Search for a Dirac Magnetic Monopole in High Energy Nucleus-Nucleus Collisions

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A new technique based on barium phosphate glass detectors was used in searching for Dirac pointlike magnetic monopoles with $n \geq 2$ in ultrarelativistic heavy ion collisions. No candidates were found in 1.05×10^9 and 3.08×10^{10} interactions of $11A$ GeV Au nuclei and 1.46×10^{10} interactions of $160A$ GeV Pb nuclei with Pb targets. The upper limits, on order of nb, on the production cross sections for Dirac magnetic monopoles and other hypothetical highly ionizing objects are well below those predicted via the Drell-Yan mechanism. [S0031-9007(97)04267-1]

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The production, in high energy particle collisions, of Dirac magnetic monopole pairs and other hypothetical particles that produce high ionization rates has been suggested [1,2]. Searches have been carried out in e^+e^-, pp, and $\overline{p}p$ interactions at various high energy colliders [3,4]. In all these searches, the monopole pairs were expected to be produced via the Drell-Yan mechanism. In nucleus-nucleus (AA) collisions, the production of monopole pairs has also been proposed [5]. In particular, the production of monopole pairs via a thermalized quark-gluon plasma [5] would make a search in AA collisions more favorable than in e^+e^- and pp collisions.

In this Letter, I report the first search for monopole production in AA collisions from three experiments conducted at AGS of Brookhaven and at SPS of CERN. Using BP-1 barium phosphate glass detector arrays, these experiments were designed to detect classic Dirac structureless monopoles in ultrarelativistic heavy ion collisions. Table I summarizes the beam, target, and detector information, together with obtained upper limits on the production cross section at 90% confidence level.

A magnetic monopole is characterized by a large ionization rate, monotonically increasing with velocity β, and rapidly changing at lowest velocities [8]. Figure 1 presents the ratio of the equivalent charge to β as a function of β for monopoles with $n = 1$ and 2. In the same graph, I also show the threshold of the BP-1 glass detector tuned optimally for this search by a suitable choice of chemical etchants [9]. As illustrated in Fig. 2, the detection threshold and dynamic range can be chosen by optimizing the type of etchant [10]. The etchant $1N$ NaOH at 70 °C yields a threshold in ionization rate corresponding to $Z/\beta \geq 85$. (Various calibrations show that the BP-1 glass responds to a certain type of ionization rate such as restricted energy loss. I use the term "ionization rate" in the text below.) It is seen that the detector is sensitive to a magnetic monopole with $n \geq 2$ and $\beta \geq 0.18$, whereas surviving beam and projectile fragments are totally invisible. This makes the technique particularly attractive for high statistics searches.

The detector arrays, consisting of a number of BP-1 glass plates and a Pb target as shown in Fig. 3, were mounted on a two-dimensional translation panel. With the beam spot ~ 1 cm^2 in size, I controlled the panel remotely and "painted" the beam uniformly on the array at normal incidence. The beam was counted by on-line electronic detectors and the entire exposure was monitored. When a highly ionizing particle passed through the detector system, it produced a trail of damage a few nanometers in size along its trajectory. This track could be made visible in an optical microscope by chemical etching. Two simultaneous etch rates controlled the development of conical etch pits: the general etch rate v_G, which removes the bulk of material isotropically, and the track etch rate v_T, which etches preferentially along the particle path. The signal of the detector, defined as the etch rate ratio $s \equiv v_T/v_G$, is a sensitive function of ionization rate, and for relativistic ions, approximately of Z/β. In the experiment, s was determined by $s = (1/\cos\theta)(G^2 + b^2)/(G^2 - b^2)$, where θ is the incident angle of the particle on the array, b is the semiminor-axis of the elliptical fit to a track mouth, and G is the thickness of bulk material removed during etching. BP-1 glass plates were etched in $1N$ NaOH at 70 °C for 6 hours, which produced $G \simeq 22$ μm.

I used an automated measurement system to scan glass plates and measure the geometry of each identified track. The on-line image analysis algorithm identified tracks and extracted parameters of an elliptical fit to track mouths. With two plates of BP-1 glass placed upstream from the target I was able to veto beam particles and fragments with energies much lower than the beam energy such that they registered as $Z/\beta \geq 85$ before reaching the target. With the downstream plates I looked for central collisions leading to products with $Z/\beta \geq 85$. For these products, one could obtain an instantaneous value of ionization rate averaged over a sampling distance $L_s = Gs/(1 + s\cos\theta) \simeq 11$–$20$ μm on each surface of the glass. For a penetrating track, a series of values of s along its trajectory is obtained. In off-line analysis, I used

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TABLE I. Summary of three experimental searches. Upper limits on Dirac monopole production cross section are given at 90% confidence level. The number of interactions was estimated based on total interaction cross sections measured at AGS [6] and SPS [7].

Experiment accelerator	E882-I AGS, BNL	E882-II AGS, BNL	P288 SPS, CERN
Beam ion	^{197}Au	^{197}Au	^{208}Pb
Energy (A GeV)	$\simeq$11	$\simeq$11	$\simeq$160
Target (g cm^{-2})	14.4	7.21	7.21
Detector (cm^3)	$5 \times 5 \times 0.07$	$10 \times 10 \times 0.1$	$10 \times 10 \times 0.1$
No. of plates	2 + 15	2 + 10	2 + 18
Beam fluence	3.50×10^9	1.92×10^{11}	6.60×10^{10}
No. of interactions	1.05×10^9	3.08×10^{10}	1.46×10^{10}
Upper limit (nb)	20	0.65	1.90

an ionization rate code and the calibrated response curve in Fig. 2 to determine Z and β simultaneously for each event by minimizing χ^2 of the fits to the measured values of s as a function of penetrating depth. As the flight distance was only up to 2 cm, the detector was sensitive to particles with a lifetime as short as $\tau \sim 10^{-10}$ sec.

Three classes of events could register in the detector arrays: (1) a Dirac magnetic monopole, signaled uniquely by a decrease of ionization rate with penetrating depth; (2) candidates for an ultradense nuclear object, recognizable by $Z \geq 85$ and $\beta \geq \beta_{\mathrm{c.m.}}$ ($= 0.915$ at AGS and $= 0.994$ at SPS); and (3) background fragments with $Z/\beta \geq 85$ and $Z \leq Z_{\mathrm{beam}}$ that slowed through a large thickness of beam pipe or in interactions leading to fragments with intermediate rapidity emitted in nearly the forward direction.

The search strategy in AGS experiment E882-I was to look for all the tracks with $s \geq 1.016$, or equivalently, $b \geq 2$ μm when $G \simeq 22$ μm. This strategy is suitable for detecting abnormal nuclear matter such as predicted by Lee and Wick [11]. The upper limit on the cross section for abnormal-nucleus production was reported in Ref. [12]. Recoils of target fragmentation were found at density of $\sim 10^2$ cm^{-2}, a broad distribution of zenith angles, and ranges less than 100 μm, so that they did not penetrate even one plate of BP-1 glass. These tracks were of no interest and were rejected by requiring a coincidence measurement on both sides of a BP-1 plate. Nine penetrating events with $Z/\beta \geq 85$ were found by both automated scan and manual scan. All of them

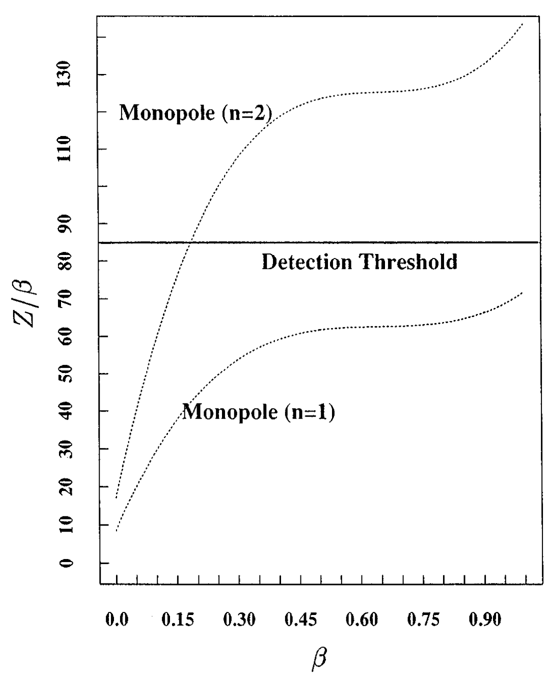

FIG. 1. The ratio of the equivalent charge to the velocity of a Dirac monopole as a function of velocity. Monopoles with $n \geq 2$ and $\beta \geq 0.18$ are detectable in the detectors.

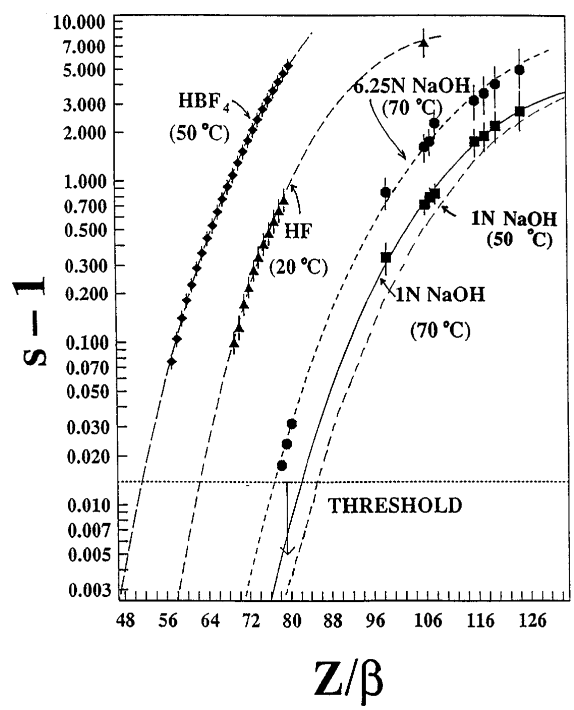

FIG. 2. The calibrated response curve of BP-1 detectors—the reduced etch rate ($s - 1$) as a function of Z/β for BP-1 glass etched in various etchants. 1N NaOH at 70 °C was used in the present work.

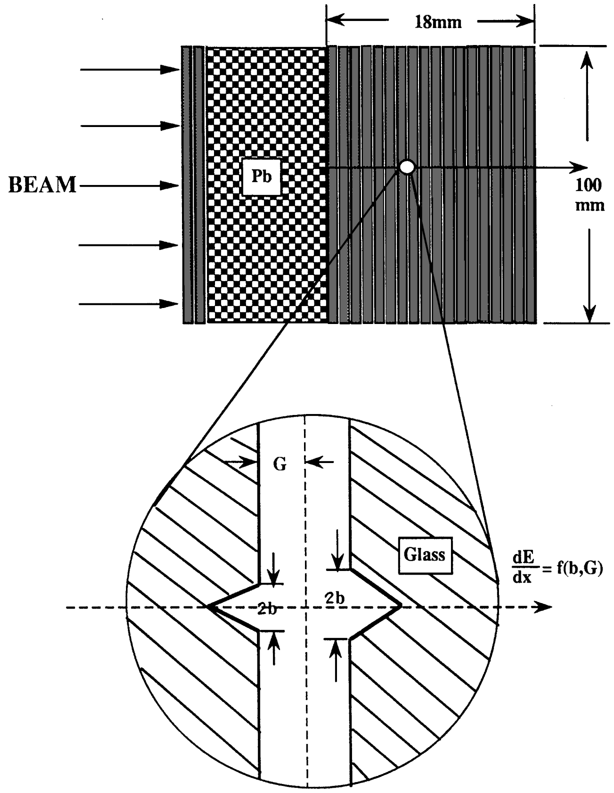

FIG. 3. Schematics of the experimental setup used in search for Dirac magnetic monopoles. Instantaneous value of ionization rate is measured at various depths as a highly ionizing particle passes through the detector array.

ranged out in the array and were unambiguously identified as slowing ions with $Z = 39$ to 82 and $\beta = 0.44$ to 0.79. None of the candidates had an ionization rate matching that predicted for a magnetic monopole with $n \geq 2$. The successful detection and identification of these background events demonstrate the effectiveness of the technique. (E882-I was originally designed for searching for abnormal nucleus production in 1992 and the result was published in 1993 [12]. After realizing that the same type of experiment could be used to detect monopoles with $n \geq 2$, two follow-up searches E882-II and P288 were conducted in 1994 and 1995, respectively, with a sensitivity improved by a factor of $\sim 10-100$.)

In AGS experiment E882-II and CERN experiment P288, the above strategy was not applicable due to the higher beam densities. I developed a restrictive scanning criterion optimized for tracks with $s \geq 5$, or equivalently, $b \geq 18\ \mu$m when $G \simeq 22\ \mu$m. Tracks with $s \geq 5$ (depths $d \geq 90\ \mu$m and half-opening cone angles $\phi \leq 13°$) should be much larger in diameter and length than tracks with lower s that were sought in the E882-I search. In both E882-II and P288 searches, no events of $s \geq 5$ penetrating two plates of detectors were found. The requirement of two-plate penetration ensures the detectability of monopole candidates in the presence of background tracks a few microns in size as long as the monopoles satisfy the kinematical requirement $\beta \geq 0.4$. For the abnormal nucleus search, the strategy is valid only for $Z \geq 120$ and $\beta \geq \beta_{\mathrm{c.m.}}$.

A powerful feature of this technique is that the detector response depends only on the ionization rate within a few nanometers along the particle trajectory and is independent of particle density up to $\sim 10^9\ \mathrm{cm}^{-2}$. To verify that the BP-1 detectors would record highly ionizing products while traversed by beam particles up to such a limiting density, I irradiated a $\sim 1\ \mathrm{cm}^2$ area of two BP-1 plates from the experimental array with fission fragments both before and after the experiment. Fission tracks have a very large value of s, which results in $b \simeq G$. Such tracks, produced both before and after the exposure, had the same appearance, from which one concludes that the beam did not adversely affect the effectiveness of the recording properties of the detector. I also etched one plate in a more sensitive etchant (6.25N NaOH at 70 °C) for a very short time and used an atomic force microscope to observe tracks corresponding to the beam and fragments at a density $\sim 10^8 - 10^9\ \mathrm{cm}^{-2}$, consistent with the on-line electronic counts.

The null result in these three experiments allowed one to place stringent upper limits on the monopole production cross section. The results are given in the last row in Table I. These upper bounds also constrain the production of other hypothetical particles with an anomalously large charge including the dyon, the subnucleon, and the vorton [2]. There seems no straightforward way to compare these upper limits with other existing limits previously obtained from experiments conducted in e^+e^-, pp, and $\overline{p}p$ interactions at various high energy colliders [3,4]. Figure 4 presents my upper limits, together with my calculated Drell-Yan cross section based on empirical formulas [13]. The Drell-Yan cross section serves as a rough point of reference for production of monopole pairs via an intermediate massive virtual photon, multiple virtual photons, or gluon-gluon fusion. My limits on the cross section are lower than the estimated ones for values of monopole mass up to 3.3 GeV for 11A GeV Au and up to 8.1 GeV for 160A GeV Pb.

The present limits are valid for classic Dirac monopoles with $n = 2$ or more. In the relation Dirac established [14] between the elementary electric charge e and the magnetic charge g [$= n\hbar c/(2e) = 68.5en$], n is known as a nonzero integer. The minimum allowed magnetic charge, so-called the Dirac magnetic charge $g_{\mathrm{D}} = 68.5e$ is obtained by setting $n = 1$. However, there is no fundamental reason for $n = 1$ to be more likely than $n \geq 2$. Here I assume that the elementary electric charge is that of electrons. If the elementary electric charge were found to be that of quarks, $(1/3)e$, one would have an elementary magnetic charge 3 times larger. If this were the case, my limits would be also valid for $n = 1$ monopoles since $dE/dx \propto g^2$. Except for the relation between g and e, there is no prediction for other properties of the Dirac

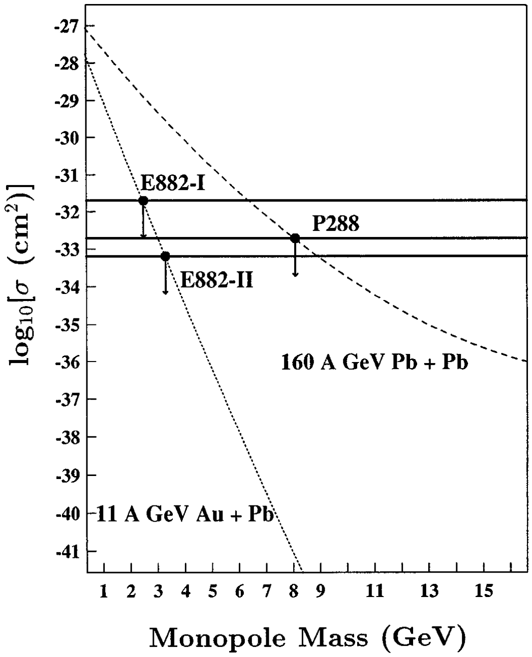

FIG. 4. The production cross section as a function of magnetic monopole mass. The upper limits from three searches E882-I, E882-II, and P288 are compared to the calculated Drell-Yan cross sections.

monopole. For example, its mass is not related to its electromagnetic properties and is not known at all. Predictions of the mass vary upwards from Dirac's original guess of 0.5 GeV [15]. Consequently, pointlike Dirac monopoles have been sought in cosmic rays and at each accelerator that opens up a new mass regime.

The present searches were made for the structureless monopoles of Dirac with limited masses. Because of form-factor suppression [1] and limited available collision energy, the highly structured monopoles of 't Hooft and Polyakov [16] are probably not accessible in heavy ion collisions. Complementary searches for supermassive grand unified theory monopoles with a predicted mass $m_{\mathrm{M}} \sim 10^{16}$ GeV have been undertaken in galactic cosmic rays [17].

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