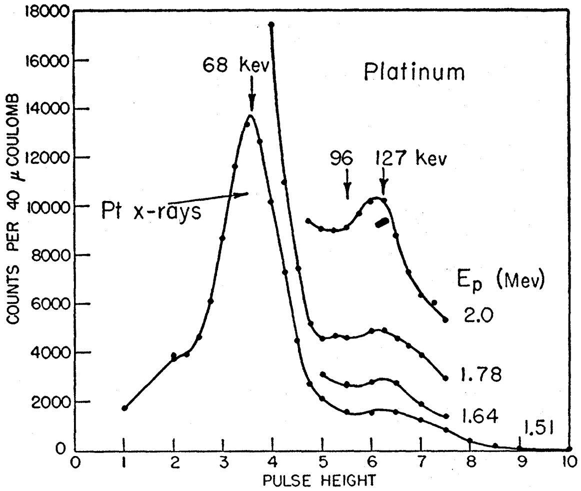

FIG. 2. Pulse-height spectrum of Pt at four proton energies E_p. A small adjustment has been made in the horizontal position of the data taken at $E_p = 2.0$ Mev in order to correct for electronic drift in the spectrometer.

higher level in $_{73}Ta^{181}$ decaying to the ground state. This would imply the presence of 345-kev radiation as well, and some evidence for this has been observed.

After studying the Au radiation, we made an amalgam and examined the increment due to Hg. There is clearly a reproducible break in the curve at an energy of about 200 kev which increases with proton energy. At least two isotopes of Hg are reported to have levels which could account for radiation of this energy.

We examined Tl (cp) and observed a well-resolved peak at 380 ± 10 kev. This radiation does not correspond to transitions between known levels to the best of our knowledge. The 280-kev radiation, from Tl^{203}, if present, would have been obscured by the Compton peak from the 380 kev and the high-energy tail of the x-rays. Preliminary tests on Bi as yet have yielded no significant results.

In the future we plan to use only thin targets since these are not only essential for accurate cross-section measurements, but also result in a greatly reduced x-ray background. We can also further reduce the x-ray background by critical absorption foils, a technique which we have already used successively to a limited extent.

We wish to express our sincere thanks to Professors Deutsch, Feshbach, and Weisskopf, and Dr. de-Shalit and Dr. Ajzenberg for their advice and encouragement.

* This work was supported by the Bureau of Ships and the U. S. Office of Naval Research.
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Radiative Corrections to Nuclear Forces in Pseudoscalar Theory*

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IT has been recently pointed out by the author, Gell-Mann, and Goldberger[1] (in a paper to be referred to as I) that a simple subset of radiative corrections to the nucleon propagation function has the effect of strongly depressing nucleon pair formation in pseudoscalar theory with pseudoscalar coupling. The effects on meson scattering and nuclear forces are then very pronounced. It is the purpose of this note to show that these effects also appear in a simple way in a consistent formulation of the relativistic two-body problem. For this we consider the Bethe-Salpeter equation for the bound state[2] (the consideration of the scattering problem is not essentially different) which has the form

$$\varphi(p_1, p_2) = S_F(p_1)S_F(p_2)\int d^4p_1' d^4p_2' \times G(p_1, p_2; p_1', p_2')\varphi(p_1', p_2'), \quad (1)$$

where $G(p_1, p_2; p_1', p_2')$ is the kernel of the integral equation. A method proposed for attacking this problem is to expand the kernel in a power series in the coupling constant but to attempt to solve the resulting simplified equation exactly. The first approximation to the integral equation [Eq. (1)] can then consistently be assumed to arise from taking all contributions of order g^2 which lead from the state $\varphi(p_1, p_2)$ to the state $\varphi(p_1', p_2')$. These are shown in the form of Feynman diagrams in Fig. 1.

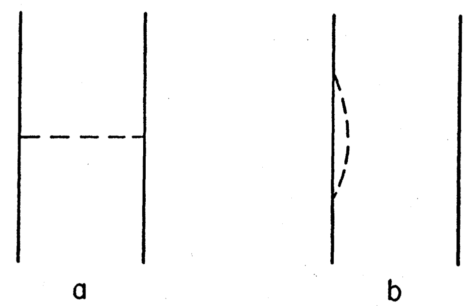

FIG. 1. Feynman diagrams for the g^2 contributions to the kernel.

Diagram (a) of this figure gives rise to the usual "ladder" approximation;[2,3] the second diagram (b) corresponds to a vacuum fluctuation for the nucleon and would give no contribution in a Born approximation calculation. The finite contribution from this graph is, however, not in general zero (vanishing only on the energy shell) and cannot be consistently dropped in this approximation. It can be treated in the following way; in the zeroth approximation (of order g^2) to the kernel, one obtains the following contributions:

$$G^0(p_1, p_2; p_1', p_2') = G^0_{\text{ladder}}\delta(p_1+p_2-p_1'-p_2') + G^0_{\text{radiative}}\delta(p_1-p_1')\delta(p_2-p_2'), \quad (2)$$

where

$$G^0_{\text{ladder}} = g^2\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2(\gamma_5)_1(\gamma_5)_2 D_F(p_1-p_1') \quad (3)$$

and

$$G^0_{\text{radiative}} = g^2\sum_{\lambda=1}^{2}\boldsymbol{\tau}_\lambda\cdot\boldsymbol{\tau}_\lambda\int[\gamma_5 S_F(p_\lambda-k)\gamma_5]_\lambda D_F(k)d^4k. \quad (4)$$

The finite parts of $G^0_{\text{radiative}}$ have been previously evaluated; in the notation of I,

$$G^0_{\text{radiative}} = -(3g^2/16\pi^2)[f(p_1)+f(p_2)]. \quad (5)$$

The only property of $f(p)$ which we shall consider here is that $f(p)$ vanishes on the energy shell but is approximately equal to one if the momentum-energy relation between $\gamma\cdot p$ and M is that of an antiparticle.

The integral equation [Eq. (1)] now becomes

$$\varphi(p_1, p_2) = S_F(p_1)S_F(p_2)\{1+(3g^2/16\pi^2)[f(p_1)+f(p_2)]\}^{-1} \times\int d^4p_1' d^4p_2' G^0_{\text{ladder}}\delta(p_1+p_2-p_1'-p_2')\varphi(p_1', p_2'), \quad (6)$$

which differs from the ladder approximation in that the propagation functions $S_F(p)$ have been replaced by $S_F'(p)$, where

$$S_F'(p_1)S_F'(p_2) = S_F(p_1)S_F(p_2)\{1+(3g^2/16\pi^2)[f(p_1)+f(p_2)]\}^{-1}.$$

The corresponding modification of the Feynman diagrams which represent the ladder approximation is to include an infinite set of radiative corrections to each nucleon line corresponding to the successive emission and reabsorption one at a time of any number of mesons. The properties of these modified propagation functions have already been discussed in I; they differ little from the original functions if particles (1) and (2) are moving as nearly free particles. If however pair formation has occurred as is characteristic of the pseudoscalar theory even when the nucleons are interacting rather weakly, then the modification of the propagation functions is very large. Accordingly the effect will be small only if an adiabatic approximation[2,3] is made to the integral equation which does not involve pair formation. The next contributions to the adiabatic approximation to the equation involve the formation of zero, one, or two nucleon pairs, as is shown in Fig. 2, which will be decreased

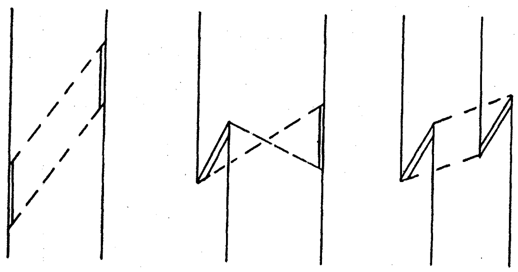

FIG. 2. g^4 contributions to the potential in the adiabatic approximation. The doubled nucleon lines represent propagation functions modified by radiative corrections.

in the nonrelativistic region by factors of approximately one, $(1+3g^2/16\pi^2)$ and $(1+3g^2/8\pi^2)$, respectively. More generally, the radiative effects tend to prevent inversion of the nucleon line in time, i.e., pair formation, which is similar to the result already discussed in I.

Similar comments also apply to the formulation of the relativistic integral equation[4] describing meson-nucleon scattering. In that problem the g^2 kernel includes not only the two usual Compton contributions but also radiative terms for both the meson and nucleon which lead to replacement of S_F and D_F by S_F' and D_F' which differ by damping radiative terms similar to those discussed above.

Finally it may be remarked that while the treatment of the radiative terms in the g^2 kernel as suggested here is fairly nonambiguous, the method of inclusion of radiative effects in higher-order terms in the kernel of Eq. (1) still remains somewhat arbitrary.

The author is indebted to Professor H. Bethe for interesting discussions of this and related problems.

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Bubble Chamber Tracks of Penetrating Cosmic-Ray Particles*

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TRACKS of penetrating cosmic-ray particles passing through an ether-filled bubble chamber under 10 cm of lead have been recorded by flash photography triggered by a twofold vertical coincidence telescope. The bubble chamber consisted of a heavy-walled cylindrical Pyrex bulb 3 cm long and 1 cm inside diameter, which communicates with a pressure-regulating device by means of a Pyrex capillary tube 45 cm long. A thermostated temperature bath of mineral oil surrounded the bulb, maintaining

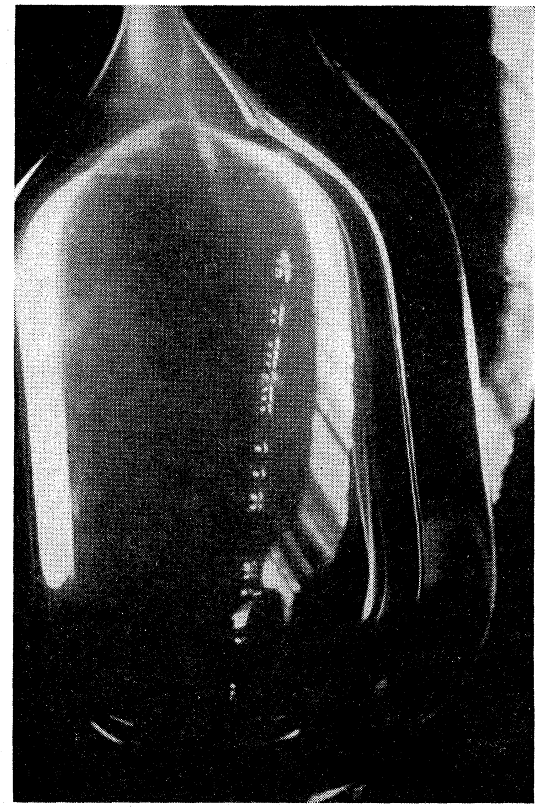

FIG. 1. Flash duration 20 microseconds, no deliberate delay, temperature 140°C.

the temperature constant within 0.5°C in the range 138°C to 143°C. The pressure-regulating device consisted of a brass cylinder of length 2 cm and inside diameter 3 cm. One end of the cylinder was sealed with a flexible diaphragm of $\frac{1}{8}$-in. Neoprene faced with Teflon to confine the ether and permit variation of its pressure by controlling the pressure of compressed gas on the outside of the diaphragm.

To prepare for taking a picture of a track, the ether was compressed by admitting compressed nitrogen to the pressure regulator at a pressure of 300 pounds per square inch so that no vapor bubbles remained in the system. Then the gas was allowed to escape, so that the ether suddenly became highly superheated at atmospheric pressure. On the average the liquid remained quietly in this unstable condition for several seconds until a violent eruptive boiling occurred. If a coincidence of the vertical counter telescope occurred during this waiting time, a picture was taken by means of a xenon discharge flashlamp. About 5 seconds were required to recompress the ether in preparation for the next event.

Figure 1 shows a track obtained at a temperature of 140°C with a flash duration estimated to be 20 microseconds. In Fig. 2 the duration was reduced to about 5 microseconds, the temperature 141°C. Here one sees a scattering of about 2°.

From these sample pictures several characteristics of bubble chambers and their possible applications to high-energy nuclear physics can be inferred. Because of the relatively high density of the sensitive medium (about 0.5 g/cc under these conditions), there is a good chance of seeing an interesting event occurring in the liquid where most of the secondaries would be visible. Since the particles recorded here are almost certainly fast mu mesons, one concludes that the bubble chamber is sensitive to minimum ionizing particles. Since the bubbles grow so extremely rapidly, there are virtually no distortions of the tracks due to convection