Comments and Communications

Creation of Mesons by High-Energy Particles

The construction of a number of electron synchrotrons in the United States raises the question as to whether it will be possible to observe the creation of mesons in these machines. It seems, therefore, to be of importance to have an estimate of the cross sections for the creation of mesons by nuclear particles, β- or γ-quanta.

The present state of meson theory is far from certain. Also, for low energies, in the neighborhood of the threshold, the Born approximation, generally used for the calculation of cross sections, is not too good an approximation, and for high energies it is still a more or less open question how, satisfactorily, to take into account radiation damping. Finally, for an exact calculation, one has to take into account the fact that the nucleons are moving in the Fermi gas in the nucleus, which is supposed to be at rest.

In view of all these points, it seems worth while to try to estimate the cross sections of meson production by simple dimensional considerations. The results obtained in this way are probably correct within factors of the order of magnitude of 10 and may give an indication of the phenomena to be expected.

This work is essentially an extension of the recent work of McMillan and Teller (*Phys. Rev.*, 1947, 72, 1). These authors determined the way in which the cross section for the creation of mesons depends on the energy of the bombarding particle by calculating the available volume in momentum space. Although their paper deals only with the case of a bombardment by nucleons, it is, of course, possible to use their method also for the case of a bombardment by β- or γ-quanta.

We shall first investigate the cross section for the creation of mesons in the neighborhood of the threshold, *i.e.* for the case where the energy of the bombarding particle is only slightly higher than the minimum energy required for the creation of a meson. In that case, the cross section can be written as the product of three factors. The first is a power of ε, where ε has the same meaning as in the paper of McMillan and Teller, whose notation we shall use throughout:

$$\varepsilon = \frac{E - E_t}{E_t}.$$

Here E is the energy of the bombarding particle; E_t, the threshold energy.

The second factor will be made up of factors $e^2/\mathrm{h}c$ and $g^2/\mathrm{h}c$, g being the coupling constant of the meson field.[1] For every electromagnetic process involved in the reaction, we get a factor $e^2/\mathrm{h}c$, and for every mesonic process, a factor $g^2/\mathrm{h}c$.

The final factor will be $\pi\lambda_t^2$, where λ_t is the wave length of a bombarding particle with threshold energy. [Under the wave length of a particle with momentum p, we understand the quantity $\lambda = \mathrm{h}/p$. For all practical purposes λ is equal to the Compton wave length of the meson, since $E_t \approx \mu c^2$ ($^t\lambda_t = \mathrm{h}/p \cong \mathrm{h}c/E \approx \mathrm{h}/\mu c = \lambda_\mu$).]

In this way we get:

$$\sigma = K\pi\lambda_t^2\ (e^2/\mathrm{h}c)^a\ (g^2/\mathrm{h}c)^b\ \varepsilon^c, \tag{1}$$

where a, b, and c depend on the reaction considered and the kind of meson produced. Formula (1) is actually only the first term of a power series in ε, the higher-order terms of which we have neglected. In order to get the numerical constant K, one would have to calculate rigorously the matrix elements corresponding to the reaction considered. We shall assume that these matrix elements do not depend on ε and that K is of the order of magnitude of unity.

For high energies of the bombarding particle, we should expect the cross section to be given by:

$$\sigma = \pi\lambda^2\ (e^2/\mathrm{h}c)^a\ (g^2/\mathrm{h}c)^b, \tag{2}$$

where again we have assumed the matrix elements not to depend on the energy. The only energy dependence arises, then, from λ^2 or E^{-2}. We may draw attention here to the fact that McMillan and Teller have essentially the same formula as formula (2), without, however, the factors $g^2/\mathrm{h}c$. It seems to us that this neglect of the influence of the coupling is the reason why they obtained a much larger cross section than Horning and Weinstein (*Phys. Rev.*, 1947, 72, 251).[2]

We have now to calculate the quantities a, b, c, in three cases, viz., bombardment by nucleons (A), by electrons (B), or by photons (C).

(A) In the first case, we can use the results of McMillan and Teller or Horning and Weinstein for the determination of c. We then get $c = 7/2$. In order to determine a and b, we have to remember that the reaction also includes, apart from the creation of the final meson, the emission and reabsorption of a (virtual) meson so that momentum can be conserved. Since no electromagnetic processes are involved, we have $a = 0$, $b = 3$, and we get for the final cross section in the neighborhood of the threshold:

$$\sigma_A = \pi\lambda_t^2\ (g^2/\mathrm{h}c)^3\ \varepsilon^{7/2}, \tag{3A}$$

which agrees with the formula of Horning and Weinstein, apart from a numerical factor of the order of magnitude of unity.

(B) If the bombarding particle is an electron, one can again use the same considerations as in case A to determine c. We have checked this result by actually calculating the available volume in momentum space ($\int d\mathbf{p}_n'\, d\mathbf{p}_n\, d\mathbf{p}_i'$), using Horning and Weinstein's method. For c we find, again, 7/2. The reaction can be described as

[1] The symbol, h, is Dirac's constant, *i.e.* Planck's constant, h, divided by 2π.

[2] I should like to express my thanks to Dr. Horning for writing me some details of the calculations leading to their final result. These have been of great help to me in checking some of the results of this note.

the emission of a (virtual) γ-quantum by the electron, the absorption of this quantum by a nucleon, and the subsequent emission of a meson. Hence, we have $a=2$, $b=1$, and

$$\sigma_B = \pi\lambda_t^2\ (e^2/hc)^2\ (g^2/hc)\ \varepsilon^{7/2}. \tag{3B}$$

(C) In the final case, where we have the photomesic effect, we get for c the value 5/2. (The volume in momentum space reduces to $\int dp_n'\ dp_n$.) Since the reaction consists of the absorption of the photon and the emission of a meson, we have $a=b=1$, and

$$\sigma_C = \pi\lambda_t^2\ (e^2/hc)\ (g^2/hc)\ \varepsilon^{5/2}. \tag{3C}$$

We may remark here that the exponent of ε is different from that obtained by Nordheim and Nordheim or Yukawa (*Phys. Rev.*, 1938, **54**, 254; *Proc. phys. math. Soc. Japan*, 1938, **20**, 720; cf. also P. Urban. *Acta Phys. Austr.*, 1947, **1**, 167). This is due to the fact that these authors did not take into account the momentum of the nucleon in the Fermi gas.

In order to get an idea as to the absolute value of the cross sections for bombarding energies well above the threshold, we can calculate the cross sections for $\varepsilon = 1$. Using $g^2/hc = 1/6$, we get:

$\sigma_A = 2.10^{-4}$ barns, $\sigma_B = 4.10^{-7}$ barns, $\sigma_C = 6.10^{-5}$ barns.

We must remind the reader here that if nuclei of atomic weight A are bombarded, the cross sections have to be multiplied by A.

Comparing equations (1) and (2), it seems that one may expect an optimum energy for the creation of mesons to exist somewhere in the neighborhood of 300 Mev ($2\ \mu c^2$).

We may refer to McMillan and Teller's paper for a discussion of the various effects which they and we neglected. It should be remarked here that in cases B and C it is always possible to satisfy the law of conservation of momentum.

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The Use of Chemicals to Prevent Molding of Herbarium Specimens

Recently Fosberg (*Science*, September 12, 1947, pp. 250–251) discussed the use of formaldehyde to prevent molding of herbarium specimens. Johnson (*Science*, March 19, p. 294) found that this type of chemical treatment is without value in preparation of specimens of *Tsuga* and *Picea*. It is of interest to note that certain chemicals were used effectively by a botanist as early as 1854 to inhibit mold.

In a recent book (*A scientist with Perry in Japan*. Chapel Hill: Univ. of North Carolina Press, 1947), James Morrow recounts in his diary the difficulties experienced in preserving herbarium material collected mostly in Japan. On page 212 there is a statement that Morrow found some of the specimens beginning to mold, and also signs of insects working among them. He therefore painted the dried plants and flowers with a preparation of corrosive sublimate, strong spirits of wine, and camphor.

In a memorial presented to Congress after the return of the Perry expedition it is stated on page 264 that Morrow collected plants at different ports and that by painting with a chemical preparation he was so fortunate as to bring them to the U. S. without injury to a single plant.

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The Robert H. Goddard Rocket Project

The Robert H. Goddard Memorial exhibit sponsored by the Daniel and Florence Guggenheim Foundation, which was opened at the American Museum of Natural History on the afternoon of April 21 (*Science*, April 23, p. 420), is an admirable expression of appreciation of the late Dr. Goddard's scientific work. This exhibit is to be shown in other cities and later placed in some public institution for permanent display.

All who have been associated with the rocket project feel a deep sense of appreciation for the generous support which the Guggenheim Foundation has given to this scientific work during its later years and for the kind words regarding Dr. Goddard, expressed by Harry F. Guggenheim and Lt. Gen. James H. Doolittle at the exercises associated with the formal opening of the exhibit.

The conception of a rocket to be flown at terrific speed by jet propulsion and the earlier stages in this great adventure of a remarkable scientist, when much of the creative thinking was done, were not adequately covered in the addresses made at the Museum. Many institutions and individuals have contributed to this enterprise.

In his biographical sketch, Gen. Doolittle stated that Dr. Goddard was born in Worcester and graduated with a B.S. degree from the Worcester Polytechnic Institute in 1908. That is correct. No mention was made of the fact that Dr. Goddard transferred to Clark University for his graduate studies in physics and from that institution received his Master's degree in 1910 and his Ph.D. in 1911. He received the D.Sc. degree, *honoris causa*, from Clark University in May of 1945.

For a brief period (1912–13) Dr. Goddard was at Princeton, where he held a Research Fellowship. While there, he worked on the mathematical theory of rocket propulsion. He returned to Clark in 1914 as a member of the faculty and continued as a member of that staff until 1943, when he voluntarily resigned his professorship in physics to accept full-time employment in the laboratories of the U. S. Navy at Annapolis.

From the time Dr. Goddard joined the faculty of Clark University he gave most of his research time to the laboratory problems associated with jet propulsion and rocket flight. In this he was supported by the Uni-