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The Determination of the Muon Magnetic Moment from Cosmic Rays

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A simple experiment suited for use in an advanced laboratory course in particle physics is described. The magnetic moment of cosmic ray muons which have some polarization is determined with an error of about ±5% after ten days of running.

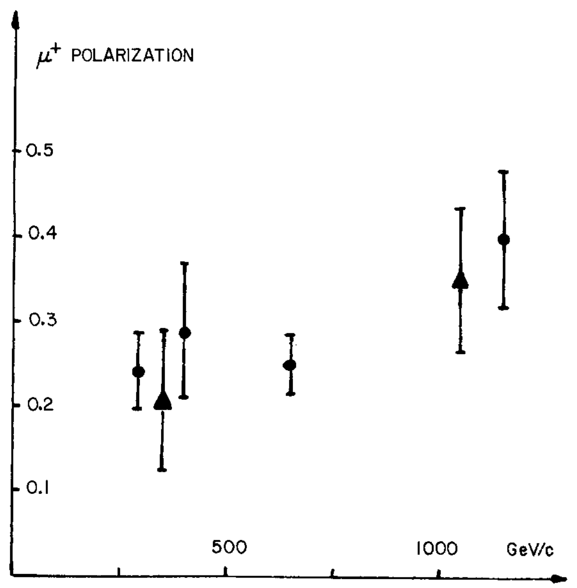

FIG. 1. Polarization of μ^+ as a function of momentum at sea level according to measurements of Ref. (4) [●] and Ref. (5) [▲].

I. INTRODUCTION

The non-conservation of parity in the decay chain $\pi\mu e$ was established in the experiment of Garwin, Lederman and Weinrich.[1] The experiment reported here uses essentially this idea. Polarized cosmic muons are stopped in a copper target located in a region of known magnetic field. The spins of the muons precess in the field and the angular distribution of the decay positrons is measured as a function of time. The magnetic moment of the muon can be calculated from the precession frequency.

II. COSMIC MUONS

Cosmic muons are produced by π and K decay in the upper region of the atmosphere. The vertical differential intensity of muons at sea level goes through a maximum at about 0.5 GeV/c.[2] The reason why cosmic muons are polarized can be understood in the following way: a vertically falling μ is emitted either forward or backward in the rest system of a vertically falling π (or K). Therefore μ of given energy in the lab can be produced by π (K) of two different energies E^+ (for a backward μ) and E^- (for a forward μ).

Now in the rest frame of the mother particle the polarization of the μ is 100% due to maximal parity violation: In this frame the spin of a μ^+ is always antiparallel to its flight direction. In the lab the spin will be parallel for a backward μ^+ and antiparallel for a forward μ^+. Hence the polarization in the lab will be zero if the number of π^+ (K^+) with energies E^+ and E^- are equal.

Complete calculations[3] involving all decay angles and the transformation of the polarization from the center of mass system to the laboratory show that a zero polarization can only be due to a flat production spectrum. Actually the polarization has been measured (Fig. 1) and found different from zero.

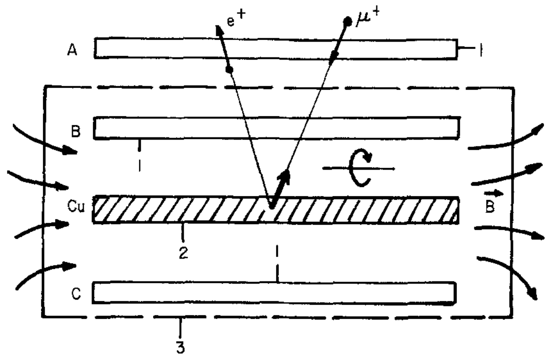

FIG. 2. Experimental arrangement: 1—plastic scintillator; 2—copper target; 3—coil.

III. PRINCIPLE OF THE EXPERIMENT

Stopped μ^- in a target material will be quickly caught by the nuclei. Stopped μ^+ will decay with the angular distribution $1+a\cos\theta$ (θ is the positron angle with respect to the spin of the μ^+). The asymmetry a, again due to parity violation varies with positron energy (0–53 MeV) between ~ -0.3 and $+1.0$ and has a mean value of $\frac{1}{3}$.

If the target is located in the magnetic field B the spin of the μ^+ will precess with frequency

$$\omega = geB/2m_\mu c \tag{1}$$

(g is the Landé factor of the μ), and the angular distribution will depend on time according to the expression $1+a\cos\omega t$.

The arrangement is shown in Fig. 2: A coincidence signal between counters A and B and no pulse from counter C were required to produce the trigger of a stopped μ^+. The decay positron was then also detected by the coincidence BA after the time t which was stored.

The number of detected positrons is

$$N(t) = N_0 \times e^{-t/\tau_\mu}[1+\alpha\cos(\omega t+\delta)] \tag{2}$$

where the experimental asymmetry α contains the factor a and depends upon the μ^+ polarization, the solid angle of accepted muons and the solid angle of detected positrons. δ is the angle of initial polarization (0° or 180°), τ_μ the mean lifetime of a μ (2.2 μsec) and N_0, a normalization constant.

IV. DESCRIPTION

The magnetic field was provided by a $100\times63\times10$-cm^3 copper coil with 1000 windings mounted on an aluminium frame. The target was $80\times63\times2.5$-cm^3. For practical reasons the target had to be thin. The density must be high to produce a high stopping rate. In addition the material had to be non-magnetic with a high radiation length to minimize the electron absorption. Copper is therefore a good candidate. The magnetic field was measured point by point with a Hall probe. It had a mean value of 11 G/A over the target volume and a dispersion of $\pm4\%$ due to inhomogeneities. The expected oscillation period was 3 muons mean lives for 1 A. The detectors were NE 102 A scintillators $80\times55\times2$ cm^3 prolonged on both sides by 30-cm light guides on which were stuck XP 1000 photomultipliers. For a field of 50 G the fringe field could be easily shielded.

The simplest logical circuit was used: after discrimination the signals from A and B were put into a coincidence vetoed by C. The output of the coincidence was used for both starting and stopping a time-to-amplitude converter (TAC). The

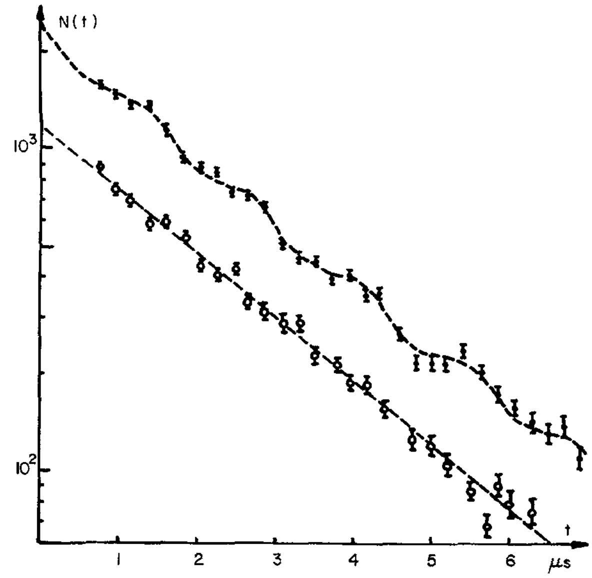

FIG. 3. Experimental results: The upper spectrum was obtained with a field of 55 G (~17 500 events), the lower spectrum with field off (~9000 events). The curves are computer fits.

zero-time offset was 0.4 μsec and the range 10 μsec. The amplitude was stored in a multichannel analyzer. The TAC and the analyzer were calibrated with a variable delay using the pulses AB and an oscilloscope. The time basis of the scope was checked by a quartz clock.

V. EXPERIMENTAL RESULTS AND DISCUSSION

We have made several measurements at earth level (alt. 350 m) and in the basement where $\sim$330 MeV/c muons could be stopped. Figure 3 shows the spectrum obtained from a 10-day run with a magnetic field of 55 G compared with a run with field off. The intensity AB was 10/sec and the number of good events 1.3/min.

The theoretical prediction formula (2) plus an additive constant term R_o representing the background was fitted to the data using the CERN minimizing computer program MINUIT. In fact the derivatives of the χ^2 function can be easily calculated and a self-made program using matrix inversion and Newton's iteration could work. The results are for 55 G:

$$N_0=2285\pm44,$$
$$R_0=25\pm6,$$
$$\delta=0.24\pm0.36,$$
$$\omega=4.57\pm0.11 \text{ MHz},$$
$$\alpha=0.067\pm0.011,$$
$$\tau_\mu=2.10\pm0.05\ \mu\text{sec}.$$

($\chi^2=1.0$ for 33 degrees of freedom). The background was mainly due to accidentals (restart falling within the 10 μsec range of the TAC and interpreted as a stop). For the field zero data of Fig. 3 the asymmetry α has been found to be less than 0.003 with $\omega=4.57$ MHz ($\chi^2=1.0$ for 34 degrees of freedom).

The μ^+/μ^- ratio is about 1.2 at 1 GeV/c^2 but the μ^- mean life is 0.163 μsec in copper (nuclear capture).[6] Hence its contribution is negligible for $t>0.5$ μsec.

From formula (1) and the data on Fig. 3, the g factor may be computed as $g=1.95\pm0.09$. The measurement precision is mainly limited by the 4% inhomogenity in the field. Table I gives a summary of the measurements for different magnetic fields.

TABLE I. A summary of measurements: measurements 3 and 4 were made at earth level; measurements 1, 2, and 5 in the basement where 330 MeV/c μ could be stopped.

	B Gauss (±4%)	ω fitted MHz	α fitted	g-factor (±4% from field inhomogenities)
1	58	4.51 ± 0.14	0.047 ± 0.011	1.83 ± 0.06
2	55	4.57 ± 0.11	0.067 ± 0.011	1.95 ± 0.05
3	43	3.69 ± 0.41	0.054 ± 0.017	2.02 ± 0.22
4	43	4.03 ± 0.20	0.040 ± 0.017	2.20 ± 0.11
5	29	2.47 ± 0.15	0.053 ± 0.014	$2.0\ \pm0.12$
			Mean value:	1.94 ± 0.08 (total error)

Our measurements show a predominance of spins up (δ is compatible with zero), which indicates that we are in a negative slope of the production energy spectrum.

VI. CONCLUSION

The computation of polarization from α turns out to be difficult because the positrons travel several radiation lengths in the copper. However, the problems involved in this experiment, like parity non conservation, polarization, cosmic rays, Dirac's prevision for the magnetic moment of leptons may help the student to become more familiar with high energy physics and its associated techniques.

Professor H.-J. Gerber has proposed this experiment: I would like to thank him and also Dr. R. Frosch for their help throughout the course of this work. I am also indepted to A. Junod and J.-L. Vuilleumier whose calculations contributed to the preparation of the experiment.

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