S. NARANAN, etc.
1957, Giugno
Il Nuovo Cimento
Serie X, Vol. 5, pag. 1773-1776

Interactions of μ-Mesons Underground (190 ~~MeV~~ mwe).

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(ricevuto il 6 Febbraio 1957)

Several workers [1,12] working underground with cloud chambers, photographic emulsions, and Geiger counters have obtained for μ-mesons underground, cross-section for their nuclear interactions of the order of 10^{-30} cm²/nucleon. Following BRADDICK and HENSBY [13], other workers [4,14] working underground with cloud chambers had reported comparatively very large cross-sections $(4\div5\cdot10^{-29})$ cm²/nucleon for the production of single penetrating secondaries by penetrating particles underground, the so called « associated pairs of penetrating particles » (A.P.P's).

With a view to study these interactions, the present experiment was performed with a multiplate cloud chamber inside an abandoned railway tunnel at Khandala (1 790 ft. a.s.l.), 80 miles from Bombay, during February-June, 1954. The cloud chamber was run inside the tunnel, in a temperature-controlled trailer caravan. The rock (*) over the apparatus was equivalent to 180 m of water (180 m w.e.). The cloud chamber was 45 cm in diameter, and had an illuminated depth of 12.5 cm. It had seven, half-inch thick lead plates inside, and a 10.5 cm lead block above, and was triggered by a triple coincidence system of Geiger counters consisting of one counter tray above, and two counter trays below the chamber.

In a total of 6 884 photographs obtained in 1 300 h of cloud chamber operation, we have 33 events where a penetrating particle is accompanied by, or has produced inside the chamber, a

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(13) H. J. J. BRADDICK and G. HENSBY: *Nature*, **144**, 1912 (1939).
(14) E. P. GEORGE, J. L. REDDING and P. T. TRENT: *Proc. Phys. Soc.*, A **66**, 533 (1953).

(*) The density of the rock was 2.9 g/cm³ single secondary particle which apparently penetrates one or two lead plates. These events if interpreted as examples of the associated pair production (A.P.P.) would give, for this type of phenomenon a cross-section of the same order of magnitude as that given by previous workers [4,14] namely $(4 \div 5 \cdot 10^{-29})\,\mathrm{cm}^2$/nucleon. However we will see below that almost all the above secondaries are consistent with being knock-on electrons.

In all the above cases where the secondary particle stops in a plate in the chamber, its track appears to be minimum ionizing in the compartment above the plate. Protons stopping in a lead plate 1.25 cm thick would appear to ionize heavily in the compartment above the plate. π- or μ-mesons would also appear to ionize heavily, except for those which stop in the bottom 3 mm of the plate, which would appear to ionize minimum. Thus, since the particles are minimum ionizing in all our cases, one is led to believe that a large majority of these secondaries could not be protons or π or μ-mesons stopping in the plate.

There are 25 photographs of knock-on electron showers, where at least one of the shower particles appears to penetrate one plate, and stops in the next, showing thereby that it is not rare for an electron to appear to penetrate one half-inch lead plate (2.2 radiation lengths). Thus, most of the secondaries which appear to penetrate one plate in the above mentioned 33 cases could be knock-on electrons, which may have produced a shower in the lead plate, with only one shower particle emerging from this plate.

We now, therefore, try to interprete these 33 events as knock-on electrons and so consider them together with all the other knock-on electrons and knock-on electron cascades observed by us. Taking D'ANDLAU's [15] experimental results on the fluctuations in the number of electrons below a lead layer two radiation lengths thick, and using the energy spectrum of electrons in equilibrium with μ-mesons in lead at a total depth of 190 m w.e., calculated from Bhabha's [16] theory, we can show that the calculated [17] and observed ratios of $N(1)/N\ (>1)$ namely 0.79 ± 0.3 and 0.55 ± 0.1 respectively, are in agreement within the statistical errors. $N(1)$ is the number of cases where only one electron emerges below the lead plate 2 radiation lengths thick, and $N\ (>1)$ is the number of cases where more than one electron emerge from the lead plate.

The above results and discussion show that all these apparently penetrating secondaries could be explained as knock-on electrons and that it is not necessary to invoke a special phenomenon like the production of A.P.P.'s with a comparatively large cross-section. These results are in agreement with those of APPAPILLAI *et al.* [18] and BRADDICK and LEONTIC [15] who have since drawn similar conclusions.

Working below such a large thickness of rock (180 mw.e.), we have observed in our cloud chamber, 6 cases of nuclear interactions of the penetrating particles underground. Five of these photographs are typical penetrating showers, while one photograph has a heavily ionizing particle coming out of the lead plate, together with some soft component. The photograph of one of the penetrating showers is reproduced in Fig. 1. Three of these interactions have their origin inside the chamber, two have a possible origin in the 10.5 cm lead block above the chamber, and one of them was possibly produced in the rock of the tunnel.

([15]) C. D'ANDLAU: *Journ. Phys. Rad.*, **16**, 176 (1955).

([16]) H. J. BHABHA: *Proc. Roy. Soc.*, A **168**, 829 (1938).

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Ignoring the interaction in the rock and the very weak interaction in the lead plate, and so taking the other four interactions, and noting a traversal of 984 m of lead by the μ-mesons, we evaluate an upper limit of the cross-section for the production of penetrating showers by μ-mesons of mean energy 47 GeV (total depth 190 m e.w.) as

$$\sigma_{\text{p.sh.}}(\varepsilon \geqslant 1\ \text{GeV}) = \\ = (5.7 \pm 2.8)\cdot 10^{-30}\ \text{cm}^2/\text{nucleon}\ ,$$

ε being the estimated energy of the interactions. This value is of the same order of magnitude $(1.2 \div 4.0\cdot 10^{-30}(\text{cm}^2/\text{nucleon}))$ as that obtained by other underground cloud chamber workers ([3-5]) working at much lower mean energies $(6 \div 14\ \text{GeV})$ of μ-mesons. Very recently HIGASHI *et al.* ([19]) working under 200 m w.e., have reported a cross-section of $(2.9 \pm 1.1)\cdot$ $\cdot 10^{-3}$ cm²/nucleon, for production of showers of energies $\geqslant 7$ GeV.

We would like to point out here that the particles producing the interactions observed by us could not be identified as μ-mesons, but are assumed to be μ-mesons. The penetrating particles observed below a total depth of 190 m w.e., cannot be a part of the nuclear interacting component produced in the atmosphere, since the latter is rapidly absorbed in the rock with an absorption length of half a metre of rock. The observed events could therefore be either produced by μ-mesons which could penetrate this thickness of the rock by virtue of their weak interactions with matter, or they are produced by locally generated nuclear interacting secondaries of the μ-meson interactions in the rock. Very recently KITAMURA and ODA ([20]) have calculated that below 200 m w.e., the ratio of the frequency of occurrence of the nuclear interactions produced by π-mesons to the frequency of those produced by μ-mesons is 1.75, for interactions of threshold energies $\geqslant 1$ GeV. This uncertainty about the nature of the penetrating particles producing the interactions, leads us to regard the above cross-section as an upper limit for the nuclear interactions of μ-mesons underground.

The above mentioned observed upper limit of the cross-section is not in disagreement with the theoretical value of $\sigma_{\text{p.sh.}}(\varepsilon \geqslant 1\ \text{GeV}) = 3.1\cdot 10^{-3}$ cm²/nucleon calculated, as first indicated by GEORGE and EVANS ([1]), by interpreting the interactions as the photonuclear interactions of the virtual photons associated with μ-mesons in flight. The poor statistics available for cloud chamber results do not permit any definite conclusions regarding the variation of this cross-section with increasing energy of μ-mesons.

Two cases of large angle scatterings of penetrating particles have been observed, where the two particles having mean (+) scattering angles of $2.6^{+0.4}_{-0.3}$ degrees and $1.7^{+0.4}_{-0.2}$ degrees have scattered through $(13.5 \pm 0.5)^\circ$ and $(22.5 \pm 0.5)^\circ$ respectively, in one of the lead plates inside the chamber. If these scatterings are due to nuclear scattering of μ-mesons, then they give a cross-section of σ (scattering) $= (6.3 \pm 4.5)\cdot 10^{-3}$ cm²/nucleon, for μ-mesons in lead. The experimental limitations in the measurement of small scattering angles, do not permit us to state anything about the anomalous cross-section ([21]) (*) for large angle scattering of high energy μ-mesons.

The following main results were ob-

([19]) S. HIGASHI, M. ODA, T. OSHIO, H. SHIBATA, K. WATANABE and Y. WATASE: *Progr. Theor. Phys.*, **16**, 250 (1956).

([20]) T. KITAMURA and M. ODA: *Progr. Theor. Phys.*, **16**, 252 (1956).

([21]) B. LEONTIC and A. W. WOLFENDALE: *Phil. Mag.*, **44**, 1101 (1953).

(*) These authors have summarized the results of sea level experiments on large angle scatterings of μ-mesons.

(+) The large angles were excluded while taking the mean of the scattering angles in the other plates.

tained for the electronic component in equilibrium with μ-mesons underground. (*a*) the average number of electrons in equilibrium with a μ-meson in lead is $0.172^{+0.012}_{-0.002}$ in good agreement with the value 0.164 calculated from Bhabha's [16] theory. (*b*) The numbers of knock-on cascade showers of energies (*) greater than 600 MeV and 1.5 GeV, are $(7.0 \pm 1.4) \cdot 10^{-5}$ and $(2.0 \pm 0.75) \cdot 10^{-5}$ per meson per g/cm^2 of lead respectively, again in good agreement with the values of $9.5 \cdot 10^{-5}$ and $2.26 \cdot 10^{-5}$ per meson per g/cm^2 of lead calculated from Bhabha's theory.

In conclusion, we would like to state that in conformity with other later experiments [17,18] there is no evidence for the existence of a large cross-section for a special phenomenon called the associated production of penetrating particles (A.P.P.). The results on the equilibrium electronic component, are in agreement with the theoretical expectations. The upper limit of $(5.7 \pm 2.8) \cdot 10^{-3}$ cm²/nucleon, for nuclear interactions of the underground μ-mesons of mean energy 47 GeV is, within statistics, of the same order of magnitude as the cross-section obtained by other cloud chamber workers at lower mean energies of μ-mesons (3 ÷ 15 GeV). The cross-section for large angle scattering of μ-mesons is of the same order of magnitude as the cross-section for nuclear interactions.

(*) The energies of the showers were estimated using Hazen's [22] experimental results.

(22) W. E. HAZEN: *Phys. Rev.*, **99**, 911 (1955).

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We have great pleasure in thanking Professor H. J. BHABHA, F.R.S., for his keen interest in the work and for helpful discussions. We have pleasure in thanking Dr. A. W. WOLFENDALE for his comments, and Mr. B. GUZDER for the prompt construction of the caravan trailer and the invaluable help rendered in transporting it to the tunnel. Thanks are also due to Mr. K. F. DINSHAW for his help in running the chamber, and to Messrs. D. COWASJEE & Co. for permission to work in the tunnel.

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