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MOMENTUM MEASUREMENTS IN NUCLEAR EMULSIONS
EXPOSED IN A MEGAGAUSS FIELD*

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ABSTRACT

Although the generation of a megagauss magnetic field inevitably destroys the field-producing coil, the explosion is radial, permitting nuclear emulsions to be exposed in the field without physical damage. We report on the measurements of particle momenta by track curvature in nuclear emulsions exposed to a pulse of electrons from the Stanford Linear Accelerator while in a 0.92 megagauss field. The errors in the curvature measurements are accounted for by the effects of multiple Coulomb scattering alone. The rms error is given by the expression $\sigma(\rho)/\rho = 2.5\ell^{-1/2}$, where ℓ (microns) is the track length upon which ρ , the radius of curvature, is based.

* Work performed under the auspices of the U. S. Atomic Energy Commission and the National Science Foundation.

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1. Introduction

During the course of an experiment performed at the Stanford Linear Accelerator on the production of magnetic bremsstrahlung by 19 GeV electrons in megagauss magnetic fields^{1, 2}), we noted that materials placed within the single-turn field-producing coil can survive with no physical damage. This is possible because the violent disintegration of the coil is entirely directed away from its axis. These observations led us to investigate the feasibility of irradiating nuclear track emulsions to ionizing radiation in single-pulse megagauss fields. The purposes were twofold: a) to examine the possibilities for improving the accuracy of momentum, i.e., curvature, measurements of particle tracks in emulsion and, as a diagnostic method, b) to examine the field profile in the central volume of the magnetic field.

In dc magnetic fields, which normally do not exceed 100 kG, the multiple Coulomb scattering of particles in nuclear track emulsion dominates over the magnetic deflection. In pulsed fields $B \leq 500$ kG, which can be generated in millisecond time intervals without coil destruction, the multiple scattering and magnetic deflection mechanisms become competitive. Theories for optimizing track information in this latter case have been given by Furth³) and Kim⁴), who showed that a significant improvement in the determination of particle momentum can be achieved in this intermediate regime when magnetic deflection and multiple Coulomb scattering are simultaneously evaluated. A magnetic field intensity in the megagauss range affects

magnetic deflection that dominate the multiple scattering of the particle. This permits the determination of particle momenta by curvature measurements alone, with the error in such measurements being determined primarily by the multiple scattering and measurable length of the particle track.

2. The Megagauss Generator

Any metallic conductor that comes into contact with a megagauss field will violently explode after no more than a few microseconds. The megagauss generator must be capable of building up the field before the coil disintegrates^{5, 6}). For a capacitor discharge system, the quarter period must be of the order of 2 μ sec, which is beyond the capability of most energy storage banks. The 60 kJ, 20 kV, 12 nH capacitor bank used in these experiments was specifically designed as a megagauss generator with high repetition rate. The destructive effects of the coil explosion are minimized by using light weight coils which are allowed to expand freely⁶).

Setup time as well as inductance are minimized by incorporating the solid dielectric switch directly into the hydraulic clamping device for the coil (figs. 1 and 2). Eighty low inductance cables (Brand-Rex type V-1434) connect the 20 capacitors to the switch, which is triggered by three exploding wires imbedded in the laminated Mylar insulation⁷). The time jitter of the switch is less than 50 nsec. More technical details are given in refs. ¹) and ⁸).

The coils used in this experiment were made of brass sheet, 2 mm thick, with an i.d. of 10 mm and an axial length of 10 mm. A 2 mm diameter hole in the coil wall was provided for the passage of the electron beam. Figure 3 shows the waveform of the magnetic field for a capacitor discharge at 15 kV, measured with an inductive pickup loop at the center of the coil. In the actual emulsion exposure, the magnetic field was determined by measuring the discharge current. The ratio of field and current was obtained in a series of calibration runs. It is impractical to determine the field distribution in the coil by direct measurements because of the small dimensions of the coil and the large number of pulsed experiments that would be needed to obtain a precise field profile. For this purpose, an analog system was developed in which an enlarged mockup of the coil is powered by an audio amplifier. The impedance is matched by a tuned air core transformer, and the frequency is adjusted to scale the c.w. skin depth in the mockup to the transient skin depth in the original coil. Figure 4 shows the field profile along the beam path. The overall precision of the field measurement can be better than 2%.

3. Exposure of the Emulsions

Discs of 7 mm diameter were fabricated from 300- μ m-thick Ilford G-5 emulsion pellicles. A stack of 20 of these discs was placed in a light-tight cylindrical Mylar container with a wall thickness of 0.45 mm. This container fitted snugly inside the coil and was simply suspended by string to keep it in place after the coil had disintegrated.

A 25 cm diameter steel cylindrical shield was placed around the coil to contain the coil fragments when the megagauss field was pulsed. The peak field for the present experiment was 0.92 megagauss. The field maximum was synchronized with the accelerator in order to irradiate the emulsion stack with a single pulse of about 10^4 electrons with energy 19 GeV and duration 0.2 μ sec. An attenuated electron beam from the Stanford Linear Accelerator, having the required characteristics and single-pulse mode of operation, was designed and operated by J. Murray and R. Gearhart¹).

4. Analysis and Results

The radius of curvature ρ of a particle track was obtained in this experiment from the magnetic deflection of the particle ϕ in path length ℓ . Our method was to measure the spatial coordinates of individual grains along the track separated by an optimal cell-distance t (defined below), using a three-coordinate, digitized microscope with 1 μ m readout on all axes. The data were then fitted to a curve-fitting computer routine that gives the radius of curvature of the particle's trajectory about its guiding center as well as its pitch angle, i.e., angle between the particle's velocity and the magnetic field.

To make an estimate of the error in our measurements of curvature, we consider here the error in ρ when the deflection angle between the first and last t -cells are used to evaluate ρ . The fractional error in ρ is $\sigma(\rho)/\rho = \sigma(\phi)/\phi$, where ϕ is the deflection of the particle in the magnetic field given by

$$\phi = 0.03 B\ell(z/pc) \text{ radians.} \quad (1)$$

The rms error $\sigma(\phi)$ in the magnetic deflection ϕ of the particle track of length ℓ is given by

$$\sigma(\phi) = [\sigma_s^2 + 2\sigma_t^2]^{1/2},$$

where the rms error in the tangential direction of the track owing to multiple Coulomb scattering is⁹⁾

$$\sigma_s = 0.071 \ell^{1/2} (z/p\beta c) \text{ radians} \quad (2)$$

and σ_t is the measurement error in the initial and final directions of the track segment owing to multiple scattering, grain size, and digitization errors.

The symbols are:

B = the magnetic induction in megagauss;

ℓ = the path length, in microns, over which curvature measurements are made;

p = the particle momentum, in MeV/c;

z = charge units of the particle;

and β = the ratio of the particle's velocity to the speed of light c .

Following Barkas¹⁰⁾, we find that the error in the direction of a particle track is minimized when it is measured over an optimum cell length $t = 11 \delta^{2/3} (p\beta c/z)^{2/3} \mu\text{m}$, where δ is the error due to grain size and digitization. The corresponding error in direction of the t -cell is then $\sigma_t = 0.23 \delta^{1/3} (p\beta c/z)^{-2/3}$ radians.

The fractional error $\sigma(\rho)/\rho$ is then

$$\frac{\sigma(\rho)}{\rho} = \frac{2.3}{B\beta \ell^{1/2}} \left[1 + \frac{2t}{\ell} \right]^{1/2}. \quad (3)$$

In this experiment, $B = 0.92$ MG, $\beta = 1$, $p\beta c/z = E$ (MeV) and $\delta \approx 0.35 \mu\text{m}$ (rms). Eq. (3) thus simplifies to

$$\frac{\sigma(\rho)}{\rho} = \frac{2.5}{\ell^{1/2}} \left[1 + \frac{2t}{\ell} \right]^{1/2}, \text{ with}$$

$$t = 5.5 E^{2/3} \mu\text{m}.$$

Curvature measurements were made on a sample of secondary electrons whose trajectories were not obscured by the primary beam. (Because of high track density and limited path length of the 19 GeV primary electrons in the 300- μm -thick pellicles, measurements on those electrons were impractical). The range of energies of the secondary electrons we measured was $2 \leq E \leq 115$ MeV. The ratios t/ℓ , in all cases, were less than 0.1, hence to good approximation, $\sigma(\rho)/\rho \approx 2.5/\ell^{1/2}$.

To ascertain whether the accuracy of the curvature measurements in the emulsions exhibit this simple behavior, we analyzed the data in the following manner: a) compute the radii of curvature for the entire track segment, $\bar{\rho}$, and for each half of the track, ρ_1 and ρ_2 . b) Evaluate $|\rho_1 - \rho_2|/\bar{\rho}$ and compare this quantity with the expected values, adjusting for bremsstrahlung and ionization energy loss along the track. Because the directions of the electrons (positrons) were unknown, we took their directions to be in the direction of decreasing curvature. The results of this analysis are shown in fig. 5, where we present the ratio $|\rho_1 - \rho_2|/\bar{\rho}$ and associated error for each event plotted versus the energy of the electron. The expected value of $|\rho_1 - \rho_2|/\bar{\rho}$, taking into account ionization and bremsstrahlung energy

losses, is indicated for each event.

We conclude that the errors assigned to the fractional differences between the radii of curvature for the first and second halves of each track, which are based upon the relation $\sigma(\rho)/\rho = 2.5\ell^{-1/2}$, fully account for the observed distribution of $|\rho_1 - \rho_2|/\bar{\rho}$. Furthermore, the changes in ρ along the electron tracks are consistent with energy-loss processes only and, hence, give no evidence for significant gradients in the B-field within the central volume of the coil.

5. Outlook for Applications

In the present work it has been demonstrated that nuclear emulsions can be exposed in megagauss fields without physical damage, and that the momentum of charged particles can be determined to accuracies limited by the expected effects of multiple Coulomb scattering. We believe it is quite striking that the radius of curvature of a 1 cm track of a particle with momenta up to 10 GeV/c in a 1 megagauss field can be measured to an accuracy $\lesssim 3\%$. This technique thus permits good momentum resolution in an emulsion volume typically 1 cm³, with the important assets of high spatial resolution, high density of recorded events, and high stopping power. Also, by allowing the curvature measurements to be made over distances 1 cm and less, the effects of distortion of the emulsion are diminished.

Possible areas of application of the megagauss technique are in studies of the meson-nucleus, nucleon-nucleus, and, in view of the recently developed heavy-ion beams at the Bevatron, nucleus-nucleus interactions. Such experiments would complement and extend the

emulsion experiments performed with pulsed magnetic fields, $B \approx 200$ kG, by White et al.¹¹⁾, Hoffman and Combe¹²⁾, and Zhdanov et al.¹³⁾. The technique is clearly suited for experiments involving a megagauss field as a target, such as the measurement of the magnetic bremsstrahlung^{1,2)}, where the positron-electron pairs from the bremsstrahlung γ -rays can be analysed for both energy and polarization. The production and subsequent stopping of Σ^- and Ξ^- in emulsion in the presence of a megagauss field also leads to new areas of hypernuclear research.

The duration of the pulse of particles must be less than 1 μ sec and at present, the volume occupied by the emulsion is limited to about 1 cm³. The shape of the volume does not have to be cylindrical; an oblong shape $3 \times 0.5 \times 0.5$ cm³, for instance, would be feasible. The variation of the coil shape is only limited by the condition that the ratio of width to axial length must remain close to unity for maintaining a good energy efficiency. An increase of the volume will soon require capacitor bank energies that offer technical difficulties to operate. A reliable system with high repetition rate might be limited to energies below 100 kJ, although larger systems appear feasible in principle. When the coil is destroyed in each pulse, a fair estimate of the repetition rate would be one pulse every 5 to 10 minutes. From the recent work of Andrianov et al.¹⁴⁾, it appears feasible to design a megagauss (or slightly sub-megagauss) system with a tantalum coil that can withstand repeated firing. Combined with a low inductance spark gap switching system, this would permit a faster repetition rate,

with the possibility for mechanized feeding and multiple exposures of the emulsions.

We wish to thank Drs. J. Murray and R. Gearhart, SLAC, for their invaluable contributions in the design and operation of the beam used in this experiment. We appreciate the interest and comments of Professor T. Erber, and acknowledge the assistance of P. J. Lindstrom in carrying out the computer analysis of the data.

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FIGURE CAPTIONS

- Fig. 1. Drawing to scale of the low inductance collector and switch assembly. The movable part of the switch that presses the dielectric packet in place and also holds the coil is cross-hatched in both views.
- Fig. 2. Cross section of the solid dielectric switch and coil clamp. An insulated clamping bolt and a cable connection are also shown.
- Fig. 3. Waveform of the magnetic field in an emulsion shot. The relative electron beam intensity versus time is also indicated.
- Fig. 4. Magnetic field profile along the beam path in the 10 mm i.d. coil used in the emulsion shot. This profile was measured in a three times enlarged model with scaled skin depth. The magnetic field is normalized with respect to its peak value. Distances are measured from the coil axis.
- Fig. 5. Fractional differences of the radii of curvature between the first and second halves of electron tracks versus energy. Errors attributable to multiple scattering are indicated. The open circles are the expected values of $|\rho_1 - \rho_2|/\bar{\rho}$ owing to ionization and bremsstrahlung energy losses of the electrons.

XBL 728-1428

Fig. 1

XBL 728-1424

Fig. 2

Fig. 3

XBL 728-1427

Fig. 4

XBL 728-1426

Fig. 5

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