The Interaction of Pi-Mesons*

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THE identification of pi-mesons as at least a principal component of the secondary particles of a hard shower[1] encouraged a tentative experiment[2] on the nuclear interaction of those particles. The results showed, in my interpretation, a very small cross section for the nuclear absorption of pi-mesons in flight. This absorption process was thought to be of the same type as a pi-minus star with a larger energy involved, where particles other than mesons would be emitted.

Greisen,[3] discussing in general the present evidence on nuclear interactions of pi-mesons, suggests for the experiments of reference 2 a different interpretation from that which I gave. Greisen's points are: (1) pi-mesons may have interactions not leading to the disappearance of the meson, but involving a loss of only a part of the meson energy; (2) such "nuclear losses" may increase the probability of recording a delayed coincidence, with respect to the case in which only ionization losses are present; (3) Experiment III of reference 2 shows that a large fraction of the delayed coincidences is due to mesons produced very near to the point where they stop inside the iron.

My experiment would indeed not give any evidence for a process in which the meson does not disappear.

In reference 2, I already wrote that scattering could not practically affect my results. The only process which could have had a significant effect on these results is the complete nuclear absorption of pi-mesons *before* the end of their range.

On the other hand, even if we assume that nuclear losses, accompanied or not by a measurable scattering, are important, my interpretation of Experiment IV of reference 2 would still be correct. Nuclear losses would just increase *both* the number of *HS* delayed coincidences and of the stopped mesons. The conclusion that every *positive* meson stopped generates a decay electron would not be changed.

The meson production inside the iron deserves some further remarks. Experiment III, on which Greisen bases his computation, gave only eleven counts. In addition, these have to be corrected because of the inefficiency of the anticoincidence tray *D* and for the casuals. This gives 10 ± 6 percent instead of 18 ± 5 percent for mesons which might be produced in the lower layer of the absorber. Further, the average number of four ionizing particles quoted by Greisen does not apply to the counter assembly used in this experiment. The correct number is definitely smaller.

If a large fraction of mesons were produced inside the iron by nucleons, the flux of ionizing particles A_2BC should be much larger than is observed and should be mainly composed of protons, which is against the evidence of Experiment I.

Indeed, Berkeley experiments[4] show that the cross section σ_π for meson production by nucleons bombarding an element like iron is less than 10^{-27} cm^2 for a nucleonic energy of around 350 Mev. Above that energy the cross section is supposed to increase, although not very rapidly.[5] If we assume that at an energy of 1 Bev σ_π is still less than the geometrical cross section, we see that for each meson produced in the iron we are bound to have several neutrons of more than 1 Bev entering the iron. At such an energy, the evidence from photographic plates shows that the protons are about as frequent as neutrons.[6] Now the spectrum of protons at the level of tray *C*, some 16 inches of lead from the top of the apparatus, cannot be made up of only high energy protons. Indeed, there is no reason to think that such a spectrum is richer on the high energy side than the spectrum of protons in the atmosphere, such as can be deduced from the experiments of Anderson.[7] In this way one concludes that for each pi-meson created inside the iron by the nucleonic cascade, much more than ten protons should cross the tray *C*. Actually the tray *C* is crossed only by less than five ionizing particles for each meson stopped in the iron, and certainly not all of them are protons.

The situation is different if we assume that even at energies of a few hundred Mev mesons may easily multiply. One meson producing another meson inside the iron, so that two mesons would appear, either emerging from or being stopped in the iron, would balance for one nuclear absorption.

If actually the meson multiplication has a large cross section even at low energies, one is surprised that it has not been noticed in the cloud-chamber experiments of Fretter and others.[8-10] On the contrary, it has been found that in the large majority the interactions have the same appearance of the nucleon-produced stars of low energy. For such events of low energy, the most frequent "stars," no transition effect was observed in photographic emulsion.[11] Finding 200 g/cm^2 as the absorption length in ice, Harding, Lattimore, and Perkins[12] interpret the result as an indication that stars *are not* produced by unstable particles.

As a conclusion we think that further experiments are certainly needed before considering as "established" any statement on the nuclear interaction of pi-mesons. At the present time we do not see that the nucleonic cascade can furnish the explanation of our results under the assumption of a large cross section for nuclear absorption of pi-mesons. If a cascade is going to reconcile our results with, say, a geometrical cross section for nuclear absorption, it seems, on the basis of the present experimental information, that the cascade has to be made up of pi-mesons almost exclusively. Such a process is bound to be observed experimentally, for instance, for the lack of neutral particles participating to the development of the cascade.

Experiments in this line are already on the point of being performed by Dr. R. L. Cool and the writer.

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[1] O. Piccioni, Phys. Rev. **77**, 1 (1950).

[2] O. Piccioni, Phys. Rev. **77**, 6 (1950).

[3] K. Greisen, Phys. Rev. **77**, 713 (1950). I am indebted to Dr. Greisen for sending me his manuscript.

[4] Kindly communicated by H. Bradner.

[5] H. Bethe and B. Rossi, Echo Lake Conference (June, 1949).

[6] Brown, Camerini, Fowler, Heitler, King, and Powell, Phil. Mag. **40**, 862 (1949).

[7] Adams, Anderson, Lloyd, Rau, and Saxena, Rev. Mod. Phys. **20**, 334 (1948).

[8] W. B. Fretter, Phys. Rev. **76**, 511 (1949).

[9] Lovati, Mura, Salvini, and Tagliaferri, Phys. Rev. **77**, 284 (1950).

[10] W. W. Brown and A. S. McKay, Phys. Rev. **77**, 342 (1950). The authors give an erroneous condition for the nuclear absorption to be detected by my apparatus.

[11] Harding and Perkins, Nature **164**, 285 (1949).

[12] Harding, Lattimore, and Perkins, Nature **163**, 319 (1949).

Photo-Alpha-Reactions in Oxygen and Nitrogen

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IN an experiment searching for new photo-nuclear reactions involving the emission of heavy particles ($Z\geq2$), an Ilford E1 emulsion, 100 microns thick, was exposed to 200 roentgens of γ-radiation from the 24-Mev betatron at the University of Saskatchewan. The plate was enclosed in cadmium at the middle of a cubic foot of paraffin to eliminate reactions caused by photoneutrons. The γ-ray beam was filtered through 20 cm of aluminum to reduce low energy radiation. A modified Van der Grinten "grain-gradation" development[1] of the plate minimized γ-ray fogging, suppressed proton tracks, and made α-particle tracks distinguishable from those of heavier particles.

The principal types of events found in 2 cm^2 of this plate included about 200 measurable three-pronged α-particle stars from the photo-disintegration of C^{12} via the 3 Mev excited level[2] of Be^8, 25 measurable four-pronged α-particle stars from the break up[3] of O^{16}, and 1010 single α-particle tracks attributed to photo-alpha-reactions in the Ag and Br of the emulsion.

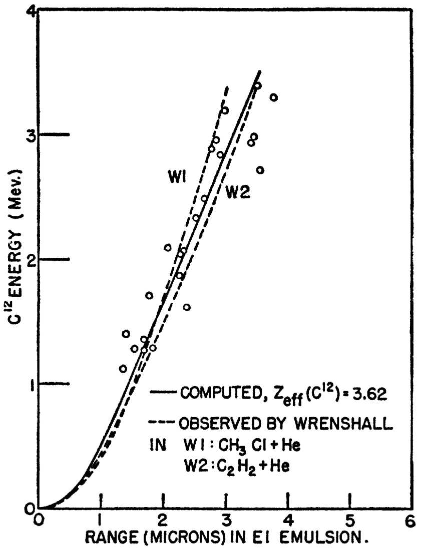

FIG. 1. Range-energy relationship for C^{12} ions in E1 emulsion. Experimental points show $E_r(\alpha)$ *vs.* range. Solid curve shows $E_r(R)$ *vs.* range for $Z_{eff}(C^{12}) = 3.62$.

A few α-particle tracks having a short, heavy stub at the origin were attributed to photo-alpha-reactions in light nuclei, in which the recoil fragment had small charge and sufficient energy to leave a measurable track. The only elements of this kind present in the emulsion are carbon, nitrogen, and oxygen; since carbon normally disintegrates into a three-pronged α-particle star, it was suspected that these events might be due to the reactions $N^{14}(\gamma, \alpha)B^{10}$ and $O^{16}(\gamma, \alpha)C^{12}$. These assignments were confirmed by the following analysis.

The energy of each recoil fragment, $E_r(\alpha)$, was calculated from the momenta and energies of its associated α-particle and γ-ray on the assumptions that it was either (1) B^{10} or (2) C^{12}. On these same assumptions it was also possible to calculate two values for the energy of the recoil nucleus, $E_r(R)$, from the functional form of the general range-energy relationship: $E/M = f(Z_{eff}^2R/M)$, by making use of the known range-energy relationship for α-particles for which a value $Z_{eff} = 2$ was used. For the recoil fragment, Z_{eff}, the ionic charge, is less than the nuclear charge since at low energies not all the atomic electrons are stripped from their orbits;[4] and it will vary from point to point along the track. However, by applying this method of analysis to the experimental range-energy points for light nuclei used in Knipp and Teller's paper,[4] we are convinced that over the limited range of energy in our experiment a constant value of Z_{eff} for the recoil nuclei is a satisfactory approximation in each case. A preliminary study of our data indicated that a value of $Z_{eff} = 0.6Z$ was sufficiently accurate to identify the reactions.

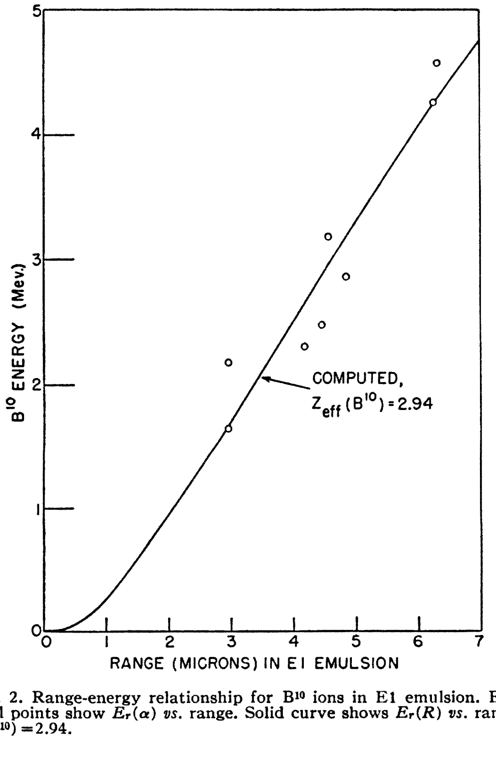

FIG. 2. Range-energy relationship for B^{10} ions in E1 emulsion. Experimental points show $E_r(\alpha)$ *vs.* range. Solid curve shows $E_r(R)$ *vs.* range for $Z_{eff}(B^{10}) = 2.94$.

For each event the recoil energies as calculated by the above two methods were compared and in most cases it was found that $|E_r(\alpha) - E_r(R)|$ was less than 0.5 Mev on one assumption as to the identity of the recoil nucleus which served to identify the reaction, and was considerably greater for the alternative assumption. In this manner, of the 32 events studied, 23 were identified as the $O^{16}(\gamma, \alpha)C^{12}$ reaction and 8 as the $N^{14}(\gamma, \alpha)B^{10}$ reaction. One event, which disagreed with both of the above assumed reactions, agreed with the assumption that it was the photodisintegration of C^{12} via the ground state of Be^8.

Figure 1 shows the range-energy relationship for C^{12} ions in E1 emulsion thus obtained. From the individual points a mean $Z_{eff}(C^{12}) = 3.62$ was calculated, and the solid line is the curve obtained from the functional equation using this value. Wrenshall[5] studied recoiling C^{12} ions in two gas mixtures and reduced the range-energy relationships thus found to standard air. By applying to these de Carvalho's stopping power formula,[6] reduced in range by 3 percent to convert from C2 to E1 emulsions, the curves *W*1 and *W*2 were obtained. The agreement with our data is satisfactory.

Figure 2 shows the range-energy relationship for B^{10} ions obtained in the same way with $Z_{eff}(B^{10}) = 2.94$ giving the best fit.

We should like to thank Dr. R. N. H. Haslam and his coworkers at the University of Saskatchewan for making the betatron irradiations, Dr. B. W. Sargent for his interest and advice on the experiment, and Mr. R. G. Hayman for his assistance in searching the plates.

[1] H. Yagoda, *Radioactive Measurements with Nuclear Emulsions* (John Wiley and Sons, Inc., New York, 1949), p. 62.
[2] Hänni, Telegdi, and Zünti, Helv. Phys. Acta **21**, 203 (1948).
[3] Goward, Titterton, and Wilkins, Proc. Phys. Soc. (London) **A62**, 460 (1949).
[4] J. K. Knipp and E. Teller, Phys. Rev. **59**, 659 (1941).
[5] G. A. Wrenshall, Phys. Rev. **57**, 1095 (1940).
[6] H. G. de Carvalho, Phys. Rev. **76**, 1729 (1949).

The Raman Spectrum of Bromine

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IN collaboration with Oswaldo Sala we have developed recently an experimental technique for obtaining Raman spectra excited by He 5875.6A. Details concerning the construction of intense He-lamps and a luminous Raman arrangement will be given elsewhere.

With this arrangement we have attempted to measure the Raman spectrum of gaseous bromine using a 50-cm long Raman tube; the first 10 cm were illuminated by the exciting radiation. The tube contained pure Br_2; the pressure was about 900 mm at