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SINGLE SCATTERING OF 10—30 Mev NEGATIVE MUONS ON CARBON

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Single scattering of μ^- mesons in a propane bubble chamber was measured. About 60,000 μ^- meson stoppages were measured. For the scattering analysis 48,100 stopped μ^- mesons possessing energies between 10 and 30 Mev were chosen. Observations were carried out on 1260 carbon nuclear path lengths traversed by the μ^- mesons. The differential angular distribution can be satisfactorily described by a Mott scattering curve if account is taken of the finite size of the nucleus. The present experiment shows that the cross section for "anomalous" scattering (if it exists) through an angle $> 45°$ cannot exceed 1.25×10^{-28} cm^2 per nucleon for the energies under consideration and does not exceed 0.7×10^{-28} cm^2 per nucleon for scattering through an angle $> 90°$. Not one case of μ^- decay of the $\mu^- \to e^+ + e^- + e^-$ type was detected in the 60,000 stoppage events.

INTRODUCTION

THE measured value of the muon magnetic moment, the cross section for the production of muon pairs by photons, and data on mesic atoms all give grounds for assuming that, at least in the region of small energies, the scattering of muons by nucleons should be the same as that of electrons having the same mass as the muons. On the other hand, on the basis of the analysis of the experimental angular distributions of muons, many authors have concluded the existence of "anomalous" scattering, which is not in agreement with the concluded purely-electromagnetic interaction between muons and nuclei (see, for example, the survey by Fowler and Wolfendale in reference 1, and also reference 2).

The results of most investigations on muon scattering, performed during the past two years at low energies,[3-6] do not contradict the notion of a muon being an ordinary Dirac particle. The scantiness of the statistical material, however, the difficulty in identifying the particles, and the low accuracies of energy and angle measurements, difficulties all characteristic of research on the scattering of cosmic muons, cast a certain doubt on the presence or absence of "anomalous" scattering.

We have measured single scatterings of negative muons on carbon, contained in the working medium of a propane bubble chamber. An important factor is that by selecting the single-scattering cases, it is possible to compare experiment with theory by using simple and exact equations for the elementary processes and to avoid complicated recalculations and averaging, connected with allowance for repeated and multiple scattering. If there actually exists some sort of non-Coulomb interaction between muons and nuclei, it should manifest itself most clearly in the investigation of single scattering by a light nucleus, such as the carbon nucleus.

EXPERIMENTAL CONDITIONS

The scattering of negative muons was measured in a propane bubble chamber (370×104×100 mm).[7] The chamber was bombarded by negative muons produced in the decay of negative pions in the beam of the proton synchrotron of the Joint Institute for Nuclear Research. The 150-Mev negative pions produced on the inner beryllium target of the proton synchrotron were deflected by the stray field of the accelerator and guided to the chamber through a three-meter collimator. The negative pions and negative muons were slowed down in front of the chamber by a copper absorber and stopped within the chamber. The absorber was chosen such as to make the number of stopped negative muons a maximum. To increase the number of stopped muons, a focusing lens was placed at the exit of the collimator, three meters from the chamber; this doubled the number of stopped muons. To register the scattering of high energy muons, three copper plates, each 0.5 cm thick, were placed in the chamber. The operating cycle of the chamber amounted to 4—10 seconds. The chamber was photographed with three "Industar-23" lenses (F = 110 mm), located opposite the plates mounted in the chamber. An average of three or four stopped muons were registered in each photograph. A total of 60,000 such muons was registered.

REDUCTION OF EXPERIMENTAL DATA

We have investigated single scatterings of negative muons scattered and stopped in the working matter of the chamber. Mesons with true range greater than 1.5 cm, corresponding to energies greater than 10 Mev, were selected. The stopped negative muon was identified by the μ-e decay.

To eliminate possible subjective errors in scanning, the statistical material was processed in the following manner.

a) Flux and energy spectrum of negative muons. To determine the flux and energy spectrum of the negative muons stopped in the chamber, two independent scannings of the same statistical material (each 50th frame) were performed. After identifying the stopped muons registered in both scannings, using the method described in reference 8, the probability was established of the observer registering a stopped muon in scanning the film. This probability was found to be 0.94 and independent of the muon range. The form of the spectrum is shown in Table I.

TABLE I. Flux and energy spectrum of negative muons stopped in the chamber

Range, cm	$p\beta$ Mev/c	Integral flux of negative muons, based on each 25th frame	Flux corrected for omissions	Flux for all frames
1.50	18.6	1815	1924	48100
2.04	21.9	1684	1785	44625
2.61	25.2	1531	1623	40575
3.30	28.5	1364	1446	36150
4.05	31.8	1218	1291	32275
4.88	35.1	1045	1108	27700
5.76	38.4	873	925	23125
6.71	41.7	694	736	18400
7.75	45.0	485	514	12850
8.82	48.3	308	326	8150
10.00	51.6	153	162	4050

Data obtained by scanning each 25th frame of the film, together with the previously determined probability of observing a stopped negative muon, yields the total flux of muons with ranges greater than 1.5 cm, stopped in the chamber, a value of 48,100 (±2.3%) events.

b) Scattering of negative muons. In the first scanning, single scatterings by an angle greater than 10°, projected in the plane of the film, were measured on all the frames. Among these, 292 particles were scattered by more than 15° over the entire range of investigated energies. A thorough second scanning of 25% of the frames showed that in the first scanning not a single scattering event was omitted on these frames. One can therefore conclude that the number of omitted scattering events is apparently less than 1.5%, amounting to four events for all the statistical material. The particle energy at the point of scattering and the energy of the negative muons entering the chamber were determined from the residual range. The error in the energy measurement amounted to 1.5%. The energy interval in which the scattering of the muons was investigated was 10 — 30 Mev, corresponding to negative-muon ranges in propane from 1.5 to 10 cm (the propane density at the instant of passage of the particles was 0.4 g/cm^3).

Before the experimental angular distribution of the negative muons scattered by carbon are compared with the theory, several corrections must be introduced into the data, for the finite dimensions of the chamber, for erroneously assigning a scattering event to the wrong angle interval, for negative-pion impurities, and for scattering by hydrogen.

Correction for the finite chamber dimensions. The finite dimensions of the chamber lead to the following two effects when particle scattering is registered.

a) Some of the scattering events are due to a flux not registered by the chamber. When the trajectory of such a scattered muon is rectified for coincidences with its direction prior to scattering, the muon may be found stopped on the chamber wall or on the plate. Owing to this effect, 22 scattering events were excluded. The result of this correction is seen in column 3 of Table II.

b) Another effect, due to the geometry of the chamber, is the reverse of the first — some of the scattered particles enter the chamber walls and become lost to observation. The probability of registering each scattering event was determined experimentally with allowance for the distribution of the μ^- mesons over the section of the chamber, the angle with which the scattered muon enters the chamber, the length of the visible range after scattering, and the scattering angle. The values of the correction factor, averaged over the angle intervals for the entire registered energy spectrum, are listed in Table III. The influence of this correction is shown in column 4 of Table II.

Assignment of particle to the wrong angle interval. The mean square error in measuring the angle amounted to ~ 1.5°. This error is due essentially to the multiple scattering and also to the finite thickness of the track. Considering the deviations in the angle measurement to be Gaussian, the

TABLE II

Angle interval, degrees	Observed number of scattering events	Number of scattering events after introducing corrections					Expected number of scattering events according to model	
		unregis-tered flux	finite chamber dimen-sions	error in angle interval	decay of negative pions in flight	scattering by hydrogen	of the finite nucleus	of a point nucleus
1	2	3	4	5	6	7	8	9
15—25	189	178	203	199	178	166	166.6	172.2
25—35	61	55	67	66	56	52	44.57	47.87
35—45	22	19	24	24	23	21	17.77	19.94
45—55	9	8	11	11	11	10	8.81	10.31
55—65	5	5	7	7	7	6	4.91	6,11
65—75	2	2	3	3	3	3	3.06	3.97
75—85	1	1	2	2	2	2	2.02	2.76
85—180	3	2	3	3	3	3	6.35	10,25

TABLE III. Magnitude of the correction factor, averaged over the angle intervals

15 —25°	1.14	65— 75°	1.47
25— 35°	1.22	75— 85°	1.50
35— 45°	1.29	95—105°	1.50
45— 55°	1.36	105—115°	1.47
55— 65°	1.42		

spilling of particles from one interval to the other was calculated (see column 5, Table II).

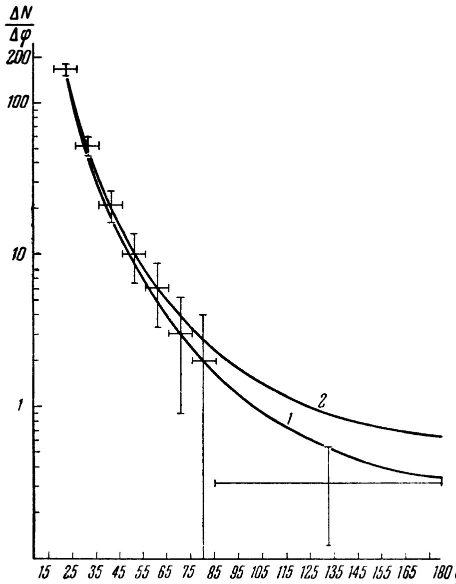
Correction for negative-pion impurity. In addition to the negative muons, negative pions were also stopped in the chamber. A special scanning has shown that a total of 8700 stopped pions were registered, terminated with visible and neutral stars; this amounts to 18% of the stopped negative muons. Some of the negative pions, decaying in flight, may simulate the single scattering of a negative muon. When selecting negative muons of energy greater than 10 Mev after scattering, this effect may be significant up to angles of 40°. A kinematic calculation has shown that approximately 120 negative pions should decay, judging from the number and spectrum of the stopped negative pions registered by us in the chamber. Among the negative muons produced in these decays, only 32 have energies in the 10 — 30 Mev range and a projected decay angle greater than 15°. The results of this correction are listed in column 6 of Table II.

Correction for scattering by hydrogen. The number of events of Coulomb scattering of μ^- mesons by hydrogen contained in the working substance of the chamber amounts to 7.41% of the number of scattering events by carbon (the correction is indicated in column 7 of Table II).

The seventh column of Table II lists the final angular distribution of the scattered negative muons with allowance for all the corrections.

RESULTS AND DISCUSSION

A total of 204,350 cm of negative-muon range in propane at energies 10 — 30 Mev, amounting to 1,260 nuclear lengths of carbon, were traced. Here, as can be seen from Table II, 263 of single scatterings by carbon were observed, at angles more than 15° in projection on the photographic film. The differential angular distribution of the scattered negative muons is shown in the diagram. The abscissas represent the projected scattering angles, and the ordinates the number of scattering events within the angular interval. The points designate the experimental data. Continuous curves 1 and 2 represent the expected Coulomb scattering by a finite and point nucleus, recalculated for the case of the projected data. The finite dimensions were taken into account by introducing the form factor, obtained in experiments on scattering of electrons by carbon (see appendix). It can be seen that the experimental data are in good agreement with the expected scattering if a finite nuclear dimension is assumed. The significance level obtained with a χ^2 test is 65%. For the curve corresponding to a point nucleus, the agreement is somewhat poor in the angle range from 85 to 180°. The



Differential angular distribution of scattered negative muons. φ – projection of the scattering angle on the photographic film. The points represent the experimental data. Curves 1 and 2 – expected Coulomb scattering for a finite and point nucleus respectively.

expected number of events within these angles is 10.25, and the observed is 3 ± 2.1. According to the finite-nucleus model, the expected number of scattering events at these angles is 6.35. Thus, for a single scattering of negative muons at 10 — 30 Mev by a carbon nucleus, no other scattering is observed, with the exception of the ordinary Coulomb scattering. The following estimates can be given for the upper limit of the cross section of "anomalous" scattering, resulting from this experiment (we consider scattering anomalous if it causes an increase in the cross section over that expected from the finite-nucleus model). The cross section of "anomalous" scattering by an angle greater than 45° does not exceed 1.25×10^{-28} cm^2 per nucleon, and that by an angle of 90° does not exceed 0.7×10^{-28} cm^2 per nucleon. The estimate is subject to the condition that the "anomalous" scattering be noted when the excess of the experimental number of scattering events over the theoretical value is greater than one statistical error.

We are now processing the data on single scattering of negative muons at 30 — 50 Mev, namely the muons which have passed after scattering through one of the plates installed in the chamber.

In connection with the increasing recent interest in the possibility of muon decay by the $\mu \to e + e + e$ scheme, we wish to note that in our chamber, from among 60,000 registered muon decays by the $\mu \to e + \nu + \bar{\nu}$ scheme, not a single muon decay into three electrons was observed. This gives a ratio $(\mu \to e + \nu + \bar{\nu})/(\mu \to e + e + e) < 1.7 \times 10^{-5}$.

In conclusion, we express our gratitude to Professor V. P. Dzhelepov for allowing us to perform measurements on the proton synchrotron and for continuous interest in this investigation, and also the staff of the Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, who collaborated in the performance of the experiment, with particular gratitude to N. B. Edovina and V. G. Svyatkina for organizing rapid development of the photographic film as received, and also to A. A. Bednyakov for effective help when working with the accelerator.

APPENDIX

Plotting the theoretical curve.

Single Coulomb scattering of Dirac particles, with allowance for spin, from a point-like nucleus is satisfactorily described, for $Z/137 \ll 1$, by the Mott formula

$$d\sigma_p = \frac{1}{4} Z^2 r_e^2 \left(\frac{m_e c}{p\beta}\right)^2 \sin^{-4}\frac{\theta}{2}\left(1 - \beta^2 \sin^2\frac{\theta}{2}\right) d\Omega, \quad (1)$$

where Z is the nuclear charge, m_e and r_e are the mass and classical radius of the electron, p and β the momentum at the velocity of the incoming particle, and θ the polar scattering angle.

Since we have measured the muon distribution over the projections of the scattering angles on the plane of the photographic film, for comparison with theory one must project Eq. (1) on a plane. When projected, Eq. (1) becomes

$$d\sigma_p = 4Z^2 r_e^2 \left(\frac{m_e c}{p\beta}\right)^2 \left[\frac{\sin\varphi + (\pi - \varphi)\cos\varphi}{\sin^3\varphi} - \frac{\beta^2}{2}\frac{(\pi - \varphi) - 0.5\cdot\pi\cos\varphi}{\sin\varphi\cos\varphi}\right] d\varphi. \quad (2)$$

Here φ is the projection of the scattering angle of the negative muon. We note that at energies of 10 — 30 Mev the spin contribution [second term in the square brackets of formula (2)] does not play any role in the present experiment.

In the transfer of the momenta prevailing in scattering of 10 — 30-Mev muons by carbon nuclei, account must be taken of the influence of the finite nuclear dimensions. This allowance leads to the introduction of a form factor F^2

$$d\sigma_f = F^2 d\sigma_p, \quad (3)$$

where σ_p is the cross section for scattering by a point nucleus, σ_f the scattering cross section by a finite nucleus, and F^2 is a factor that takes into account the charge distribution in the nucleus. The experiments of Fregeau and Hofstadter[9,10] have shown that the distribution of the charge in the carbon nucleus is best described by a form factor obtained on the basis of the oscillator shell model

$$F^2 = [1 - \alpha x^2 / 2k^2 (2 + 3\alpha)] \exp[-x^2/4k^2], \quad (4)$$

where $x = (2a/\lambda\!\!\!^{-}) \sin(\theta/2)$, θ is the polar scattering angle, $a = 2.4 \times 10^{-13}$ is the mean square radius of the carbon nucleus, $\alpha = 4/3$, $k^2 = 3(2+5\alpha)/2(2+3\alpha)$. The three dimensional distribution described by formula (3) was projected on a plane to obtain a theoretical distribution of the scattered muons over the projections of the scattering angle, with allowance for the finite nuclear dimensions.

In plotting the theoretical scattering curve, the entire interval of investigated momenta $p\beta$ was broken up into ten sub-intervals with equal $\Delta(p\beta)$. For each such sub-interval, the average scattering cross section was obtained by integration, with allowance for the energy distribution of the muon flux and under the assumption that the energy losses due to ionization are constant in this interval. The latter approximation leads to an inaccuracy in the cross section for the first sub-interval, where $\Delta(p\beta)/p\beta$, at most, is less than 0.5%. This was followed by calculation of the theoretical value of the number of particles scattered by angles, whose projections are greater than 15°. The ten curves thus obtained were summed over the corresponding angular intervals, and yielded the theoretical differential distribution of particles over the scattering angles.

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