Space Properties of the π Meson*

R. L. GARWIN,† G. GIDAL, L. M. LEDERMAN, AND M. WEINRICH
Columbia University, New York, New York

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Measurements have been made of the circular polarization of the decay photons emitted from an "unpolarized" sample of π^0 mesons, the asymmetric emission of μ^+ mesons from cyclotron-produced π^+ mesons, and the asymmetric emission of μ^+ mesons from π^+ mesons produced in weak interactions. All three experiments give negative results.

I. INTRODUCTION

THIS report describes three different investigations of the spatial properties of the pion.

The complete failure of the laws of conservation of parity and of charge conjugation demonstrated in the beta and $\pi\to\mu\to e$ decay interactions[1] led us to search for deeper violations of accepted symmetry principles in two classes of interactions involving π mesons. It appeared to us that the K^+ decay into 2 or 3 pions offered one intriguing possibility, involving the production in a weak interaction of pions, which in strong interaction experiments behave like pseudoscalar spin-zero particles. Our investigation was directed towards demonstrating that such pions exhibit identical spatial properties as those produced in nucleon-nucleon collisions.[2]

Another interesting point is that conservation of linear and angular momentum imposes on the 2-photon decay of the π^0 the requirement that both photons in a given decay be right-circularly polarized or both be left-circularly polarized, but these considerations in no way forbid the emission exclusively of right- (or of left-) circularly polarized photons.[3] Indeed, one can easily visualize a spin-zero system which radiates only right-handed photons, e.g., singlet muonium (μ^+e^-) in the bremsstrahlung that accompanies μ^+ decay.[4]

II. CONSERVATION OF PARITY IN π^0 DECAY

The π^0 experiment was carried out by using the spin-dependent Compton effect to detect the handedness of photons emitted at 90° from the target in the Nevis cyclotron. Since the π^0 lifetime is $\sim 10^{-15}$ sec, all the π^0's produced will decay in the target, which is thus a bright source of π^0-decay photons. In this experiment, Compton recoils ejected from a magnetized iron foil are counted directly, the competing pairs (for which there is no spin dependence) being rejected by pulse-height requirement in a thin counter.

The geometry of Fig. 1 was used. Photons from π^0's decaying in the beryllium cyclotron target were viewed through 2-in.-square apertures at the entrance to the shield wall, the exit from the shield wall, and through an 8-in. thick local collimator of lead blocks. Ten feet of lithium, as shown, reduced the neutron flux to a negligible level. A sample of spins polarized with a

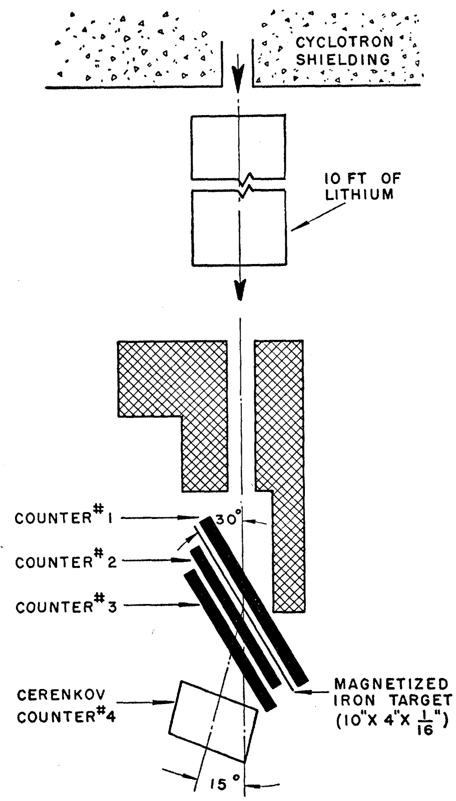

FIG. 1. Apparatus for counting Compton recoils from high-energy photons. Reversal of magnetization in the iron plate allows a measurement of the degree of circular polarization of the π^0-decay photons. Pairs are rejected by using as the "event" counts (12343′) with pulses 3′ being all those pulses from 3 larger than a given discriminator setting.

* This work is supported by the U. S. Atomic Energy Commission and the Office of Naval Research.
† Also at International Business Machines Watson Laboratory.
[1] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957); Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957); J. I. Friedman and V. L. Telegdi, Phys. Rev. **103**, 1681 (1957).
[2] See, for example, C. O'Ceallaigh's report on interaction properties of pions from τ^+ decay in *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, April, 1957* (Interscience Publishers, Inc., New York, 1957), Chap. 8.
[3] R. L. Garwin, *Proceedings of Seventh Annual Rochester Conference on High-Energy Nuclear Physics, April, 1957* (Interscience Publishers, Inc., New York, 1957).
[4] This assumes conservation of leptons. See for example, T. D. Lee, reference 2.

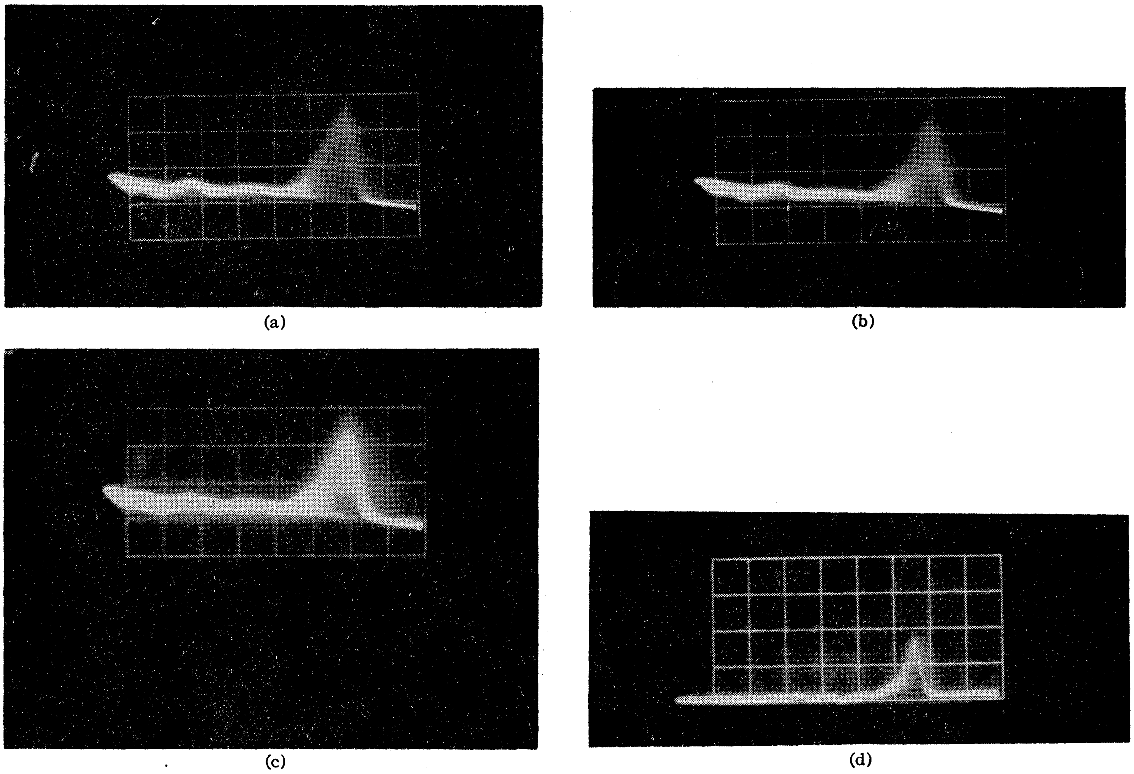

FIG. 2. Pulse-height spectra in counter 3. (a) Pulses from a lead foil at the target position, which give ($\bar{1}234$) coincidence; (b) pulses primarily from single electrons incident, which give (234) coincidence; (c) pairs plus singles (234), with lead foil in target position; (d) pulse spectrum of *c*, but with anticoincidence ($234\bar{3}'$) showing the pulse-height spectrum of the pulses which we count as Comptons.

large component along the beam direction was produced by an iron sheet $\frac{1}{16}$ in. thick which was inclined 30° to the beam direction. This was magnetized by a current momentarily applied to a coil wound on the return yoke. A G.E. fluxmeter was used to monitor the change of flux in the magnetization of the iron.

Fifteen times as many pairs as Compton recoils are produced by 70-Mev photons in iron. Upon including the polarizability of only 2 of the 26 electrons in iron, the ratio of Compton cross section for photon and electron spins antiparallel to that for photon and electron spins parallel is 1.16.[5] This ratio is reduced to 1.010 if no discrimination is made against pairs, requiring 4×10^4 counts to obtain one standard deviation for incident photons which are 100% polarized. Pairs ejected from the iron foil produce ionization loss in counter 3 at least twice that produced by a single minimum-ionizing particle traversing the counter except in rare cases in which one member of the pair was scattered through more than 60° or was stopped in the thin sheet. Compton electrons recoiling in a direction to be counted in the Čerenkov counter (4) give a pulse in counter 3 corresponding to minimum ionization. Calculations by Landau[6] and Symon[7] show ~10% standard deviation in the distribution of ionization loss in $\frac{1}{4}$-in. plastic for high-energy electrons (in fact, almost independent of counter thickness) allowing one to hope to separate electronically the Compton recoils from the pairs. Actually, the situation is better from our point of view, since we are not interested mainly in efficiency but in a clean separation, and the relatively few cases of long-range secondaries are simply not counted. Alternatively, the downward fluctuation from the median ionization loss of pairs is small, thereby spreading very little into the single-electron spectrum.

By recording as "events" coincidences ($\bar{1}234\bar{3}'$) we may reject pairs rather efficiently without losing many Compton counts. $\bar{1}$ serves to prevent single electrons of pairs ejected from the collimator from counting as Compton recoils. The requirement of a pulse in counter 2 prevents pairs produced in the pulse-height measuring counter 3 itself from registering as Compton recoils, as would be the case if the pair were produced in the latter half of the counter. The water Čerenkov counter 4 eliminates neutron-induced and accidental background. In order to eliminate the pairs, the pulse height in counter 3 was examined and if found to be larger than a preset value, this output was fed back as an anticoincidence pulse $\bar{3}'$. In an early stage of the experiment pulses from counter 3 were reduced in amplitude a desired amount by a 100-ohm potentiome-

[5] H. A. Tolhoek, Revs. Modern Phys. 28, 277 (1956).
[6] L. R. Landau, J. Phys. U.S.S.R. 8, 201 (1944).
[7] K. Symon, thesis, Harvard University, 1948 (unpublished).

ter. These were fed to an anticoincidence input on a circuit of standard type.[8]

As monitor we recorded the rejected pairs (234) in another channel of the 3-channel, 10-input coincidence-anticoincidence analyzer. The counters 1, 2, 3, were 6810 photomultipliers without amplifiers viewing $\frac{1}{4}$-in. thick plastic scintillators, while 4 was a 5819 and was used with three distributed amplifiers. With 10 ft of lithium, counting rates proved to be low enough to allow the use of a linear amplifier-discriminator to generate pulse 3′ which could then be used to cancel the $(\bar{1}234)$ fast coincidence pulse. This was more convenient than the fast anticoincidence, since the slow electronics were in the control building with the experimenter. Figure 2(a) shows the pulse-height spectrum in counter 3 of pairs from lead at the target position [scope triggered on $(\bar{1}234)$ output of coincidence circuit]; Fig. 2(b) the pulse-height spectrum of "singles," i.e., not Compton recoils, but predominantly (about $\frac{2}{3}$) single electrons of pairs produced in a $\frac{1}{4}$-in. Pb sheet placed 10-in. ahead of counter 1. In this case the scope was triggered by (234). Figure 2(c) shows the pulse spectrum from pairs and Comptons; while Fig. 2(d) exhibits the pulses from counter 3 which give output as $(\bar{1}234\bar{3}')$ to trigger the scope or to count as "Comptons." The curves of Fig. 3 show the same pulse-height spectra but are now counts of "events" $(\bar{1}234\bar{3}')$ plotted against discriminator setting for the production of $\bar{3}'$ from 3. The "pairs" and "singles" curves were obtained in the geometry discussed above, while the curve labeled (b) is the $(\bar{1}234\bar{3}')$ counting rate as a function of discriminator setting for a carbon target between 1 and 2. About 23% of the cases in which charged particles are ejected from carbon by 70-Mev photons should be Compton recoils (as compared with $\sim$2% for lead), and the Comptons are clearly visible as small pulses (coincidences persisting to low discriminator settings). The curve (b) is so normalized that the theoretical pair contribution is equal to that from lead [curve (a)] in Fig. 3. The difference between (b) and (a) should now be purely Compton recoils, and is drawn as curve (c).

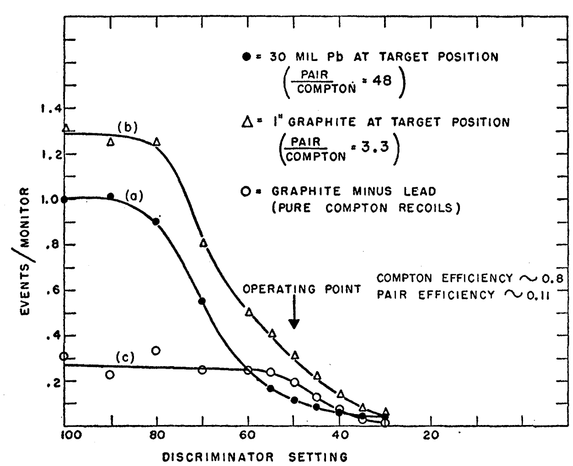

FIG. 3. Pulse-height spectra from (a) lead in target position (pure pairs), (b) carbon in target position (pairs $+\sim$25% Comptons), and (c) the difference between (b) and (a). Curve (c) shows no pair characteristics and is clearly the response of our apparatus to pure Compton recoils.

It was possible, by setting the discriminator at 50, to reduce the lead ("pair") counting rate by a factor 9, while reducing the counts due to Compton electrons a factor of only 1.2. This allows a tenfold reduction in counting time and very greatly improves the sensitivity of the experiment in view of any small hypothetical systematic errors.

Since the counters were those from the μ-resonance experiment[9] and were unaffected by 2000 oersteds in that experiment, the 1-oersted field of the remanent induction in the iron is completely negligible. The experimental procedure consisted of five-minute runs with the iron magnetized along the beam direction, alternated with five-minute runs of opposite magnetization. The effect of drifts, etc., was negligible.

From the observed ratio (1.001±0.004) of counts with field forward to field backward, and from our calibration which shows that from iron under our requirements there still remain twice as many pairs being counted as Comptons, we find a π^0 photon polarization

$$(P=2.0\pm 9.0\%).$$

The error includes some ignorance of the extent to which background dilutes the spin-dependent effect. A positive result could possibly have been interpreted as evidence for higher spin π^0's,[10] were it not for the fact that our observations were made under conditions which preclude polarization of such particles.

The π^0 decay is generally considered to proceed via two steps: (1) The Yukawa reaction $\pi^0\to p+\bar{p}$ (also $\Lambda^0+\bar{\Lambda}^0$, etc. may contribute), and (2) $p+\bar{p}\to 2\gamma$. This experiment would detect violations of parity conservation in either or both reactions. Lee and Yang[11] have reviewed the evidence for parity conservation in some strong and electromagnetic reactions. They found for the latter the mixing of parity-nonconserving terms to be $F^2<10^{-6}$. For the strong interactions, only nuclear scattering and nuclear γ-correlation data were available. In these cases F^2 was found to be $\lesssim 10^{-3}-10^{-4}$. Since our observation measures an interference term, we find for the meson reaction a parity-mixing coefficient $F^2\lesssim 8\times 10^{-3}$.

The technique demonstrated here may well be of value in other investigations where one has systems with initial polarization of high-energy photons.

[8] R. L. Garwin, Rev. Sci. Instr. **24**, 618 (1953).

[9] Coffin, Garwin, Sachs, Penman, and L. M. Lederman, Phys. Rev. **106**, 1108 (1957).

[10] C. N. Yang, Phys. Rev. **77**, 242 (1950).

[11] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956). See also E. Henley and B. Jacobson, Phys. Rev. **108**, 502 (1957).

TABLE I. $\pi-\mu$ decay of π's from τ decay.

π energy	<12 Mev	<15 Mev	Total
B/F	71/39=1.8	85/54=1.6	186/160=1.16

III. ASYMMETRIES FROM τ-π-μ DECAY

In the K^+ study,[12] we have selected τ^+ as a source of weakly produced pions and have searched for a correlation between the direction of the pion relative to that of the τ^+ and that of its decay muon relative to the initial direction of the π^+. No correlation was found between $\pi-\mu$ angles and $\tau-\mu$ angles, the latter being distributed isotropically. The agreement with isotropy in the $\pi-\mu$ angular distribution expected for a spin-zero pion is poor only for low-energy pions, as shown in Table I. Although a front-to-back asymmetry was specifically sought, an energy dependence was not sought but appeared in the examination of the data. It is expected that of the many potential subgroups, some should contain large fluctuations and the subgroup of 110 π^+ mesons with energy ≤ 12 Mev showed the largest deviation from isotropy. Since the energy region was selected which showed the largest asymmetry, it is not known what statistical significance should be given to the results. Since all the events were detected by referring to previously located τ^+'s,[12] no bias is involved in the distributions. However, we feel the effect warrants continued investigation. In fact, it has recently been emphasized by various investigators[13–15] that even for cyclotron-produced pions, the $\pi\rightarrow\mu$ decay distribution had not been extensively studied, although it had been explicitly noted[16] that polarization of the pion beam would certainly confuse the pion-spin experiment.

IV. SEARCH FOR ASYMMETRY IN CYCLOTRON-PRODUCED PION DECAY

We have used the well-known $\mu-e$ correlation in the apparatus of GLW[1] to search for a $\pi\rightarrow\mu$ asymmetry in the Nevis 80-Mev π^+ beam. The pions are stopped in a wire-wound graphite block and the μ's formed by subsequent $\pi-\mu$ decay are caused to precess through appropriate angles, the electron counting rate being used as an analyzer for an assumed angular anisotropy in the emission of muons of tne form:

$$P(\pi,\mu)=1+b\boldsymbol{\mu}\cdot\boldsymbol{\mu}_{\max},$$

where $\boldsymbol{\mu}_{\max}$ is a unit vector in the direction of the maximum asymmetry and $\boldsymbol{\mu}$ is a unit vector in the direction of the muon momentum. Since there is no reason in this case to suppose that the correlation is with the pion momentum vector (a spin $\sigma>0$ would allow polarization *normal* to the production plane) this experiment actually determines the distribution in space of the decay electrons from the $\pi^+-\mu^+-e^+$ decay,

$$P(\pi,e)=1+c\mathbf{e}\cdot\boldsymbol{\mu}_{\max},$$

where $b=-10c$, the factor 10 coming from $P(\mu,e)$ and from the folding process. In GLW,[1] the quantity $\boldsymbol{\pi}\cdot\boldsymbol{\mu}_{\max}$ (projection of the asymmetry vector in the beam direction) was found to be 0.03 ± 0.09. In this experiment, we studied precessions of $\pm90°$, $0°$, $180°$ in the horizontal plane and $\pm90°$ in a vertical plane at 30° to the beam direction. The three components of $b\boldsymbol{\mu}_{\max}$ are exhibited in Table II, where the y axis is

TABLE II. Space components of cyclotron $\pi\rightarrow\mu$ emission asymmetry.

x	0.004 ± 0.018
y	0.025 ± 0.018
z	-0.016 ± 0.012

to the *left* (as seen by the incoming beam), x is in the direction of the pion beam (π), and z is *up*. In the horizontal plane, the distribution observed is

$$P(\pi,\mu)_1=1+(0.025\pm0.025)\cos(\theta-80°).$$

We note that if no prejudice is imposed upon the direction of an assumed asymmetry, the least-squares solutions automatically increase the error appropriately as here stated.

An example of the tests made for spurious effects is the following: In order to test the field sensitivity of the counters in this experimental search for a small effect, we used for the 180° precession in the horizontal plane alternately $\pm180°$. The average of these two sets was used for the 180° point, and the difference (which was less than one standard deviation) showed that there was no significant field sensitivity (the wire-wound carbon block was equipped with a sheet-iron flux-return path as in our original experiments, thereby reducing the external field). A small asymmetry with $\boldsymbol{\mu}_{\max}$ at 45° could be produced because of the finite range of the μ's and a nonuniformity of π's stopping in the target, so that more μ's might escape from the carbon through the back face than through the front, giving a small bias to the distribution at birth of stopped μ's. Because of the small range of the μ mesons and the large straggling of the pions, this effect is expected to be very small, as is the forward-directed asymmetry which would be caused by polarized-muon

[12] This experiment was carried out in collaboration with the Columbia nuclear emulsion group of Bierman, Baumel, Harris, Lee, Orear, and Taylor.
[13] C. M. G. Lattes, report at Varenna Conference on Cosmic Rays, June, 1957 (private communication).
[14] M. Bruin, Physica 23, 553 (1957).
[15] We are indebted to V. L. Telegdi for communicating the details of his and other investigations at the Chicago cyclotron.
[16] Durbin, Loar, and Steinberger, Phys. Rev. 83, 636 (1951); Clark, Roberts, and Wilson, Phys. Rev. 83, 649 (1952).

contamination of the pion beam. Scanning of nuclear emulsions exposed in the position of our carbon block has confirmed the expectations that there exists no muon contamination and no dangerous nonuniformity of stopping pions.

It is apparent that we find no evidence for asymmetry in this study of cyclotron-produced pions.[17] Anisotropies containing even powers of $(\boldsymbol{\sigma}_\pi \cdot \boldsymbol{\mu})$ are not detected in this experiment.

[17] An electronic search for azimuthal variations in $\pi-\mu$ decay in flight by the Chicago group of Crewe, Kruse, *et al.* (private communication) has also yielded negative results.

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Diamagnetism of a Dense Electron Gas

GREGOR WENTZEL
Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

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The theory of Coulomb interactions in a dense electron gas at zero temperature is formally simplified by the introduction of an equivalent Hamiltonian which gives the correct high-density value for the correlation energy. In the corresponding approximation, the diamagnetism of a dense electron gas is found to be the same as that of noninteracting electrons. Coupling with longitudinal sound waves, or a periodic potential, fails to produce a Meissner effect.

1. INTRODUCTION

MUCH progress has been made lately in the study of the Coulomb interactions in a dense electron gas.[1–3] Particularly noteworthy is a paper by Sawada[2] which succeeds in formulating the high-density problem in such a fashion that the pertinent solutions can be constructed in closed form, avoiding the perturbation expansion of Gell-Mann and Brueckner[1] and reproducing their result for the correlation energy. The suppression of long-range Coulomb interactions manifests itself in a simple damping factor (depending on the momentum transfer q), in formal analogy with the so-called damping effect in "scalar pair theory"[4] (equivalent to a renormalization of the coupling constant). Indeed, Sawada invokes this formal analogy as a guide for the construction of his rigorous solutions. Bloch's phonon-like pairs[5] (excited electron plus hole) are the analogs to the "mesons" in pair theory.

It is the purpose of this paper to re-examine some properties of a dense electron gas, taking account of Coulomb interactions in Sawada's approximation. The emphasis will be on the diamagnetic properties, for instance the question: can a dense electron gas behave like a superconductor in a magnetic field (Meissner effect)? Schafroth[6] arrived at a negative answer by treating the Coulomb interaction as a perturbation, in arbitrary order. But this procedure is unreliable since the nonmagnetic energy diverges in every approximation but the first. We shall replace the dubious perturbation expansion by Sawada's high-density approximation and derive the same negative result (for zero temperature). It will also be shown that, in this respect, nothing is changed by coupling the electrons with longitudinal sound waves,[7] or by admitting a periodic lattice potential (Bloch wave functions).

In order to simplify the calculations, we shall first reformulate Sawada's theory in terms of an equivalent Hamiltonian, allowing us to make fuller use of the analogy with meson pair theory. This procedure will prove particularly helpful in the study of diamagnetism.

2. EQUIVALENT HAMILTONIAN

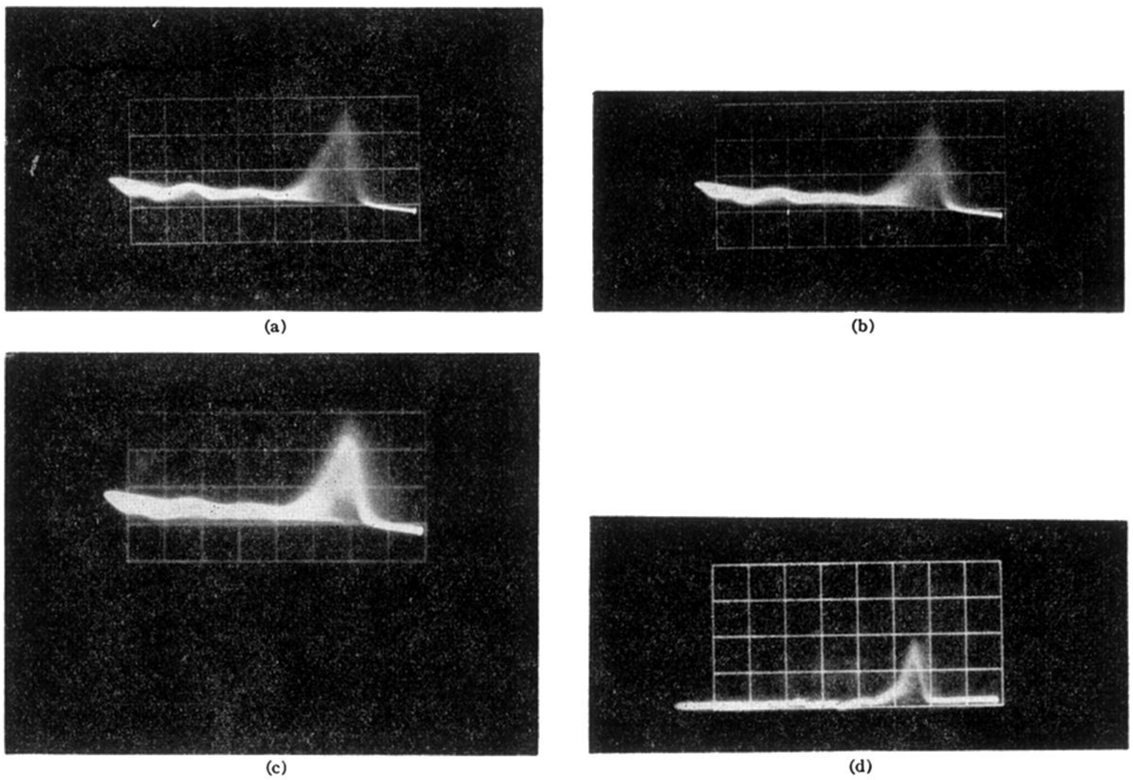
Regarding H_C, the Coulomb interaction potential, we follow Sawada[2] entirely and adopt his approximations as he justified them by comparison with Gell-Mann's and Brueckner's work. In the first place, we discard from H_C all matrix elements which do not contribute to the ground state energy in the limit of infinite electron density.[8] Then, we can rewrite H_C in the following abbreviated form:

$$\begin{gathered} H_C=\tfrac{1}{2}\sum_q \lambda_q C_q^* C_q+\text{const}, \\ \lambda_q=4\pi e^2 q^{-2}\Omega^{-1}, \quad (\hbar=1), \\ C_q=\sum_p (c_{p,q}+c_{-p,-q}^*), \quad c_{p,q}=a_p^* a_{p+q}, \end{gathered} \tag{1}$$

where a, a^* are the fermion absorption and emission operators, and it is essential that p always stands for a momentum vector *inside* the Fermi sphere, and $p+q$ always for one *outside* (the spin will be ignored for the

[1] M. Gell-Mann and K. A. Brueckner, Phys. Rev. **106**, 364 (1957).
[2] K. Sawada, Phys. Rev. **106**, 372 (1957).
[3] Sawada, Brueckner, Fukuda, and Brout, Phys. Rev. **108**, 507 (1957).
[4] G. Wentzel, Helv. Phys. Acta **15**, 111 (1942).
[5] F. Bloch, Helv. Phys. Acta **7**, 385 (1934).
[6] M. R. Schafroth, Nuovo cimento **9**, 291 (1952).

[7] See Schafroth's criticism of H. Fröhlich's theory of superconductivity: M. R. Schafroth, Helv. Phys. Acta **24**, 645 (1951).
[8] Example for an omitted matrix element: two excited electrons make transitions both remaining outside the Fermi sphere.



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