β^+ spins parallel and antiparallel to the β^+ momentum, respectively.) Designating the annihilation cross sections for $M=0$ and $M=1$ by σ_0 and σ_1, their ratio σ_0/σ_1 by R, and the counting rates for polarized *electron* spins parallel and antiparallel to the positron momentum by C_p and C_a, respectively, we easily obtain the following expression for our iron-nickel alloy ($Z_{\rm eff}=27$): $C_a/C_p=1+0.0741nP(R-1)/(R+1)\equiv 1+\delta$, with n, the effective number of electron spins aligned parallel to the incident positron beam, equal to $N_B\cos\theta/gs$. N_B is the effective number of Bohr magnetons per atom for the material used (1.7) and g is the electronic gyromagnetic ratio ($s=\frac{1}{2}$, and we assume $g=2$ for want of a more accurate value). If we insert values of R appropriate for our geometry with an approximate acceptance cone of 45 degrees half-angle, we obtain the theoretical values $\delta=1.6\%$ and $\delta=2.4\%$ for completely polarized positrons of 2 Mev and 1.5 Mev, respectively. The larger effects observed at the highest photon energies indicate that the effective acceptance cone is narrower since R increases with decreasing acceptance angle. This is as expected since the energetic positrons producing the higher energy gamma rays have undergone less multiple scattering.

Photoproduction of Pion Pairs in Hydrogen*

MICHEL BLOCH AND MATTHEW SANDS
California Institute of Technology, Pasadena, California
(Received August 23, 1957)

NEGATIVE pions from the interaction of γ rays with protons are presumed to arise from events in which two or more pions are produced. Pions which emerge from a high-density, hydrogen-gas target in the bremsstrahlung beam of the Caltech synchrotron have been selected for charge and momentum by a wedge-magnet analyzer and detected in a scintillation-counter telescope. Discrimination against electrons was obtained with a Čerenkov counter in anticoincidence.

The yields of negative pions obtained at a laboratory angle of 60° for several pion laboratory energies T_- and for several bremsstrahlung cutoff energies $k_{\rm max}$ are given in Fig. 1(a). The yields, $d^2\sigma^*/dT_-d\Omega_-$, are expressed as a cross section per proton, per effective quantum (the energy flux divided by the maximum photon energy), and per unit energy and solid angle of the emitted pions. The yields obtained at a laboratory angle of 120° are given in Fig. 1(b). The photon beam was monitored with a thick ionization chamber whose energy dependence has been calibrated against a "quantameter" constructed according to the design of Wilson.[1] Other instrumental parameters were calibrated by using the yield of positive pions from the single-production resonance with the synchrotron operating at 500 Mev. Background runs with an evacuated target gave corrections of from 5% to 15% of the hydrogen yields. Smaller corrections have been made for counts due to cosmic rays and accidental coincidences. The arrows in the figure indicate the energy thresholds for the production of pion pairs with one pion at the required energy and angle.

The data for a maximum bremsstrahlung energy of 600 Mev agree with the results reported by Friedman and Crowe.[2] The results for 50-Mev pions at 60° show qualitative features similar to those reported from Cornell[3] at 35°.

Owing to the finite thickness of the radiator in the synchrotron, the energy spectrum of the photon beam used for these experiments does not have the ideal

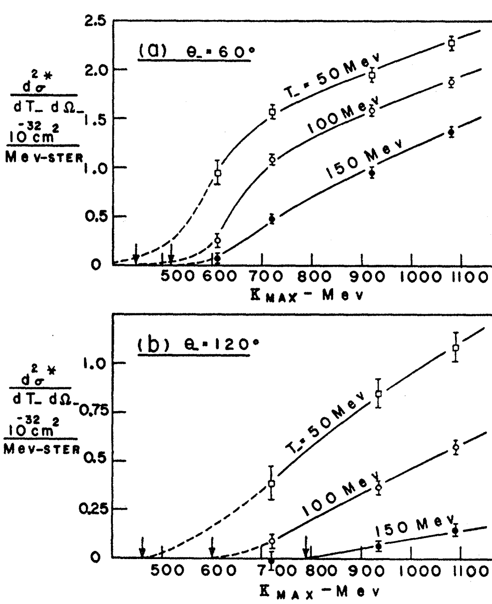

FIG. 1. Yields of negative pions from $\gamma+p$, as a function of the bremsstrahlung cutoff energy $k_{\rm max}$, for pion kinetic energies T_- and laboratory angles θ_-.