First Results from a Search for Magnetic Monopoles by a Detector Utilizing the Drell Mechanism and the Penning Effect

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A search for massive moving magnetic monopoles has been performed with a combined detector of proportional chambers and scintillation counters. Mixed gas of helium and 10% methane was used for the proportional chambers, because ionizations occur by the Drell mechanism and the Penning effect. No candidate for the monopole was obtained during 150 days of live time. The upper flux limit of 7.2×10^{-13} cm^{-2} sr^{-1} s^{-1} for monopoles is obtained for the velocity range from $\sim 3\times10^{-4}c$ to $1c$ at a 90% confidence level.

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Grand unified theories (GUT's) predict the existence of magnetic monopoles with extremely large masses of about 10^{16} GeV. Such monopoles are accelerated to velocities around $10^{-3}c$ by galactic magnetic fields. Recent results from the Irvine-Michigan-Brookhaven proton decay experiment[1] have indicated that the minimal SU(5) may be broken. Alternative theories, such as the supersymmetric GUT's[2,3] and the Kaluza-Klein theory,[4] predict monopoles heavier than 10^{16} GeV. The velocities for such monopoles might be smaller than $10^{-3}c$. Therefore it is very important to search for monopoles with velocities around $10^{-3}c$ and smaller. The energy-loss mechanism for monopoles has not been clear for the range of velocities less than $10^{-3}c$. Recently, however, Drell *et al.*[5] presented an excellent theory for the energy loss of monopoles in the velocity range from $10^{-4}c$ to $10^{-3}c$ in a simple material such as helium. We call their theory "the Drell mechanism" hereinafter. In this paper we report the first results from a monopole search based on the Drell mechanism by using proportional chambers together with a result from a search using scintillation counter technique for detecting.

Cabrera's method[6,7] is a better technique for detecting a monopole with arbitrary velocity; however, it is very difficult to get a large sensitive area in this method. Although Errede *et al.*[8] have reported experimental flux limits using monopole catalysis of nucleon decay, the value of the catalysis cross section is still not clear. Accordingly, it is important to look for the monopoles more directly by the use of the Drell mechanism.

Our detector to search for monopoles consists of nine layers of proportional chambers (PRC),[9] six layers of scintillation counters (SC), and fourteen iron layers. The size of the detector is about 3.9 m (width) by 3.2 m (length) by 2.4 m (height). The number of the SC's in each layer is nineteen. Each SC has area 240×20 cm^2 and thickness 1 cm. The number of the PRC's in each layer is four. Each PRC has effective area 246×92 cm^2 and thickness 2 cm. The decay time constant for a PRC output is set at 5 μs. The thickness of the iron layers is 12 cm for the inner layers and 1 cm for the two outer layers.

The time of flight was measured with time-to-digital converters (TDC) having a time resolution of 50 ns for PRC's, and fast TDC's having a resolution of 0.5 ns and slow TDC's having a resolution of 50 ns for the SC's. Ionization losses were measured by analog-to-digital converters (ADC) for the SC's and the PRC's. There are 36 PRC's. Each PRC has its own TDC and ADC. The detector is situated on the ground near sea level at the Institute for Cosmic Ray Research in Tokyo. Details of the detector and the data acquisition system have already been reported elsewhere.[10]

Our experiment was divided into two stages. The experiment was performed mainly by the SC's during the first stage, and mainly by the PRC's utilizing the Drell mechanism and the Penning effect in the second stage.

During the first stage, a trigger signal was generated with use of signals from the SC's. The velocity region of a trigger was between $10^{-4}c$ and $0.1c$. The area–solid-angle product for this trigger was 11.0 m^2 sr. Threshold levels for SC's and PRC's were set at $\frac{1}{20}$ minimum ionization ($I_{\rm min}$). PR gas (Ar + 10%CH_4) was circulated through the PRC's. Monopoles with velocities from $2.5\times10^{-4}c$ to $0.1c$ can be measured if Ritson's calculation[11] for the scintillator is valid. However, Ahlen *et al.*[12,13] pointed out that the lower limit on velocity to detect monopoles with a scintillator is about $6\times10^{-4}c$. No candidate for the monopole was obtained during this first stage. The upper flux limit of 1.8×10^{-12} cm^{-2} sr^{-1} s^{-1} for the magnetic monopole is obtained at a 90% confidence level.

In the second stage, the gas in the PRC was changed to He + 10%CH_4. Drell *et al.* have shown that large energy losses occur for low-velocity monopoles in helium gas. When the monopole goes through the helium gas, helium atoms are excited by the process

$$\mathrm{He} \rightarrow \mathrm{He}^*,$$

where He* is a metastable state of the helium atom. This He* then collides with a methane molecule, which leads to an ionization of the methane through the Penning effect as follows:

$$\mathrm{He}^* + \mathrm{CH}_4 \rightarrow \mathrm{He} + \mathrm{CH}_4^+ + e^-.$$

This process occurs because the ionization potential of the methane molecule (13 eV) is smaller than the energy level of the He* (20 eV). The lifetime of the metastable state is greater than 10^{-3} s and the mean collision time between the He* and a methane molecule is about 30 ns. Thus, the Penning effect virtually always occurs before the metastable state decays radiatively. Data by Bortner and Hurst[14] have clearly demonstrated this in any arbitrarily mixed combination of helium and methane.

The calculated curve for ionization loss of the monopoles in He + 10%CH_4 is shown in Figs. 1 and 2. The efficiency of ionization for the Penning effect is estimated to be 83%,[15] and a new calculation of the Drell mechanism,[16] which is smaller than the old one by a factor of 2, is used. The Drell mechanism can be applied for the range of velocities up to around $10^{-3}c$. The ionization loss of the monopoles with large velocity is calculated by using Ahlen's formulas.[17]

The trigger signals for the second stage were generated by the successive delayed sixfold coincidence of respective layers of PRC's. Combinations of six layers from the first layer to the sixth layer, and from the fourth layer to the ninth layer, are used for this trigger. It is possible to trigger for particles which traverse the detector from both directions. The threshold level for the ionization loss in the PRC's was set at $3I_{\mathrm{min}}$. The summed maximum gate width was 360 μs which sufficiently covered the range of the velocities from $10^{-4}c$ to $1c$. The trigger efficiency for sixfold coincidences is estimated to be 1.0 for the energy losses larger than about $7I_{\mathrm{min}}$. It was not necessary to use veto signals for muons, and so we can measure monopole velocities up to $1c$. The area–solid-angle product for this trigger was 24.7 m^2 sr which was more than twice that used in the first stage.

Saturation effects due to heavily ionizing particles such as fast monopoles will be negligibly small, be-

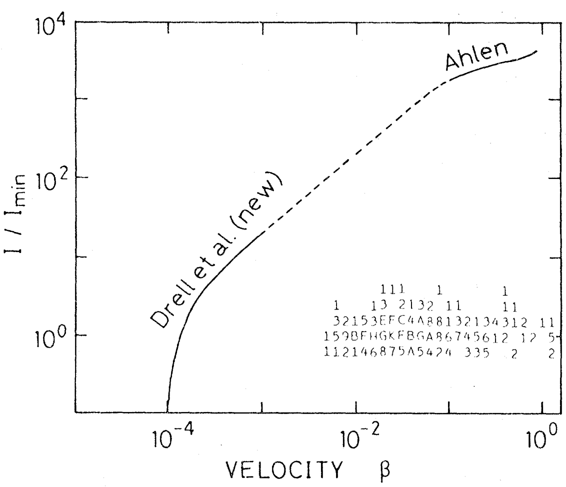

FIG. 1. The curve shows the calculated ionization loss for monopoles having the Dirac charge, as a function of velocity, in a mixture of helium and 10% methane. The printed characters represent observed data points with the stage-two arrangement obtained when the detector was operated so as to be triggered by muons. Numbers, letters, and asterisks indicate number of events in each bin, where the number increases as $1, 2, \ldots, 9, A, \ldots, Z, *$.

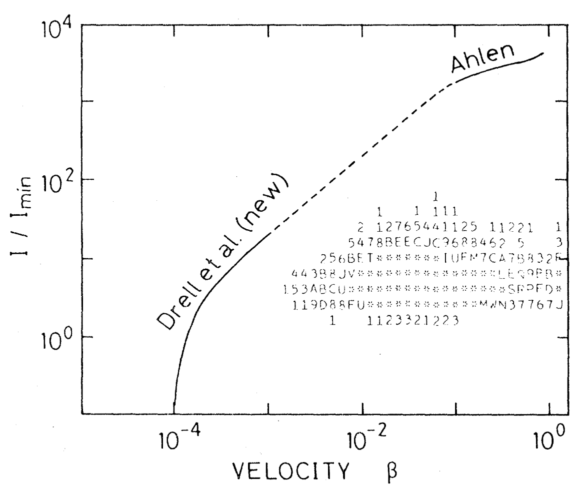

FIG. 2. The curve again shows the calculated ionization loss for monopoles having the Dirac charge as a function of velocity. The printed characters represent observed data points obtained with the stage-two arrangement when the detector trigger was set to respond to monopoles, as described in the text. The character code is the same as that noted in the caption for Fig. 1. It is seen that no data points fall in the region where monopoles are expected.

cause the high voltages for the PRC's have been set so that no saturation is produced even for 5.5-MeV α rays in the gas.

Measured data of the ionization losses for muons are also shown in Fig. 1 as a function of the velocity. The muon events are distributed around a velocity of about $10^{-1.5}c$. This behavior is due to the fact that the maximum drift time in the PRC is about 1 μs. An exactly similar distribution has been obtained by a Monte Carlo simulation based on the same assumptions. The value of the drift time is larger than the expected one because the gas used has small drift velocity compared with normal gases[18] and because of the low electric field (except near the anode wires). It is concluded that muons do not give signals that can be mistaken for monopoles.

The data of the second stage were analyzed according to the following conditions: (1) The number of SC's hit in each layer is less than five. (2) The number of PRC's hit in each layer is less than three. (3) There is at least one straight track in the PRC's. (4) The value of χ_t^2 is less than four for the time of flight. (5) The value of χ_i^2 is less than three for the ionization loss. χ_t^2 and χ_i^2 are defined as follows:

$$\chi_t^2 = \frac{1}{n-2}\sum_{j=1}^{n}\frac{(t_j - t_{\rm fit})^2}{\sigma_{\rm drift}^2 + \sigma_{\rm sys}^2},$$

where t_j is the time in layer j, $t_{\rm fit}$ is the fitted value, and $\sigma_{\rm drift}$ is the drift-time error of 200 ns. $\sigma_{\rm sys}$ includes an alignment error of the detector of $1.6\times10^{-2}/\beta$ ns which corresponds to the error of 0.5 cm.

$$\chi_i^2 = \frac{1}{m-1}\sum_{j=1}^{m}\frac{(I_j - \bar{I})^2}{\sigma_{\rm ion}^2 + \sigma_{\rm sys}^2},$$

where I_j is ionization loss normalized by the $I_{\rm min}$ in layer j, $\bar{I}$ is the average value of ionization losses normalized by the $I_{\rm min}$, and $\sigma_{\rm ion}$ is ionization error of $0.6\sqrt{\bar{I}}$ which is obtained from the distribution of ionization losses of muons. $\sigma_{\rm sys}$ is the systematic error of $0.2\bar{I}$ which includes the errors of an evaluation of the $I_{\rm min}$, fluctuation of the timing of gate pulses to the ADC's, and ambiguity of pulse shaping.

For events satisfying the above conditions during live time of 3.6×10^3 h, the ionization losses of the particles going through the PRC's are plotted in Fig. 2 as a function of velocity. The curve of energy loss of the monopoles is also shown. Events with large ionization losses were checked in detail, and proved to be showers produced by muons. They could be recognized from the variation of the ionization losses in each layer of the PRC's and the SC's. It is concluded that there is no candidate for the magnetic monopole.

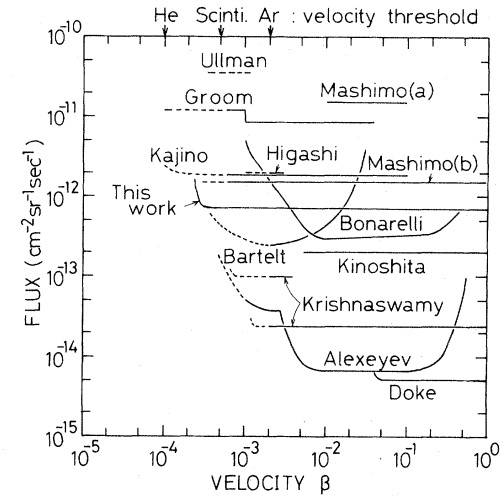

FIG. 3. Compilation of upper limits on the flux of magnetic monopoles as a function of velocity β at a 90% confidence level for ionization/excitation experiments. The broken lines mean that it is impossible to measure if calculations for the energy losses taking into account the binary encounter approximation for scintillators and argon gas are valid.

The present upper limit of magnetic monopole flux based on the second-stage measurements is shown in Fig. 3 together with other experimental results.[10,19–28] If a conjecture of energy loss taking into account a binary-encounter approximation[12,13] is applied, the lower limit of the velocity range for the scintillator is about $6\times10^{-4}c$, and that for the PRC using argon gas is about $2\times10^{-3}c$.

In conclusion, the upper limit of the monopole flux in the second-stage measurement is 7.2×10^{-13} cm^{-2} sr^{-1} s^{-1} at a 90% confidence level over a wide velocity range from $\sim3\times10^{-4}c$ to $1c$. The limit rises as the velocity decreases because the trigger efficiency decreases for low-energy losses. Our present experimental limit is the best one in the velocity region from $\sim3\times10^{-4}c$ to $10^{-3}c$ and exceeds the theoretical upper bound of $\sim3\times10^{-12}$ cm^{-2} sr^{-1} s^{-1} presented by Arons and Blandford[29] for a monopole mass of 10^{18} GeV. It is hard to reconcile the first candidate measured by Cabrera[6] with the present null result.

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