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

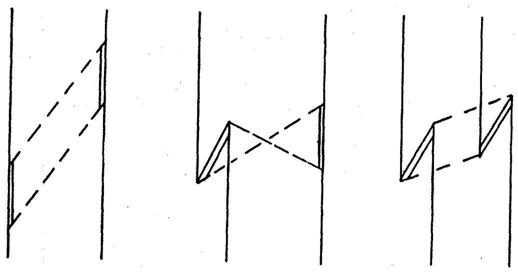

FIG. 2. g^4 contributions to the potential in the adiabatic approximation. The doubled nucleon lines represent propagation functions modified by radiative corrections.

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.

* Supported by a grant from the National Science Foundation.

[1] Brueckner, Gell-Mann, and Goldberger, Phys. Rev. **90**, 476 (1953).
[2] E. E. Salpeter and H. A. Bethe, Phys. Rev. **84**, 1232 (1951).
[3] M. Lévy, Phys. Rev. **88**, 72 (1952).
[4] Compare, for example, Karplus, Kivelson, and Martin, Phys. Rev. **90**, 1072 (1953).

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

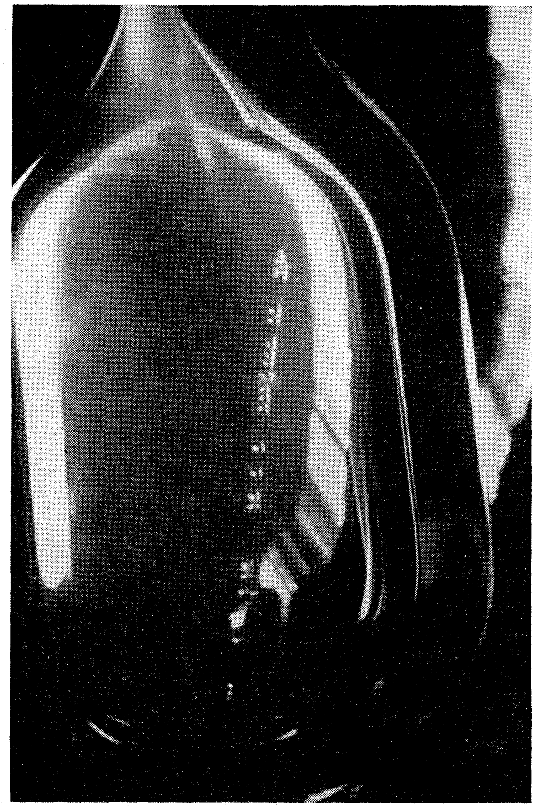

FIG. 1. Flash duration 20 microseconds, no deliberate delay, temperature 140°C.

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 currents in the liquid. Another interesting possibility arising from the rapid bubble growth is that one could take multiple exposure photographs of events so that a measurement of bubble size could tell the relative ages of tracks in the range 0 to 100 microseconds. It should be possible to construct larger bubble chambers, to use liquids of various composition and density, and to calibrate the bubble density along a track in relation to the ionization density.

In order to estimate the conditions under which a bubble chamber will be useful as a detector of ionizing radiation, and to guide the choice of a working liquid, an approximate theory of the stability of charged bubbles in superheated liquids has been developed. To understand the result let us first suppose that as a result of thermal fluctuations a tiny spherical bubble at least several molecular diameters across is formed in the liquid and that a single ion is made inside the bubble by an ionizing event. It is easy to show that the ion will run to the surface of the bubble, and that the energy contribution of its electric field is such as to encourage the collapse of the bubble. If, on the other hand, the bubble contains a number of ions, they will distribute themselves roughly uniformly over the surface and aid its growth. When only two or three ions are present, the result is not clear cut, and depends on the detailed shape of the bubble and the mechanism by which the ions are prevented from escaping into the bulk of the liquid.

The main result of the theory, in the continuously distributed charge approximation, is that for a bubble carrying n charged ions to grow to visible size, the liquid must be superheated so that the normal saturated vapor pressure p_∞ exceeds the actual applied pressure on the system by the amount

$$p_n(T)=3/2\left(\frac{4\pi}{n^2e^2}\right)^{1/3}[\sigma(T)]^{4/3}[\epsilon(T)]^{1/3}. \quad (1)$$

This result neglects the dependence of the surface tension σ and dielectric constant ϵ on the curvature of the surface and on the pressure.

To find the temperature at which a bubble chamber will operate, one plots $p_n(T)$ and $p_\infty(T)$ *versus* T on the same graph. The intersections for the various n give the required temperatures and pressures. For diethyl ether the predicted and measured temperatures are closer than 10°C if n is something between 2 and 10.

If ionizing radiation is the limiting factor in an experimental attempt to obtain high superheats in pure liquids, one would expect the present theory to predict maximum attainable superheats. For the few liquids for which good data are available the agreement is within 20°C or better.

In its broad outlines this analysis parallels that of droplet growth in a supersaturated atmosphere. The present multiple-charge modification extends the effect so that ionizing events can make a growth-aiding contribution to the surface free energy of a particle of new phase in any nucleation situation in which the two phases have a difference of dielectric constant. This fact may have interesting consequences for the influence of ionizing radiation on nucleation in supercooled liquids, supersaturated solutions, etc.

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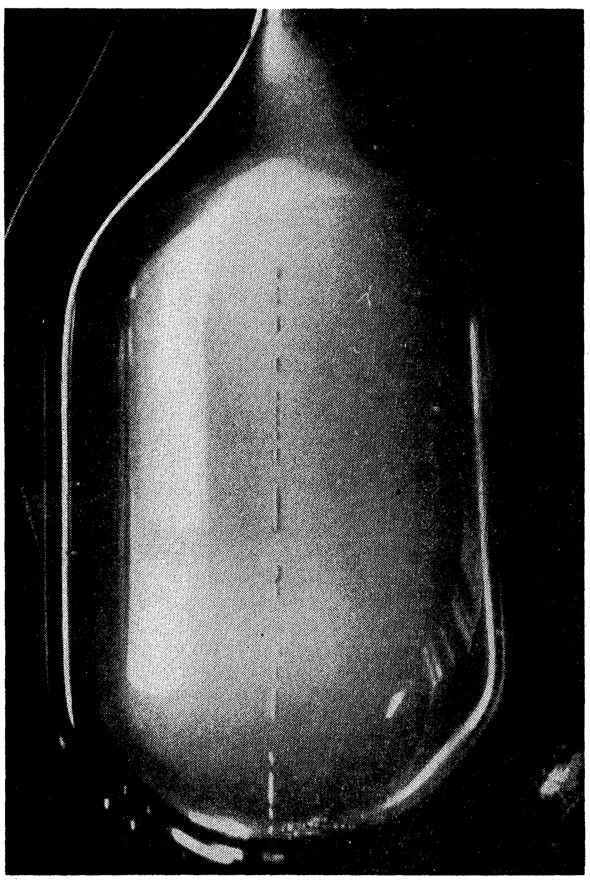

FIG. 2. duration 5 microseconds, no deliberate delay, temperature 141°C.

Patterns in Alpha Spectra of Even-Even Nuclei

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THE present communication aims to bring out some definite regularities in the spectra of even-even alpha emitters without elaborating particularly on the possible significance of these findings regarding alpha-decay theory and spectroscopic states of heavy nuclei. Most of the data to be discussed were obtained over the range of elements from curium 96 to radium 88 since it is inherently difficult to make the necessary measurements for elements below radium.

We shall first suggest some means to identify the energy states which seem to recur generally and to designate the alpha transitions leading to these states. The first rule for even-even alpha emitters is that the most prominent alpha group leads to the ground state of the product nucleus as would be expected from previous alpha-decay theory. (This is not the case for nuclear types having odd nucleons.) In addition, an alpha group is invariably found which leads to a level with spin 2 and even parity, and the abundance of this group likewise conforms in first approximation with the expectations from unadorned alpha-decay theory. The energy level of this excited state will be termed the *first even-spin state* and lies about 40 kev above the ground state at plutonium, increasing with decreasing mass number as already described.[1,2] In low abundance are found alpha groups leading to other levels which we shall term *second and third even-spin states.* In the few cases for which gamma-ray data are available it seems probable that these levels have even parity as well as even spin and may very well be 4+ and 6+ states. There is some fragmentary evidence in our work that an odd-spin odd-parity state is appearing in a limited region, but this will not be discussed further at present.

Bohr and Mottelson[3] have suggested that nuclides well beyond a closed shell have states in which the nucleus acts as a rigid rotator. The energy of such rotational levels should be proportional to $J(J+1)$, where J is the total angular momentum quantum number. If we consider the 2+ and 4+ states to be rotational states, the ratio of the energies should be 3.3. Figure 1 shows

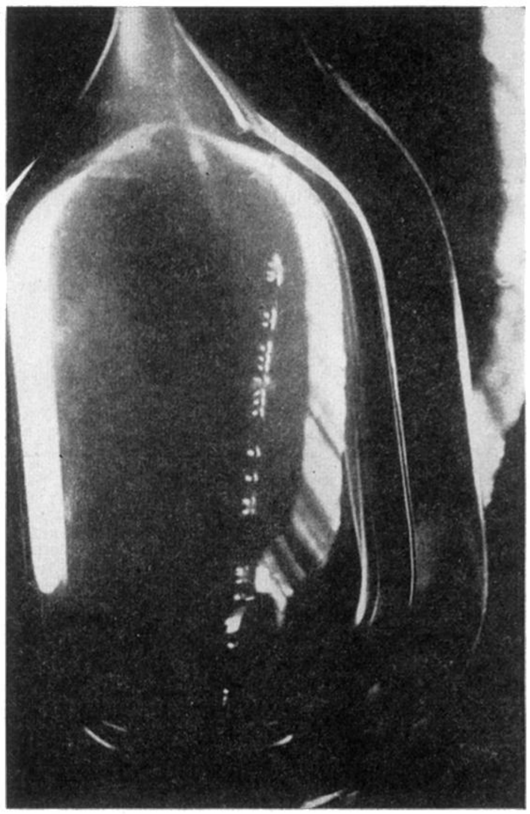

FIG. 1. Flash duration 20 microseconds, no deliberate delay, temperature 140°C.

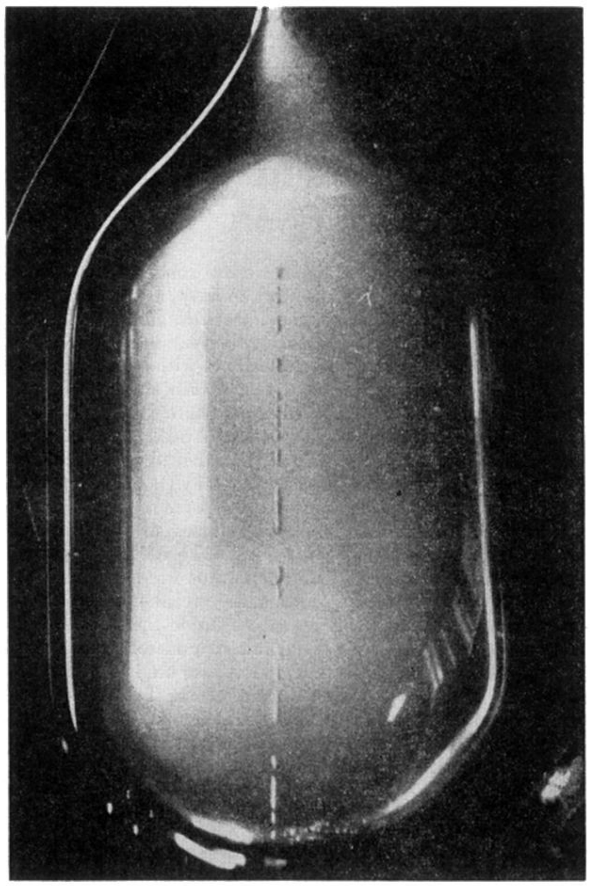

FIG. 2. duration 5 microseconds, no deliberate delay, temperature 141°C.