Use of the magnetic induction of iron in cosmic-ray and high-energy physics

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The idea of using magnetic induction in solid magnetized iron for determination of the momentum of penetrating charged particles of high energy, proposed by D. V. Skobel'tsyn in 1929, is set forth. The principal scientific results in cosmic-ray and high-energy physics obtained using the magnetic induction of magnetized iron and the prospects for its application in new areas are presented.

The idea of using of solid magnetized iron for determination of the momentum of penetrating charged particles of high energy was first advanced[1] by D. V. Skobel'tsyn.[1)]

The idea is as follows. According to electromagnetic theory, the Lorentz force acting on an elementary particle of charge e moving with velocity $\mathbf{v}$ in magnetized iron is $\mathbf{F} = \mu(e/c)[\mathbf{vH}]$, where $\mathbf{H}$ is the magnetic field strength and c is the velocity of light. The magnetic permeability μ of iron has a magnitude of several thousand, so that the gain in $\mathbf{F}$ and consequently in the magnitude of deflection of particles in such a magnetic field is obvious. As a result of the fact that the deflection of the charged particle is increased, the upper limit and accuracy of measurement of its momentum are increased. At the same time the iron core of the magnet is used as an absorber of electrons, γ rays, and other particles accompanying the penetrating particle. It should also be mentioned that the angular deflection of the penetrating particle as the result of Coulomb scattering in the iron core can be significantly less than the deflection due to the action of the magnetized iron if the longitudinal size l of the core is sufficiently large. For example, the angular deflection of a particle in a magnetic field is $\vartheta \sim l$, and the rms deflection angle of the particle in iron as the result of Coulomb scattering is $\langle \vartheta_{sc}^2 \rangle^{1/2} = (E_s/E)(l/l_0)^{1/2} \sim l^{1/2}$, where E is the particle energy in MeV, $E_s = 21$ MeV, and $l_0 \simeq 1.76$ cm is the radiation length in iron. Consequently the relative Coulomb scattering $\vartheta_{sc}/\vartheta \sim l^{-1/2}$ decreases with increase of l.

The development of this experimental technique in nuclear physics and cosmic-ray physics experimentally proved the correctness and usefulness of Skobel'tsyn's idea. By 1930–1931 devices based on this idea had been built, which consisted of blocks of magnetized iron and Geiger-Muller counters connected in coincidence.[2,3] These devices permitted determination of the sign of the charge and evaluation of the energy of penetrating cosmic-ray particles. In Refs. 2 and 3 the magnetic induction $B = \mu H$ reached a high value (about 17 000 G).

Subsequently the idea of deflection of charged particles in ferromagnetic material attracted the attention of theoreticians, in particular C. F. von Weizsäcker. He solved the Dirac equation for scattering of a charged particle in a ferromagnetic material with use of Heisenberg's ideas of the quantum-mechanical theory of ferromagnetism and also showed that the magnetic induction $\mathbf{B}$ is responsible for the deflection of a charged particle in magnetized iron. Thus, Skobel'tsyn's idea received additonal justification on the basis of the quantum theory.[2)]

On the basis of this idea Conversi, Pancini, and Piccioni[5] and Ticho and Schein[6] in the 1940s obtained fundamentally new results regarding the decay and absorption of cosmic-ray muons. These authors[5,6] used magnetized iron in combination with groups of Geiger-Müller counters connected, depending on their function, in coincidence, anticoincidence, or delayed coincidence. In these experiments the difference in the behavior of positively and negatively charged stopped muons in materials with various Z was demonstrated experimentally for the first time. The lifetime of the positive muon $\tau_+ \approx 2.1$ μsec was determined and the dependence of τ_- for negative muons on Z of the material was obtained ($\tau_- \sim Z^{-4}$ for light elements).

Beginning with the 1950s, many groups of physicists have used magnetic spectrometers the main element of which is a magnet or magnets with an iron core in study of cosmic-ray muon production processes. These devices are distinguished by a high limiting detectable momentum of the muons and a large aperture with economical use of the current in the magnet coil. The method of deflection of muons in strong magnetic fields has become widely used at this time in experiments on cosmic rays. Its main advantage is that it is a method of direct measurement of the momenta of muons, in contrast to other, indirect methods used in study of cosmic rays (for example, the method of the muon absorption curve in soil, etc.).

The determination of the momentum of a muon by the magnetic spectrometer method is based on the well known relation connecting the muon momentum p_μ with the angular deflection of the muon ϑ (in radians) and with the line integral of the magnetic induction $\int_0^L B(l)\,dl$ in gauss·cm:

$$p_\mu = 300\,\vartheta^{-1} \int_0^L B(l)\,dl\ (\mathrm{eV}/c),$$

where l is the coordinate in the longitudinal direction of the magnet and L is the longitudinal dimension of the magnet.

The momentum spectrum and angular distribution of cosmic-ray muons measured at sea level are characteristics very sensitive to the muon production processes in the upper layers of the atmosphere, as has been shown in theoretical calculations.[7,8]

Up to the present time the spectrum and angular distri-

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bution of muons have been well studied in the region $p_\mu \lesssim 10^3$ GeV/c in which the experimental data obtained by various methods agree. Comparison of experiment with theory[7,8] shows that in this momentum region muons are produced in decay of $\pi^\pm$ mesons arising in the upper layers of the atmosphere as a result of interaction of the primary cosmic radiation with nuclei of air atoms.

To investigate the nature of muon production in the higher-momentum region $p_\mu > 10^3$ GeV/c, at the present time large magnetic spectrometers with large aperture Ω and large maximum measurable momenta p_m have been built. We should mention first of all the MARS spectrometer[9] ($p_m = 5000$ GeV/c, $\Omega = 800$ cm$^2\cdot$sr) which records muons in a direction close to the vertical, and the spectrometers MUTRON[10] ($p_m = 17\,000$ GeV/c, $\Omega = 1100$ cm$^2\cdot$sr) and DEIS[11] ($p_m = 6000$ GeV/c, $\Omega = 1100$ cm$^2\cdot$sr) which record horizontal muons.

The authors of Refs. 10 and 11, on the basis of an analysis of their experimental results, reach the conclusion that muons are generated in the decay processes $\pi \to \mu$ and $K \to \mu$, with a ratio of the number of decaying kaons and pions $N_K/N_\pi \approx 0.15$ for the interval $E_\mu = 1$–10 TeV.

Data on the muon energy spectrum also carry important information on the pion-production process. As was first shown in Ref. 12, the energy spectrum of pions produced in the energy region up to about 100 GeV has a scaling nature, in any case for large values of the Feynman variable $x > 0.2$. This conclusion, as is clear from the experimental data on the spectrum of muons in the higher energy region,[9,10,11] remains valid up to pion energies about 10 TeV. For further investigation of the production of pions and kaons by this method it is necessary first of all to perfect magnetic spectrometers further by increasing their aperture and also by increasing the accuracy of measurement of the deflection of muons in the magnet by the detecting devices.

A further important application of Skobel'tsyn's idea is the use of magnetic spectrometers for study of the muon component of extensive air showers (EAS).[13,14] For example, in Ref. 13 a large underground magnetic spectrometer with a maximum detectable momentum $p_m = 10^3$ GeV/c and an aperture 1400 cm$^2\cdot$sr was used to study muons over a wide energy range $E_\mu = 10$–500 GeV in EAS with a total number of particles $N_e = 10^5$–10^6. The lateral distribution and energy spectrum of muons obtained in this experiment have permitted the conclusion that Feynman scaling is violated, that extrapolation to the energy region 10^{15}–10^{16} eV of those models of hadron-hadron interactions which are valid at energies achieved in accelerators (10^{14} eV) is valid, and that there is no anomalously large transfer of energy to muons in interaction of cosmic rays with energy 10^{15}–10^{16} eV.

Therefore, realization of the idea of use of magnets with an iron core has already provided many important results in nuclear physics and in high-energy cosmic-ray physics. There is no doubt that further improvement of the experimental technique based on this productive idea will lead to new scientific results. In this connection we can mention the use of Skobel'tsyn's idea for investigation of the interaction of colliding beams of electrons (30 GeV) and protons (820 GeV) in the latest experiment at HERA.[15] In this experiment it is proposed to study inelastic *ep* scattering in the region of four-momentum transfers a factor of ten larger than the values so far achieved $Q^2 \sim 10^4$ (GeV/c)^2.

[1)] O. Piccioni in the collection "The Birth of Particle Physics" (Cambridge University Press, 1983, page 222) wrote: "The adventurous idea of using solid magnetized iron to study the high-energy cosmic particles was first described (in 1929) by Dmitry Skobeltzyn despite the fact that at that time such particles were supposed to be electrons. The message was read by Mott-Smith in the United States, who built an iron magnet and tried it." Mott-Smith himself in Ref. 3b mentions that the construction of a magnet of solid magnetized iron "... would be feasible and convenient for deviating these very penetrating particles, as was first pointed out by Skobeltzyn."

[2)] At the present time there is also a purely *experimental* proof of the validity of this idea. The results of investigations of the energy spectrum of cosmic-ray muons by various methods can be reconciled only under the condition that the force acting on an elementary particle of charge e in magnetized iron is $\mu(e/c)\mathbf{v}\times\mathbf{H}$.

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