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A research for anomalous scattering of μ mesons by nucleons

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Scattering at angles larger than 18^0 of μ mesons by an Fe plate 6 cm thick has been investigated by means of a counters-hodoscope which allows to distinguish two energy bands: one from 180 MeV to 300 MeV, the other from 300 MeV to infinity.

In about $2,5 \times 10^5$ penetrating particles impinging on the scatterer, 3 scattered particles have been observed in each of the two above mentioned energy bands. An upper limit for the cross section for anomalous scattering of μ mesons by nucleons is deduced.

1. Introduction.

Some years ago B. Ferretti pointed out, in various seminars and discussions, that all measurements of anomalous scattering of mesons gave values of the cross-section of the order of 10^{-28} cm^2 per nucleon[1]).

Such a value was appreciably smaller than that expected under the assumption that the mesons observed in cosmic rays at sea level can be identified with the particles responsible of nuclear forces.

Moreover all the measurements in question were based on very poor statistics and, generally, open to serious critisisms that induced to suspect that the scattering cross-section could be still smaller than the value quoted above.

As an example let us consider Code's results which appear to be among the more reliable ones. This author measured the momentum of the particles by their magnetic rigidity so that he could state, in each case, the electric polarity. Out of 359 tracks photographed, 10 had suffered a large deflection while the average number of deflections expected on purely coulombian scattering of mesons was 1,5. For 7 of these 10 cases, Code gives all details and of these 7,6 are positive and 1 is negative. This observation strongly suggests that the apparent anomalous scattering is due to a small admixture of protons with the mesons.

Therefore we thought that it was worthwile to investigate the anomalous scattering of mesons at sea level using a high intensity experimental device.

This was drown and built almost completely, in collaboration with M. Ageno and G. Bernardini who have contributed in a substancial way to the present work, although at a later time they have devoted their activity to other researches.

The time necessary to complete the experimental device turned out to be much longer than expected on account of various reasons indipendent from us. In the mean time the interest of the problem was deeply changed on account of the discovery of Conversi, Pancini and Piccioni[2]) on the different behaviour of μ mesons at the end of the range in materials of different atomic number.

According to the discussion first given by Fermi, Teller and Weisskopf[3]) and later detailed and extended by other authors[4]), the Conversi Pancini Piccioni effect shows that the interaction constant of low energy μ mesons with nucleons, is 10^6 times smaller than that expected under the assumption that μ mesons are the particels responsible of the nuclear forces.

Considering that the cross-section is proportional to the fourth power of the interaction constant, one can conclude that the cross-section for anomalous scattering of μ mesons against nucleons ought to be 10^{-24} times smaller than the cross-section expected for the particels responsible of the nuclear forces.

In spite of that we thought that it was worthwile to carry the experiment to an end just on account of the character of direct observation of fast μ mesons scattered by nucleons.

Arguments in favour of this resolution were mainly of two types:

1. it is not evident that conclusions drawn from the Conversi Pancini Piccioni effect can be extrapolated to high energy mesons;

2. inside the limits of validity of such an extrapolation, μ mesons do not interact appreciably with nucleons, with forces different from that due to the electromagnetic field. Therefore they appear to be the particles more convenient for the investigation of the electromagnetic field of a nucleon at the very short distances.

It is possible that the previously mentioned points of view have some connection with the observations of Evans and George[5]) who found an appreciable production of stars in the sensitive emulsion of plates exposed to cosmic rays at sea level under layers of matter varying from a few meters to 70 meters water equivalent. The intensity of such an effect decreases with depth slightly slower than the intensity of μ mesons.

If these rather preliminary results will be confirmed one could conclude in favour of a weak interaction (cross section of the order of 10^{-30} cm^2) between nucleons and μ mesons of at least 10^9 eV energy.

2. The experimental device.

Fig. 1 shows our experimental device which is drown, in a schematic way, in Fig. 2.

The solid angle of the impinging particles is defined by two telescopes, B_1' B_2' B_3' B_4' and B_1'' B_2'' B_3'' B_4'', placed one behind the other, in order to increase the intensity. Counters A are in parallel

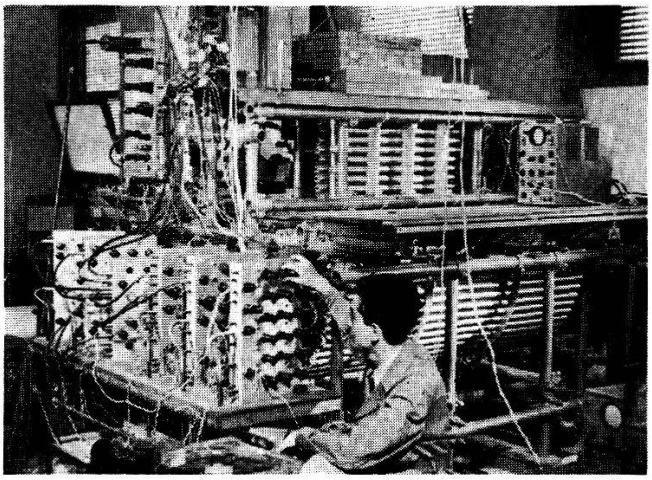

Fig. 1.

and placed under 15 cm of Pb and above 5 cm of Pb, so that the soft component is completely absorbed and the spectrum of the hard component is used from its maximum up towards higher energies. $F_c + F_l$ are an anticoincidence set of counters for lateral protection. The scatterer, 6 cm thick, covers almost exactly the solid angle defined by the two telescopes B′ and B″.

Counters C and D are connected to an hodoscope of neon lamps and give some rough informations about the direction of motions of the particles impinging on it. Two layers of Pb, 2,5 cm thick each, are placed in front of counters C and between counters C and D. Counters E are all in parallel and separated from counters D by 10 cm Pb. Counters G are a second anticoincidence set. In table 1 we give the numbers and length of all counters whose diameter was 4 cm.

Other interesting geometrical features are the following:

a) telescopes B′ and B″
maximum angle with the vertical direction:
in the plane of Fig. 2 . . . . $\vartheta_0 = 8^0$
in direction perpendicular to the plane of Fig. 2 . $\varphi_0 = 20^0$

b) hodoscope C + D
minimum angle of deflection in the plane of Fig. 2 $\alpha_m = 18^0$
maximum angle of deflection in the plane of Fig. 2 $\alpha_M = 110^0$
maximum angle with the vertical in direction perpendicular to Fig. 2 . . . . $\Phi = 60^0$

Table 1.

Type of counter	Number	Lenght in cm
A	4	60
B	8	20
B'	8	20
C	12	50
D	16	50
E	28	135
F_c	28	60
F_l	20	100
G	13	100
	137	

By means of circuits that will be described later, we count the ollowing type of events:

N_1 A + B (or B′) + (C + D) — F — G
N_2 A + B (or B′) + G + (C + D) — F
N_3 A + B (or B′) + G — F
N_4 A + B (or B′) + (C + D) + E — F — G

N_3 is the total number of particles crossing the two telescopes with a range larger than R_0 = 20 cm Pb + 6 cm of Fe (or Pb). Therefore this number gives the intensity of the impinging radiation.

N_2 is the number of particles (single or multiple) crossing the two telescopes and not the anticoincidence F, that give rise in the scatterer to at least a particle crossing the hodoscope C + D.

Two types of events give the main contribution to N_2:

a) electronic secondaries of single penetrating particles emitted at a large angle with an energy large enough to cross at least 5 cm Pb;

b) penetrating showers produced by ionizing particles in the scatterer with at least one particle emitted at a large angle with an energy large enough to cross at least 5 cm Pb. We include, in this type of events, also penetrating showers of two particles: the impinging one and a recoiling particle.

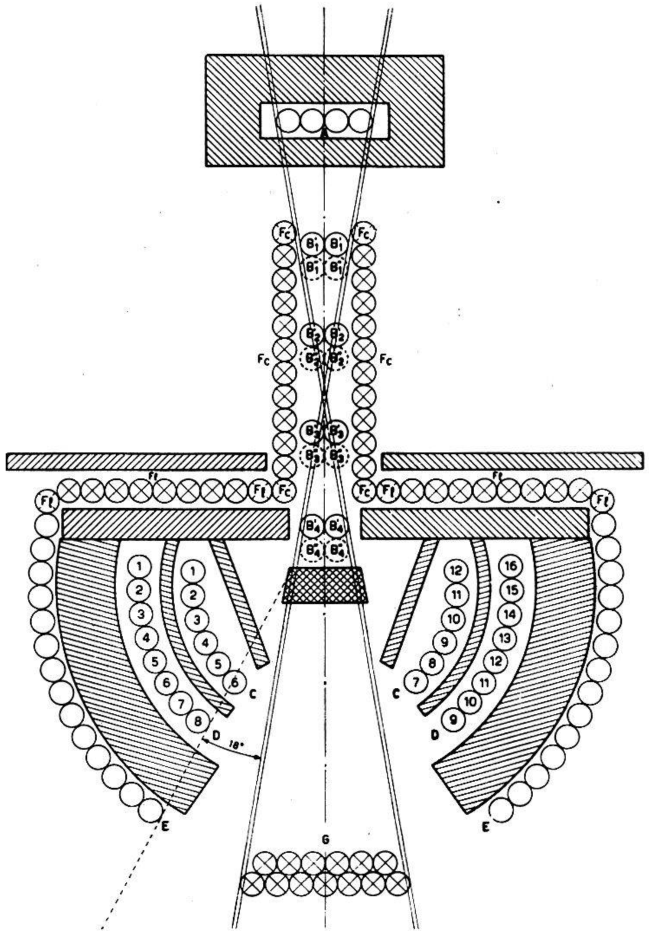

Fig. 2.

N_1 is the number of particles scattered at an angle larger than 18^0 having after the collision a residual range between

$$R_m = 5 \text{ cm Pb} + 7 \text{ cm Fe (or Pb)} \qquad (E_\mu = 180 \text{ MeV})$$

and

$$R_M = 15 \text{ cm Pb} + 7 \text{ cm Fe (or Pb)} \qquad (E_\mu = 300 \text{ MeV})$$

N_4 is the number of particles scattered at an angle larger than 18^0 having after the collision a residual range larger than

$$R_M = 15 \text{ cm Pb} + 7 \text{ cm Fe (or Pb)}.$$

Our hodoscope was triggered by a master pulse in such a way that it was photographed automatically for all events of type

$$N_1, \quad N_2, \quad N_4$$

These three cases could be distinguished one from the other by the glowing of convenient neon lamps: one, that we will call S, for events of type N_2 and one, that we will call E, for events of type N_4.

The intensity of the impinging particles N_4 was large enough ($5{,}4\ \mathrm{min}^{-1}$) to allow to check every few hours during the measurements that all counters A, B′, B″ and F were working properly.

In order to check the behaviour of counters C and D every day we have looked at the hodoscope, for about half an hour, events of type

$$B_4 + C + D \quad \text{and} \quad B_4 + C + D + E$$

due to showers and mesons impinging obliquely on the counters.

Every two days we checked the plateau of all counters and the pulses both at the input and at the output of all tubes.

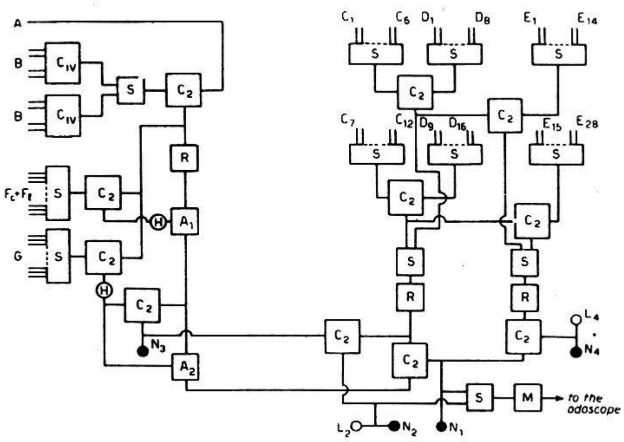

Fig. 3.

Only three counters have been substituted during all the measurements because their plateau, initially of about 150—200 volt, was reduced to about 30—40 volt.

Our circuits can be devided in three main parts:

1. a pilot circuit composed of coincidence and anticoincidence sets;

2. an hodoscope;

3. various authomatic devices, introduced to eliminate electric disturbances, which allow a continuous operation of the apparatus.

The pilot circuit (Fig. 3) supplies a master pulse to the hodoscope for every event of type N_1 or N_2; at that moment all the neon lamps are in condition to glow, but the hodoscope provides that only that neon lamps will actually glow that are connected to counters that have been crossed by a particle.

Pulses of each counter, or group of counters, are amplified and send to coincidence circuits $\underline{C}_2$ (double) $\underline{C}_4$ (fourfold). $\underline{S}$ are used to collect pulses coming from many similar circuits. $\underline{A}$ are anticoincidence circuits and $\underline{R}$ circuits introduced to equalize and delay the pulses to be feed in later coincidence circuit; $\underline{H}$ are circuits that lengthen in time the pulses and finally $\underline{N}$ circuits that trigger the mechanical counters. The resolving time of the coincidences was 10 μsec.

In Fig. 4 we give the scheme of one unit of the hodoscope.

The pulse of the counter, amplified by the first tube, is send contemporarily to the pilot circuit of Fig. 3 and to a double coincidence circuit which transmits the signal only if the pulse of the counter is time coincident with the master pulse coming from the pilot circuit.

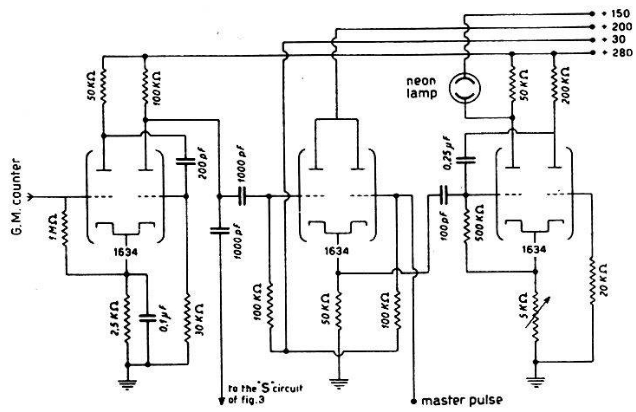

Fig. 4.

3. The experimental results.

The measurements have been performed with two scatterers, one of Fe, the other of Pb, both 6 cm thick. The mean angles for multiple coulombian scattering, calculated according to the WILLIAMS

Table 2.

E_μ	$\bar{\alpha}$	
MeV	Fe	Pb
180	$4^0\ 40'$	$8^0\ 40'$
240	$3^0\ 30'$	7^0
300	3^0	$5^0\ 50'$

formula[6]), are given, as a function of the kinetic energy of μ mesons in table 2. As we see from Fig. 2, the experimental device has been drown in such a way that the minimum angle of scattering ($\alpha_m = 18^0$)

was much larger than $\bar{\alpha}$ for the Fe scatterer but not for the Pb scatterer; this element was used in order to check this point.

In table 3 we give our results on scattered particels.

As a comment to table 3 we can say that only in one case, with Pb scatterer, we had a large angle scattering ($C_{11}D_{15}$, Fig. 2); in all other cases the particles recorded were scattered at small angles. For instance in case of Fe, at low energy, we had one C_8D_{11} event and two C_7D_9 events.

We do not consider here the events of type N_2 whose interpretation is often not evident also because an appreciable fraction of them is due to random coincidences. For events of type N_1 the random coincidences are negligible.

Table 3.

Scatterer	Time	Total number of impinging particles (N_3)	Number of scattered particles of low energy ($N_1 - N_4$)	Number of scattered particles of high energy N_4
Fe	$765^h\ 10^m$	249.168	3	3
Pb	$230^h\ 16^m$	73.769	13	—

Finally in a convenient absorption measurement we found that the number of mesons with range between R_m and R_M represented 4,7 percent of the total number of mesons of range larger than R_0 (N_3), in excellent agreement with what one can deduce from the Wilson spectrum (4,77 percent)[7].

4. Discussion.

Now we can try to use the data of table 3 to give an upper limit of the scattering cross section of μ mesons by nucleons.

Considering that the number of nucleons per cm² of our Fe scatterer is $2{,}82 . 10^{25}$ and using the results given in table 3 for Fe at face values, we get the following order of magnitude

$$\sigma \approx \frac{3 \times 4}{2{,}82 \times 10^{25} \times 2{,}49 \times 10^5} \backsimeq 1{,}7 \times 10^{-30} \frac{\text{cm}^2}{\text{nucleon}} \text{ for } E_\mu \geq 300 \text{ MeV}$$

$$\sigma \approx \frac{3 \times 4}{2{,}82 \times 10^{25} \times 2{,}49 \times 10^5 \times 4{,}7 \times 10^{-2}} \backsimeq 3{,}6 \times 10^{-29} \frac{\text{cm}^2}{\text{nucleon}}$$

$$\text{for } 180 \text{ MeV} \leq E_\mu \leq 300 \text{ MeV}.$$

The factor 4 is due to the solid angle ($\sim$ ¼) defined by the hodoscope.

But 3 counts are different from 10 counts slightly more than $2\sqrt{10} = 6.3$ so that we conclude that, according to the data of table 3 and assuming that no other effect contributes appreciably to the scattered particles that we have observed, it is very improbable that the scattering cross section of μ mesons by nucleons is larger than the following values:

$$\sigma = 5 \times 10^{-30} \frac{\text{cm}^2}{\text{nucleon}} \text{ for } E_\mu \geq 300 \text{ MeV}$$

$$\sigma = 1 \times 10^{-28} \frac{\text{cm}^2}{\text{nucleon}} \text{ for } 180 \text{ MeV} \leq E_\mu \leq 300 \text{ MeV}$$

Finally we have considered all other effects, different from anomalous scattering of μ mesons by nucleons, which can contribute to the few scattered particles that we have observed; the numbers

Table 4.

	Fe		Pb	
	low energy	high energy	low energy	high energy
observed	3	3	13	—
multiple coulombian scattering	<0.04	—	7	—
single coulombian scattering by nuclei	0.26	0.026	0.07	0.007
single coulombian scattering by protons	0.48	0.62	0.18	0.23
spin interaction (spin 1) . . .	—	4	—	1.5
scattered protons	2—3	2—3		

given in table 4 have been calculated taking into account the actual geometric conditions of the experiment and the actual time of the measurements.

Single coulombian scattering has been calculated considering as scattering centers, once the Fe or Pb nuclei, of finite size[6]), and once all protons present in the scatterer.

The electromagnetic interaction for spin 1 can be disregarded as we have other evedences to day against such an assumption.

Therefore from table 4 we conclude that the scattered particles observed with Pb are mostly due to multiple coulombian scattering while in the case of Fe they can be due, at least in part, to scattered protons. This effect has been calculed using the data on protons at

9.000 meters on sea level[8]), reduced at sea level[9]), and assuming a cross section against nuclei of the order of $\frac{1}{3} \sim \frac{1}{4}$ of the geometrical cross section. The more uncertain point in such an evaluation is the angular distribution of the scattered protons.

We can conclude that probably the cross section for anomalous elastic scattering of μ mesons by nucleons is much smaller than the above given upper limit.

A more detailed account of this experiment will appear in "Il Nuovo Cimento", while further experiments are in progress.

Our thanks are due to M. AGENO and G. BERNARDINI for their contributions to the present work and to B. FERRETTI for many valuable discussions. Dr. M. A. TUVE, director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington has given to us a part of the radio equipment used in this experiment.

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