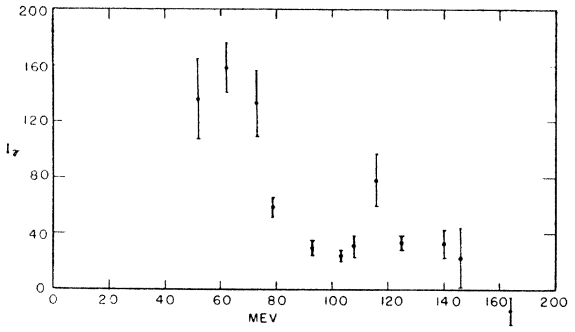

FIG. 2. Gamma-ray intensity as a function of energy. Resolving power "window" is triangular, of 45 percent total base width. One-half its area is contained within ±7.5 percent of peak.

target. If there were sufficient scattered proton flux hitting the hydrogen vessel, then the background count would be much higher. It is known from the experiments of Crandall, Moyer, and York[5] that the cross section for gamma-ray production in H_2 is less than 0.02 of that in carbon; since there is more weight of steel than of H_2 "seen" by the pair spectrometer, and since the background is always less than one-half the total count, the H_2 counts cannot be due to direct production.

Several experiments were made using materials other than H_2. Null results were obtained in helium, carbon, polyethylene (CH_2) and lithium hydride. The fact that null results were obtained in hydrogeneous materials like CH_2 and LiH is a matter of particular interest. It indicates that the probability of final capture in a K-orbit in H_2 in a hydrogeneous compound is small (in fact is less than 1×10^{-3} in CH_2 and less than 3×10^{-3} in LiH). The physical reason is presumably that although a fairly large fraction of π^--mesons is initially captured into high Bohr orbits in hydrogen, the neutral π^-−H system will then diffuse through the lattice and make collisions with C or Li atoms, respectively. During the collisions the π^- in the high Bohr orbit has a large probability of being captured by a Li or C nucleus, with consequent production of a nuclear star rather than a gamma-ray.

The case of absorption of π^--mesons in H_2 as compared with absorption in other materials is a singular one, since the reaction $\pi^-+H^+\rightarrow n$ is possible only in the presence of other nucleons; for absorption by the free proton an additional particle of integral spin must be emitted. Such an additional particle might be a single photon, or, if energetically permitted, a neutral π^0-meson. The details of the absorption process have been discussed by Marshak and Wightman[6] and Wightman.[4] In particular, it has been shown that the sum of the slowing down time, capture time, and arrival time in the K-orbit, caused by collisions leading to Auger electrons, is sufficiently short to compete effectively with the $\pi-\mu$-decay time.[7]

The results plotted in Fig. 2 permit us to state definitely that (1) the emitted gamma-rays are not monochromatic near 130 Mev; (2) the group of points near 130 Mev is not just the tail of a distribution near 70 Mev; the points are significantly higher than the amount inferred from the finite resolving power and a peak near 70 Mev. In terms of number of counts the intensity at 130 Mev approximately equals the intensity at 70 Mev; the curve (Fig. 2) results from the conversion factors pertaining to the spectrometer.

Accordingly let us consider three processes:

$$\pi^-+H\rightarrow n(9\text{ Mev})+\gamma(132\text{ Mev}), \quad (1)$$

$$\pi^-+H\rightarrow n+2\gamma, \quad (2)$$

$$\pi^-+H\rightarrow n+\pi^0+Q, \quad \pi^0\rightarrow 2\gamma \quad (3)$$

Process (2) can almost certainy be ruled out. First, the distribution function seems to be incompatible with any reasonable distribution from a two gamma-process. Second, it is very difficult to see how a selection rule favoring a two gamma-process over a one gamma-process could be constructed.

Accordingly we are led to interpret the results of Fig. 2 in terms of competition between processes (1) and (3). These processes have been discussed by Marshak and Wightman;[6] in particular they derived the lieftimes of processes (1) and (3) under various assumptions as to the character of the meson. The evidence concerning gamma-rays from the cyclotron target[2] in combination with the recent results on gamma-gamma-coincidences obtained from material bombarded in the 330-Mev x-ray beam of the synchrotron[8] is highly convincing that a π^0-meson exists and also that it cannot have spin 1.

If the interpretation that both processes (1) and (3) exist is inferred from the data, then some important approximate quantitative conclusions can be drawn. The first conclusion relates to the mass of the π^0-meson. The width of the "π^0-peak" is defined by the Doppler shift of the gamma-ray emitted by the decay of the π^0-meson and is thus a measure of the reaction energy Q of process (2). If δ is the fractional half-width of the π^0-peak, we can easily show that $\delta=p/M_{\pi^0}$, where p is the momentum of the π^0 and the neutron. From the data we can conclude that $\delta<0.21$, and hence we obtain a direct measure of the upper limits on the kinetic energies of the neutron and π^0. Accordingly the mass difference ΔM between the π^-- and π^0-mesons must obey the inequality: $1.3\text{ Mev}<\Delta M<4.7$ Mev. It is expected that further experiments will narrow these limits considerably.

Since the π^- is principally captured from an orbit of zero angular momentum, and since the kinetic energy of the π^0 is so small that it can be emitted as an S wave only, one can conclude that the π^-- and π^0-mesons have equal parity. Direct calculations[6] based on the various forms of meson theories using the relative magnitudes of π^0- and gamma-yields have been made and yield estimates of the coupling constants involved.[9]

It should be pointed out that the above calculations are significant only if the qualitative arguments for process (3) can be justified.

The authors are indebted to Mr. Hugh Smith for mechanical design and to the operating crew of the 184-in. cyclotron for bombardments. The authors have benefited greatly by discussion of this problem with Drs. Wick and Marshak.

* This work was performed under the auspices of the AEC.

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An Oscillographic Method for Observing Magnetic Resonance Spectra

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A NUMBER of paramagnetic salts, especially those containing ions of the iron group, under the influence of a high frequency magnetic field H and of a steady magnetic field H_0, normal to the former, show one or more peaks of energy absorption for different values[1] of H_0 according to the formula:

$$hc/\lambda=g\beta H_0,$$

where g is Landé's constant, β is Bohr's magneton, and the other symbols have their usual meanings.

This resonance absorption has been investigated by several authors, at least qualitatively, by means of a resonant cavity, enclosing a single crystal or powder of the substance placed in the

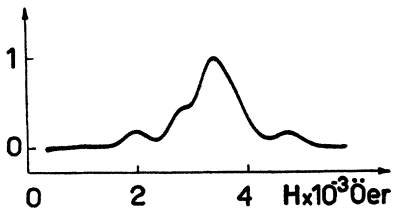

FIG. 1. Oscillogram of the spectrum for potassium chrome alum.

maximum of the magnetic field H and therefore in a node of the electric field, in order to reduce the electric losses. At the same time the substance is subjected to a static magnetic field, the intensity of which is checked with great accuracy. The energy absorption is recorded through the measure of the loaded Q-factor of the cavity. The investigations are carried out with a static method, being the absorption diagram determined point-by-point by many successive measurements.

In the present dynamical method the absorption spectrum is obtained on a cathode-ray oscillograph. On the X-axis the deflection of the cathode beam is proportional to the magnetic field $H_0(t)=H_{01}+H_{02}\sin 2\pi\nu t$ ($\nu=50$ c.p.s.). An integrating circuit is connected with two coils linked with the magnetic field and situated just above and below the absorption cavity. Through a phase shifter, the phase difference between the magnetic field inside and outside the cavity is corrected; the output voltage is applied to the X-axis of the oscillograph.

The Klystron oscillator, which supplies the high frequency power with a wave-length $\lambda\sim 3.16$ cm, is modulated at a frequency of 5×10^4 c.p.s. Such a frequency modulation is transformed into an amplitude modulation determined by the resonance curve of the cavity. A microwave receiver, with a silicon crystal rectifier, placed in a small resonant cavity, is coupled with the measuring cavity. The voltage at the terminal of the crystal is brought to a selective amplifier, tuned to the second harmonic of the modulation frequency (10^5 c.p.s.). At the output of the amplifier the voltage amplitude is a function of the Q of the cavity and hence of the energy absorption. Small variations of Q, and there are always such, are proportional to the variations of the voltage. These are amplified and applied to the input terminals of the Y-axis of the oscillograph, that records directly the oscillogram of the spectrum under examination.

In the discussion of the theory[2] the crystal is assumed to be a square-law detector, since the energy is quite low in the receiver. The fractional deflection on the Y-axis depends linearly (with good approximation) on $\Delta Q/Q$, the term of second-order being ~ 3 percent of the term of first order up to $\Delta Q/Q<5$ percent, assuming for the parameters of the system generator-cavity-detector the following values: $Q\sim$some hundreds; the ratio between mean frequency of the Klystron and the resonance frequency of the cavity $\sim 1:10^{-4}$; the alternating repeller voltage being of the amplitude of ~ 6 volt and of the stated frequency (5×10^4 c.p.s.); $\lambda\sim 3.16$ cm as stated above, and taking into account also the Klystron characteristic parameters. The deflection of the cathode beam does not depend on the variations of the real part of the magnetic permeability, which necessarily accompany the variations of the imaginary part.

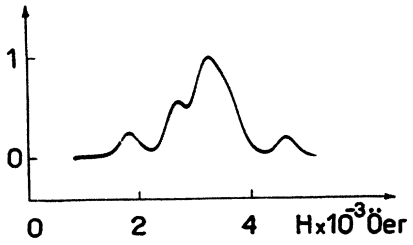

FIG. 2. Oscillogram of the spectrum for ammonium chrome alum.

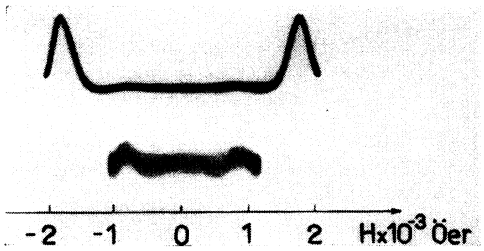

FIG. 3. Oscillogram of the spectrum for ammonium chrome alum, for low values of the magnetic field. The lower curve, traced with the greater amplification, shows the presence of the peak for $H=900$ oersted.

With this method two chrome alums, (potassium chrome alum and ammonium chrome alum) have been examined. In Figs. 1 and 2 the spectra of these salts are shown for the orientation (111). It is worth noting the presence of a small peak of absorption not observed previously, with $H=900$ oersted; this fact is shown on Fig. 3, referring to the spectrum of ammonium chrome alum, which has been obtained with $H_{01}=0$, $H_{02}\sim 2200$ oersted. The splitting determined by the electric field owing to the presence of water molecules of crystallization, is $\delta=0.12_2$ for potassium chrome alum and $\delta=0.13_4$ for ammonium chrome alum.

The authors wish to acknowledge the assistance of Professor Daglio and Dr. Garelli.

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Erratum: On the Role of the Subsidiary Condition in Quantum Electrodynamics

[Phys. Rev. **78**, 149 (1950)]

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IN Section III, pp. 151 and 152, the transverse field $\mathfrak{A}_\mu(x)$ defined by Eq. (46), a field $\mathcal{A}_\mu(x)$ defined by Eq. (32),

$$\mathcal{A}_\mu(x)=A_\mu(x)+\partial_\mu B(x),$$

and the ordinary vector potential $A_\mu(x)$ have been confused by a series of typographical errors. $\mathfrak{A}$ should be replaced by $\mathcal{A}$ everywhere on p. 151. A should be replaced by $\mathcal{A}$ in Eq. (34) and on the left-hand side of (48). The last sentence of Section III should read: We may therefore replace $\mathcal{A}_\mu$ by the transverse field $\mathfrak{A}_\mu$ in this case.

The following note was to have been added in proof but was omitted through error. In a recent Letter to the Editor (Phys. Rev. **77**, 420 (1950)) F. J. Dyson discusses the role of the longitudinal photons in Schwinger's theory. Dyson's result is essentially contained in his Eq. (7), which is an immediate consequence of our Eq. (81) as it should be since the definition of the vacuum state is the same as in the present paper.

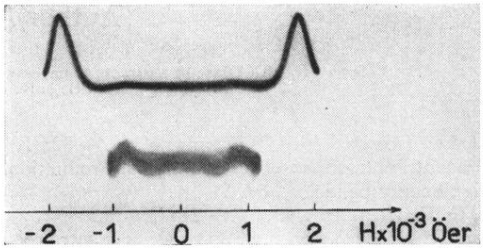

FIG. 3. Oscillogram of the spectrum for ammonium chrome alum, for low values of the magnetic field. The lower curve, traced with the greater amplification, shows the presence of the peak for $H=900$ oersted.