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A Proposal for A High-Sensitivity Search for Dirac Magnetic Monopoles and Ultradense Nuclear Matter in 160 A GeV Pb on Pb Collisions at CERN SPS

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EXPERIMENT SUMMARY

PURPOSES:	Search for Dirac magnetic monopoles, ultradense nuclear matter, and other exotic composites
DETECTORS:	20 BP-1 glass detectors, each 100mm×100mm×1mm
MEASUREMENT:	Use automated scanning system at Berkeley
BEAM REQUESTED:	$10^{10} - 10^{11}$ Pb ions at 160 A GeV
BEAM LINE:	Parasitic to NA50 apparatus at T6 beam line
INSTRUMENTATION:	Beam monitor is needed to count beam to within 20%
TIME REQUESTED:	6 – 24 hours if beam intensity is $(1 - 5) \times 10^7$/pulse
ON-SITE COMPUTER:	Not needed

I. PHYSICS GOALS

We propose a small-scale experiment to search for two types of hypothetical particles that might be produced in $\sim 10^{10}$ collisions of 160 A GeV Pb on Pb. The first is the long standing Dirac magnetic monopole [1]. The second is ultradense nuclear matter suggested by Lee and Wick [2] and other possible forms of exotic composites.

1. Dirac Magnetic Monopoles

The magnetic monopole was introduced as early as 1931 by Dirac [1] in order to explain the quantization of the electric charge. Dirac also established a basic relation between the elementary electric charge e and the magnetic charge g. The discovery of a monopole should be of fundamental importance and have great impact on physical theories. Searches for particles carrying such a magnetic charge have been carried out at particle accelerators as well as in galactic cosmic rays for decades [3]. However, none of the searches to date has produced convincing evidence for its existence.

The magnetic charge of a monopole is expected to be $g = ne/2\alpha = 68.5ne$ where n is an integer and e is the fundamental electric charge. The mass of the Dirac monopole is not related to its electromagnetic properties. If the classical radius of a monopole is on the order of that of an electron, its mass would be $m_M \sim g^2 m_e/e^2 \sim 2.4n^2$ GeV. Predictions of mass vary widely from Dirac's original guess of 0.5 GeV upwards.

In addition to Dirac magnetic monopoles, other hypothetical particles that can produce high ionization rates in matter have been predicted. Examples are the highly structured monopoles of 't Hooft and Polyakov [4] (mass $\sim 10^{16}$ GeV [5]) and extended balls of electric charge predicted in non-Abelian gauge theories [6]. Because of form-factor suppression, the cross section for producing objects with extended structure may be impossibly low [7]. In our experiment, we will focus only on Dirac pointlike monopoles.

For detection of a Dirac magnetic monopole using an ionization detector, its energy loss rate dE/dx needs to be estimated. dE/dx of magnetic monopoles with magnetic charge g and velocity βc has been extensively studied [8]. When $\alpha << \beta$, dE/dx is well established by calculations analogous to that for electrically charged particles:

$$(dE/dx)_m \sim (g\beta/e)^2 (dE/dx)_e. \qquad (1)$$

where $(dE/dx)_e$ is the energy loss rate for a proton. $(dE/dx)_m$ of a monopole with magnetic charge g is equivalent to $(dE/dx)_e$ of a particle with electric charge $g\beta$. Therefore, $(dE/dx)_m$ is nearly constant as a function of velocity. This behavior is fundamentally different from that of an electrically charged particle, where $(dE/dx)_e$ is roughly proportional to β^{-2}. When $3 \times 10^{-4} < \beta < 0.2$, we have:

$$(dE/dx)_m \sim Cn^2\beta. \qquad (2)$$

where C is a constant, depending on the medium. Ionization rate of a monopole changes substantially only at very low velocity, $\beta < 10^{-2}$.

To summarize, a magnetically charged particle is characterized by (1) a large constant ionization rate when $\beta > 0.2$, and (2) a decrease near the end of range as a function of depth penetrated. In Fig. 1, we present the ratio of the equivalent charge to velocity as a function of velocity for monopoles with $n = 1$ and $n = 2$. We estimate that our detector is sensitive to a $n = 2$ magnetic monopole with $\beta > 0.1$ and with various possible masses up to ~ 8 GeV.

The production of Dirac magnetic monopole pairs in e^+e^-, pp, $\bar{p}p$, and AA collisions has been speculated about by several authors [7, 9]. Extensive searches for monopole pair production in e^+e^- [10], pp, and $\bar{p}p$ collisions [11] have been performed at various high energy colliders. In each of these, an upper limit on its production cross section has been placed. In all these collisions, the monopole pairs are expected to be produced via Drell-Yan mechanism. Moreover, in heavy ion collisions the thermal production of monopole pairs has been predicted [12]. However, no search has been made in nucleus-nucleus collisions so far. Only one exploratory search is being conducted by us using 11 A GeV Au beam at BNL AGS.

2. Ultradense Nuclear Matter

The possibility that stable or metastable abnormally dense nuclei might exist in nature or might be created in a high energy nucleus-nucleus collision has been suggested by several authors [2, 13, 14, 15, 16, 17, 18]. In a particular version of the theory, Lee and Wick [2] proposed a model in which an abnormal nucleus would have a density several times that of normal nuclei, a large volume binding energy (~ 130 A MeV), and a large atomic number, $Z \sim A/2 >> 100$. To create abnormal nuclei they suggested compressing nuclear matter to a high density in a relativistic nucleus-nucleus collision. In a recent calculation for finite normal and abnormal nuclei, the authors [19] claim that nuclei with $A > 86$ may have bound abnormal states and nuclei with $A > 165$ may have bound abnormal nuclei with binding energies larger than those of corresponding normal nuclei.

Several attempts to find a trace abundance of abnormal nuclei in nature have led to negative results [20, 21]. Earlier attempts to produce them in heavy ion collisions led also to negative results. In collisions of ^{40}Ar on Pb at 1.1 – 1.6 A GeV and of ^{40}Ar on Ca and U at 0.1 – 0.45 A GeV at the Bevalac, upper limits of ~ 50 and ~ 100 nb have been placed on the production cross section of nuclei with $Z > 26$ and lifetime $\tau > 10^{-9}$ sec [22, 23]. We have recently conducted a high-statistics search for ultradense nuclear matter using 11 A GeV Au beam at Brookhaven AGS [24]. In 10^9 collisions of ^{197}Au on Pb we found no nuclear products with $Z > 84$ and $\tau > 10^{-9}$ sec emitted within an angle of 140 mrad to the beam direction, allowing us to set an upper limit of 20 nb on the production cross section at 90% confidence level. An upgrade run on which we are currently working will improve the limit by a factor of ~ 100.

The availability at CERN SPS of very heavy Pb ions with energies one order of magnitude greater than at BNL AGS would lead to the possible formation of ultradense nuclear composites. We will conduct a no-background search for candidates for an abnormally dense nucleus with a charge larger than 85 and with a velocity at least as large as the center-of-momentum velocity $\beta_{c.m.} = 0.994$. In collisions of 160 A GeV Pb on Pb, the energy density will reach ~ 3 GeV fm^{-3}, which would favor the formation of an abnormally dense nuclear object.

II. DETECTOR AND TECHNICAL DESIGN

We will use BP-1 phosphate glass track-etch detector [25]. With its excellent charge resolution for the identification of relativistic high-Z ions. BP-1 has been used in a series of studies of charge-changing interactions in high energy nuclear physics. BP-1 has been also used in a previous search for Lee-Wick matter and an on-going search for monopoles at BNL AGS. The detection principle is simple. When a charged particle passes through a plate of glass, a large fraction of the bound ions within a few nm of the particle's trajectory is permanently displaced as a result of the energy deposition associated with the ionization rate of the particle. When etched in a suitable chemical reagent, etching occurs along the trajectory of a particle with charge Z and velocity βc at a rate v_T that exceeds the general etch rate v_G. A pair of conical etch pits is developed at the points of entrance and exit of the particle in each sheet of BP-1. When viewed through a microscope focused on a surface, the mouth of an etch pit is seen as a dark elliptical cone. The detected signal is defined as $s \equiv v_T/v_G$. It is empirically known that s is a sensitive monotonic function of dE/dx, and to a good approximation, of $(Z/\beta)^2$. s can be determined by measuring the geometry of the tracks:

$$s = \frac{1 + (b/G)^2}{1 - (b/G)^2}\frac{1}{\cos\theta}, \tag{3}$$

where b is the semi-minor axis of an elliptical fit to an etch pit mouth, θ is the incident angle with respect to normal, and G is the thickness of material removed on one side of the glass plate during the etch.

In this experiment, we will exploit one of the useful features of the BP-1: its sensitivity can be tuned by a suitable choice of chemical etchants [26]. Fig. 2 shows the dependence of the etch rate ratio on Z/β – a curve often called the response curve. One sees from Fig. 2 that the detection threshold and dynamic range can be chosen by using different etchants. In this experiment, we will use 1N NaOH at 50 °C, which yields a threshold in dE/dx corresponding to $Z/\beta > 85$.

The detector module will consist of 20 sheets of 100 mm × 100 mm × 1 mm BP-1 glass detectors and a Pb target as shown in Fig. 3. The dimension of the whole module will be ~ 40 mm along the beam direction and 100 mm × 100 mm perpendicular to the beam. The thickness of the Pb target will be 14 mm, which is equivalent to $\sim 40\%$ of interaction length. On each surface of the glass, we will be able to obtain an instantaneous value of dE/dx within a sampling distance of 50 μm for a highly-ionizing particle created in the target. With the two plates of BP-1 glass placed upstream from the target we can veto beam particles ($Z = 82$) and fragments ($Z < 82$) which have energies much lower than the beam energy so that they register as $Z/\beta > 85$ before reaching the target. With the 18 downstream plates we will look for central collisions leading to products with $Z/\beta > 85$ emitted from the target within an angle of ~ 1 rad along the beam direction. For these products, we will have 36 measurements of dE/dx along their trajectories in ~ 5.4 g cm^{-2} penetrating depth. In the case that the particle stops in the stack, we will have less data points for dE/dx, but will have information on its mass. These measurements of dE/dx, as a function of penetrating depth, will enable us to determine Z and β simultaneously for each registered particle. As demonstrated in our previous studies, Z can be measured to ± 2 and β can be measured to within $3 - 5\%$. No beam particles, or projectile fragments, or singly charged particles will be recorded in our detector, which eliminates the major background at a density of $10^8 - 10^9$ cm^{-2}.

Three classes of events are expected in this experiment: (1) A Dirac magnetic monopole is signaled by a decrease of dE/dx with penetrating depth. (2) Candidates for an ultradense nuclear matter are recognizable by $Z > 85$ and $\beta > \beta_{cm} = 0.994$. (3) Background would be projectile fragments that slowed through a large thickness of beam pipe or in interactions leading to fragments with intermediate rapidity emitted in nearly the forward direction. We show these three classes of events in Fig. 4. In Fig. 5, we show the sensitive region in the parameter space of Z and β. As the flight distance is only 20 mm, our detector is sensitive to particles with a lifetime as short as $\sim 10^{-10}$ sec.

We will use a fully automated scanning measurement system developed at Berkeley to scan all glass plates and measure the geometry of each identified track. The system consists of a 512 pixel $\times$ 480 pixel CCD camera, a microscope, an image processor, and a computer. The on-line image analysis algorithm identifies tracks and extracts parameters of elliptical fit to tracks. We will look for penetrating tracks with ~ 1 rad and obtain a series of values of Z/β at every 0.3 g cm^{-2} interval along its trajectory for each particle. In off-line analysis, we will use a dE/dx code and our calibration response curve to determine Z and β for each event by minimizing χ^2 of the fits to our measured Z/β values as a function of penetrating depth.

III. BEAM REQUIREMENT

We will expose the detector module to a focused or defocused high intensity Pb beam at 160 A GeV in the upcoming November–December run of 1995. We would like to accumulate a total fluence of $10^{10} - 10^{11}$ Pb ions, if and when this fluence is feasible. The "painting" technique will be employed to uniformly distribute the beam over the transverse cross section of the 10 cm $\times$ 10 cm module. We will remote-control the detector module using our X-Y moving stage to paint the beam spot over the module. Only rudimentary beam monitoring to within 20% is required. No other on-site computing or electronics is required.

It is technically easy for us to arrange the experiment parasitic to NA50 experiment at T6 beam line. We have discussed details of our proposal with Dr. Peter Sonderegger, the contactperson of NA50 and a CERN physicist. There are several easily accessible candidate places to mount our small-scale detector module. With schemes developed in previous runs, we expect that the setup process of our apparatus will take only $\sim 1-2$ hours. It can be done when NA50 has a beam shut down for floor activities. We would like to use NA50 beam monitor to count beam to within 20%. The dedicated beam time is requested such that we obtain the total fluence of $10^{10}-10^{11}$ Pb ions. Given the beam intensity of $(1-5)\times 10^7$ Pb ions/pulse, it translates to $6-24$ hours of effective beam time. In Table I, we list the beam fluence, number of interactions, and expected cross section we can reach for various beam intensities and beam times. One sees that in the worst case where the beam intensity is only 1×10^6 Pb ions/pulse, the sensitivity we can reach in a 6 hour run will still be ~ 55 nb on the production cross section for either monopoles or ultradense matter.

Table I. The expected sensitivity in cross sections for various conditions of beam intensity and beam time.

Intensity (Pb/pulse)	**Time** (hours)	**Thickness** (λ_I)	**Fluence** (Pb Ions)	**Interactions** (times)	**Cross Section** (nb at 90% c. l.)
5×10^7	24	0.20	2.2×10^{11}	3.9×10^{10}	0.5 nb
5×10^7	11	0.20	1.0×10^{11}	1.8×10^{10}	1.1 nb
5×10^7	6	0.40	5.4×10^{10}	1.8×10^{10}	1.1 nb
1×10^7	24	0.40	4.3×10^{10}	1.4×10^{10}	1.4 nb
1×10^7	11	0.40	2.0×10^{10}	6.5×10^9	3.0 nb
1×10^7	6	0.40	1.1×10^{10}	3.6×10^9	5.5 nb
1×10^6	24	0.40	4.3×10^9	1.4×10^9	14 nb
1×10^6	6	0.40	1.1×10^9	3.6×10^8	55 nb

No one has realistically calculated the cross section for either monopole or ultradense matter production. A meaningful search for monopole pair production requires a sensitivity below the Drell-Yan cross section for pair production. In Fig. 6, we present the calculated Drell-Yan cross section based on empirical formulae [27]. 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. We conclude that our limit on the cross section will be lower than the estimated cross section for monopole production for values of monopole mass up to at least ~ 8 GeV. For ultradense nuclear matter, our limit will be $\sim 1-2$ orders of magnitude more stringent than the existing limits.

IV. EXPECTED ACCOMPLISHMENT

In this simple small-scale experiment, we want to achieve two goals:

To search for Dirac magnetic monopole ($n = 2$) production with high statistics in an angle of ~ 1 rad to the beam direction in central collisions of 160 A GeV Pb on Pb. This experiment will be the first search for monopole pair production in heavy ion collisions at CERN SPS. Given a fluence of 10^{11} Pb ions, this search will reach the sensitivity of ~ 1 nb in its production cross section for point-like monopoles with mass up to ~ 8 GeV.

To search for ultradense nuclear matter and other exotic composites with $Z/\beta > 85$, $\beta > \beta_{cm} = 0.994$, and $\tau > 10^{-10}$ sec produced within ~ 1 rad to the beam direction in central collisions of 160 A GeV Pb on Pb. In this no-background search, we expect a sensitivity of ~ 1 nb in the production cross section, given a fluence of 10^{11} Pb ions. This limit is $\sim 1 - 2$ orders of magnitude better than previously achieved by us using a 11 A GeV Au beam at BNL AGS.

V. PERSONNEL AND TIMETABLE

One of us (YDH) will devote full time to the project. The other (PBP) will spend $\sim 20\%$ of his time on the project. A technician, M. Solarz, will provide engineering and experimental assistant needed for the project.

We have experience in using heavy ion beams at CERN SPS and other facilities, in using the glass detector techniques, in image processing, and in data analysis (see Appendix). The detector module and the X-Y moving stage will be prepared at Berkeley and shipped to CERN in August–October of 1995. The experiment will be carried out in the November–December Pb run. After the run, we will etch glass plates at Berkeley. Scanning and measurements will be made with the automated scanning microscope system at Berkeley. We hope to obtain expected results within four months after the exposure.

We believe that our small-scale experiments with the automated track-recording technique show that many interesting things can be done using only a small amount of beam time, as we demonstrated in the past runs. We hope a positive decision can be made in time for us to conduct the experiment during the 1995 November–December Pb run.

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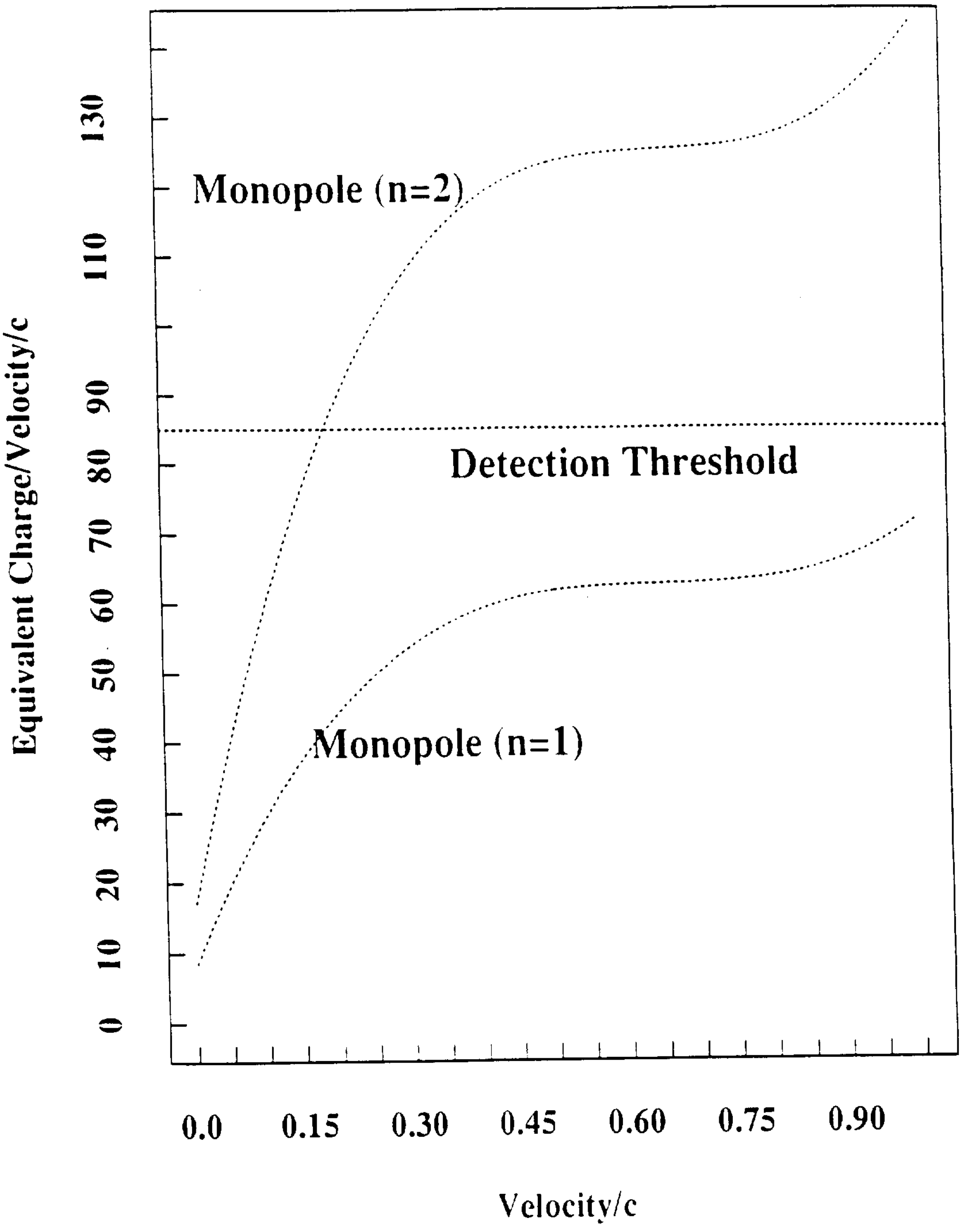

Fig. 1 The equivalent value of Z/β in terms of ionization rate for monopoles with magnetic charge $n = g/g_o = 1$ and 2. The selected threshold of our detector is also shown. Monopole with $n = 2$ and $\beta > 0.2$ are detectable.

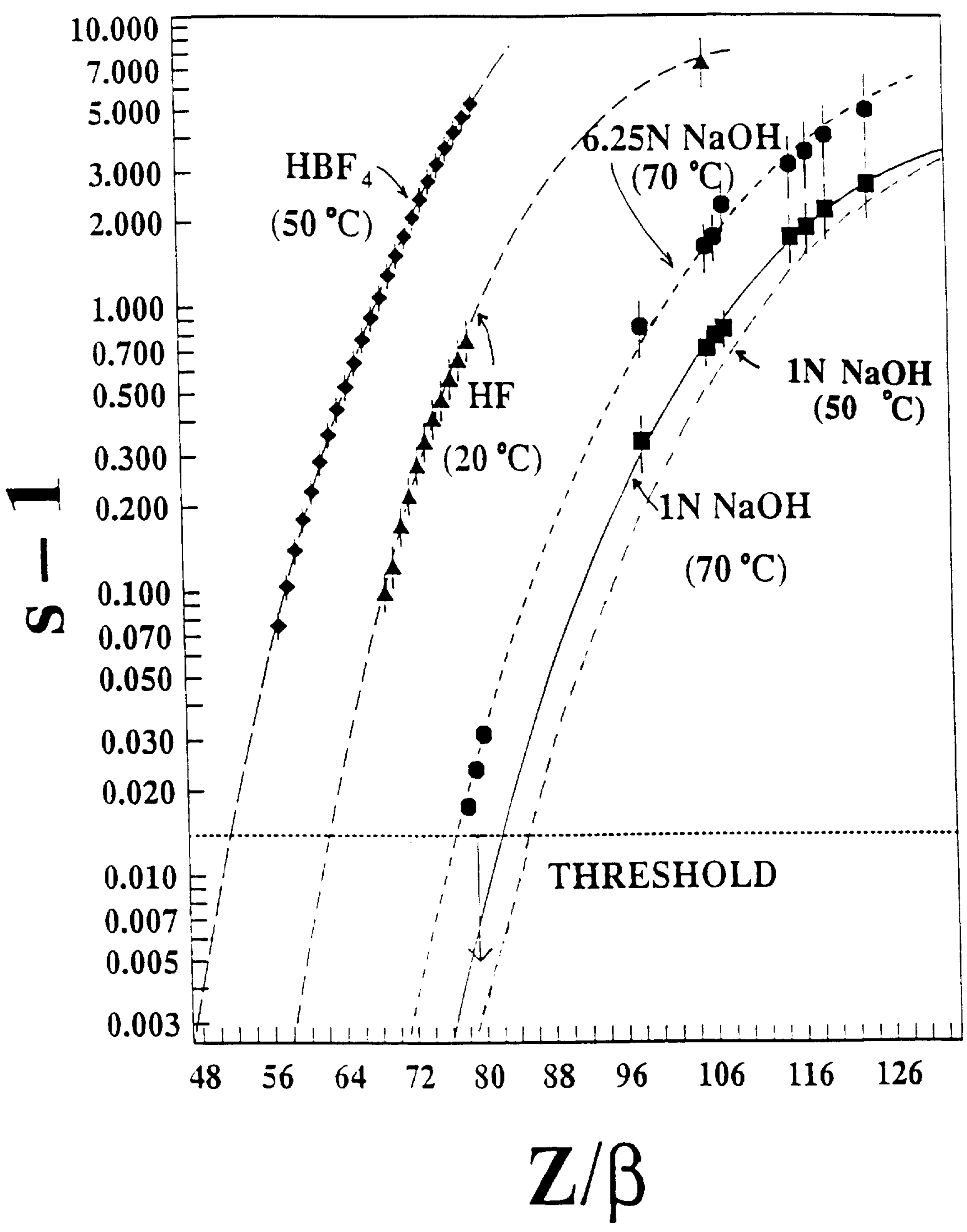

Fig. 2 The calibrated response curves for BP-1 glass etched in various etchants: 49% HBF_4 at 50 °C, 49% HF at 18 °C, 6.25N NaOH at 50 °C, 1N NaOH at 70 °C, and 1N NaOH at 50 °C. The detector signal $(s-1)$ is shown as a function of Z/β. The threshold for 1N NaOH at 50 °C is at $Z/\beta = 85$.

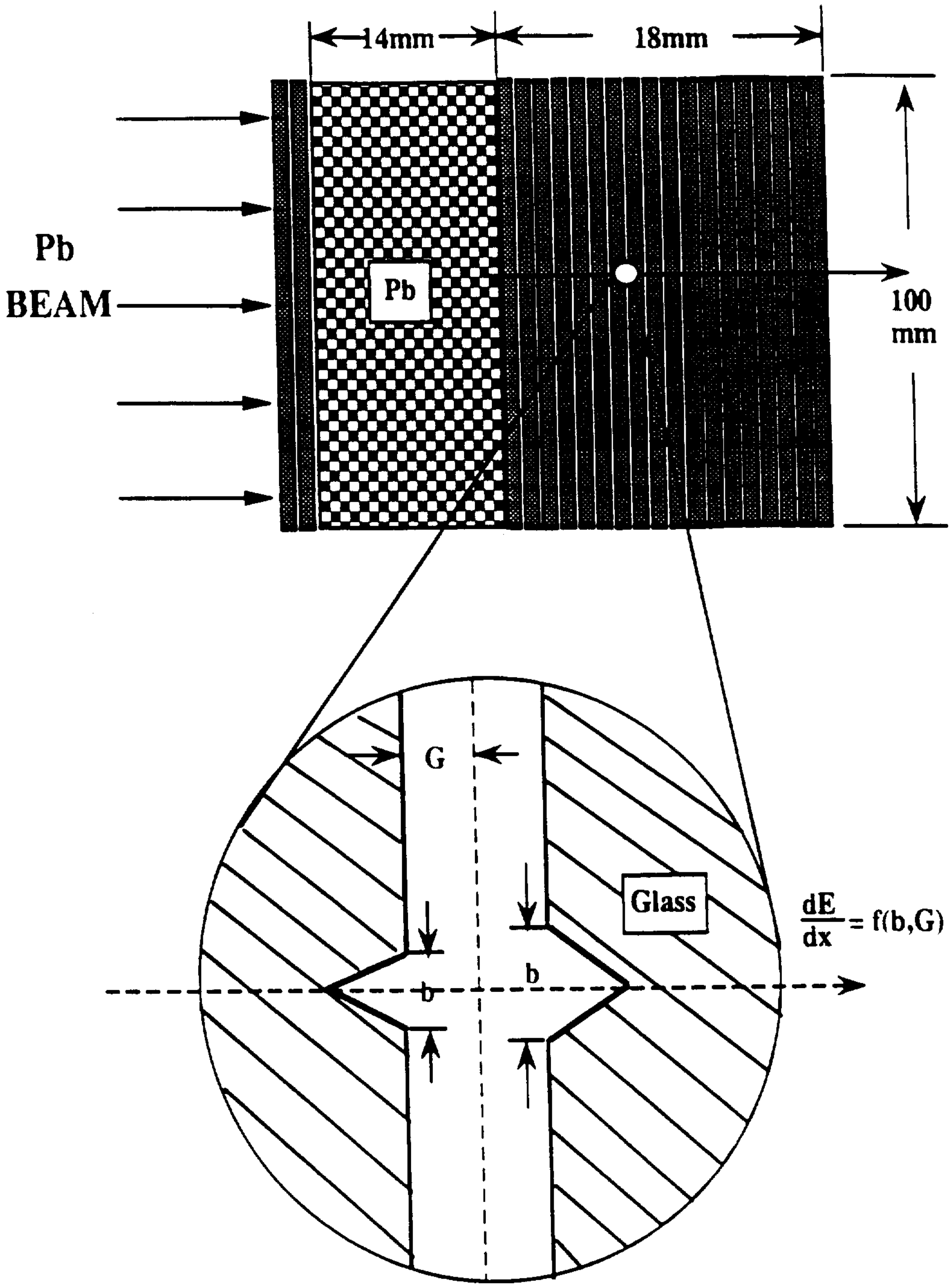

Fig. 3 The detector module to be used in this experiment. The module consists of a 14 mm thick Pb plate as a target and 20 plates of BP-1 glass. On each surface we can measure the instantaneous values of dE/dx for a penetrating particle. Each glass plate has a dimension 100 mm × 100 mm × 1 mm. A X-Y moving stage will be used to paint the beam spot over the area of 100 mm × 100 mm.

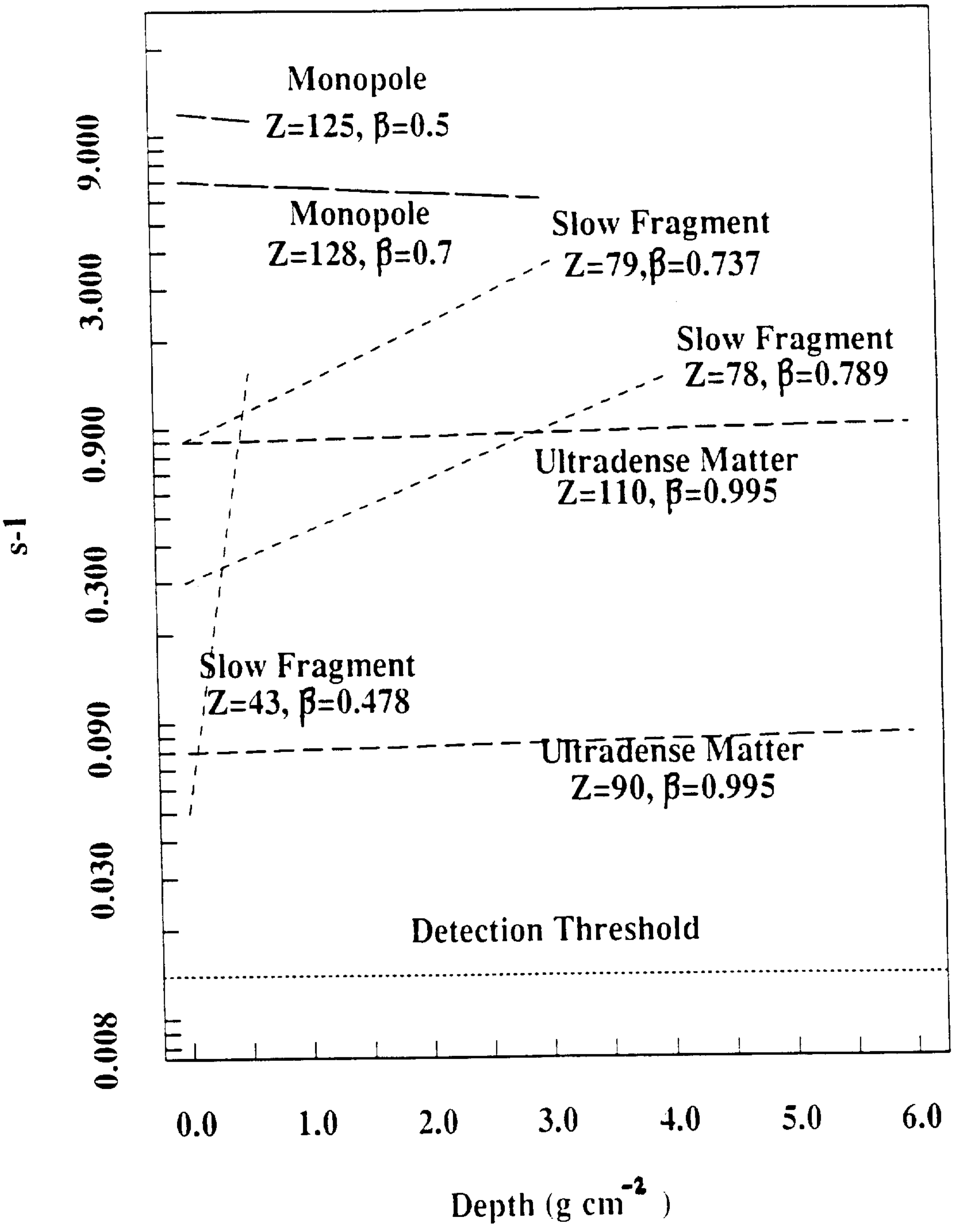

Fig. 4 The detected signal $(s-1)$ measured at various depths downstream from the target in the detector module. Simulation samples for three classes of events are shown.

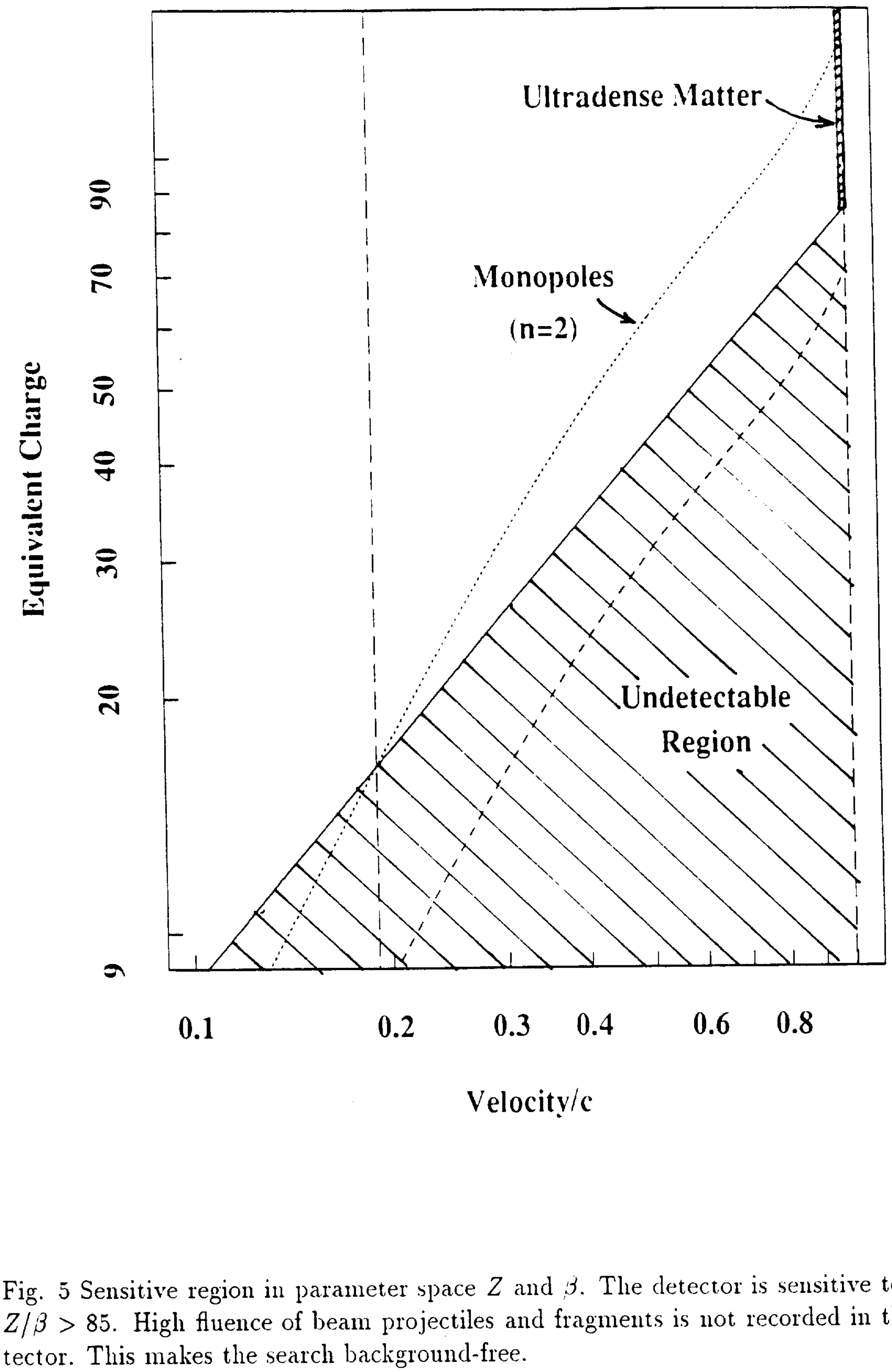

Fig. 5 Sensitive region in parameter space Z and β. The detector is sensitive to only $Z/\beta > 85$. High fluence of beam projectiles and fragments is not recorded in the detector. This makes the search background-free.

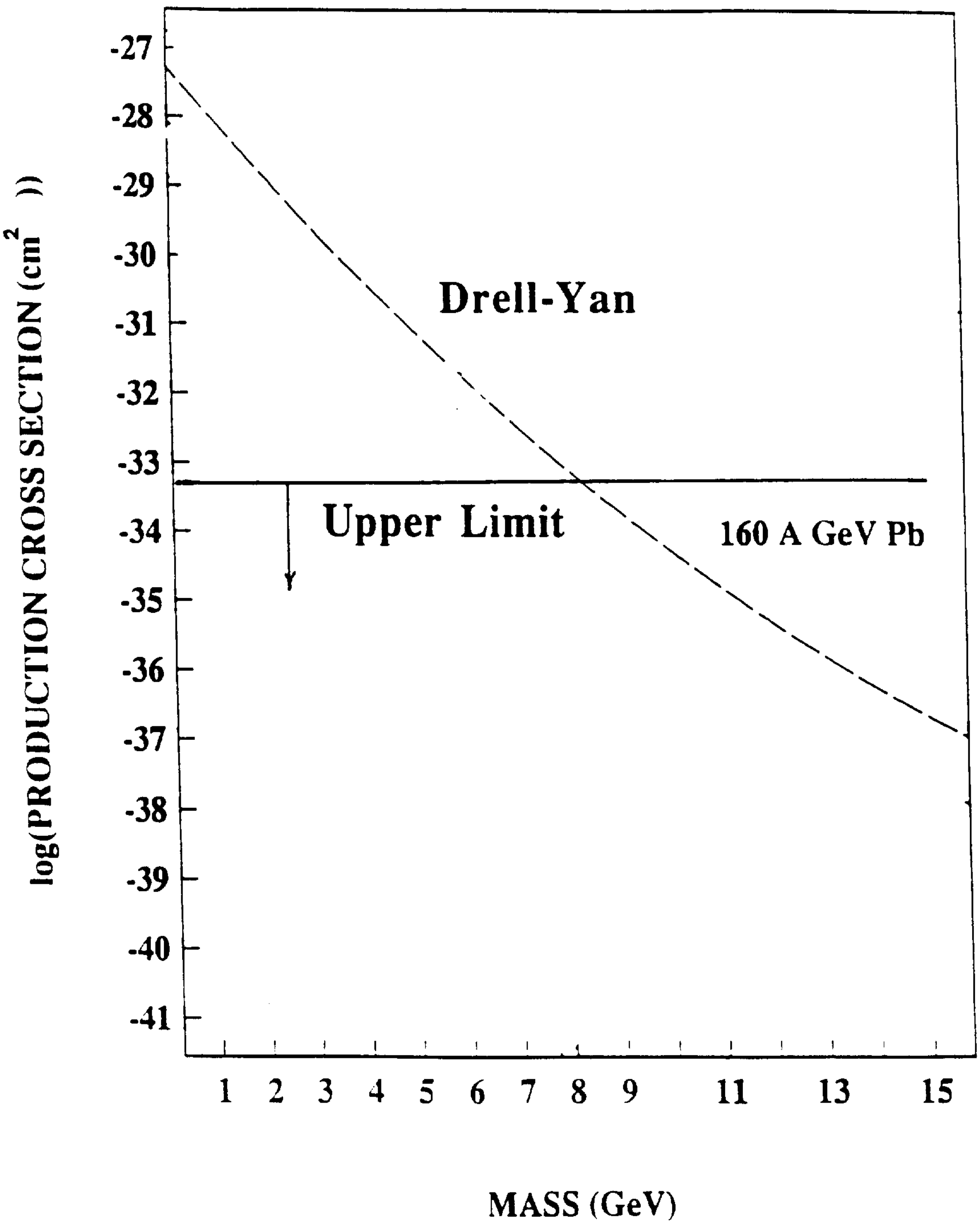

Fig. 6 The production cross section for Dirac magnetic monopoles as a function of its hypothetical mass. The cross section for pair productions via Drell-Yan mechanism is calculated using empirical formulae. Our experiment will reach a sensitivity of $\sim$ 1 nb, which is below the Drell-Yan cross section for monopole mass up to $\sim$ 8 GeV.

APPENDIX:
PUBLICATIONS RELATED TO HEAVY ION PROGRAM

The Berkeley group has carried out a series of small-scale experiments with high energy heavy ion beams at CERN SPS and BNL AGS using track-etch detection technique since 1987. These experiments have allowed to explore physical processes occurring in heavy ion collisions as well as to study the performance of track-etch detectors. Our heavy ion program has led to the following publications:

1. EMU02 at CERN SPS

1987 **Charge and angular distributions of fast fragments produced in 3.2-TeV ^{16}O collisions with Pb.** G. Gerbier, W. T. Williams, P. B. Price, and Ren Guoxiao, Phys. Rev. Lett. **59**, 2535 (1987).

1988 **Electromagnetic spallation of 6.4-TeV ^{32}S nuclei.** P. B. Price, Ren Guoxiao, and W. T. Williams, Phys. Rev. Lett. **61**, 2193 (1988).

1989 **Fragmentation of secondary beams of 200 GeV/N nuclides.** W. T. Williams, Y. D. He, Ren Guoxiao, and P. B. Price, Proc. 1st Intern. Conf. on Radioactive Nuclear Beams, Berkeley, California, 49 (1989).

1990 **Electromagnetic spallation of 6.4 TeV ^{32}S and secondary beams.** P. B. Price, Y. D. He, Ren Guoxiao, and W. T. Williams, Proc. of 21st Intern. Cosmic Ray Conf., Adelaide, Australia, 3, 412 (1990).

1991 **Measurement of charge-changing cross sections of 200 A GeV S and fragments with Cu target.** Ren Guoxiao, High Energy Phys. Nucl. Phys. **215**, 323 (1991).

1992 **Sensitivity study of CR-39 plastic track detectors.** Y. D. He and P. B. Price, Nucl. Tracks Radia. Meas. **20**, 491 (1992).

1993 **Behavior of 200 A GeV S and fragments in collisions with Cu target.** Ren Guoxiao and Jing Guiru, J. Phys. G **19**, 1211 (1993).

1995a **Enhancing the sensitivity of CR-39 detectors to relativistic ions by etching in potassium and sodium hydroxides.** Y. D. He and M. Solarz, Nucl Instr. Meth. B (1995) in press.

1995b **Dependence of CR-39 etch rates on concentration of etched products in sodium hydroxide etchant.** M. Solarz and Y. D. He, Nucl Instr. Meth. B (1995) submitted.

2. E793 and E882 at BNL AGS

1990 **Interactions of projectile fragments at 14.5 A GeV: A search for anomalons.** Y. D. He, P. B. Price, and W. T. Williams, Phys. Lett. B **252**, 331 (1990).

1991a **Behavior of nuclear projectile fragments produced in collisions of 14.5 A GeV ^{28}Si with Pb and Cu targets.** P. B. Price and Y. D. He, Phys. Rev. C **43**, 835 (1991).

1991b **Search for fractional charge states in high-energy heavy fragments produced in relativistic heavy-ion collisions.** Y. D. He and P. B. Price, Phys. Rev. C **44**, 1672 (1991).

1991c **Search for fractional charge states in projectile fragments produced in collisions of 14.5 A GeV ^{28}Si with Pb and Cu targets.** Y. D. He and P. B. Price, Proc. 21st Intern. Cosmic Ray Conf., Dublin, Ireland, **4**, 734 (1991).

1993a **Measurement of cross section for charge pickup by 11.4 A GeV gold ions.** Y. D. He and P. B. Price, Phys. Lett. B **298**, 50 (1993).

1993b **Search for abnormal nucleus production in heavy-ion collisions.** Y. D. He and P. B. Price, Phys. Rev. C **48**, 647 (1993).

1993c **Measurement of cross sections for electron capture and stripping by highly relativistic ions.** A. J. Westphal and Y. D. He, Phys. Rev. Lett. **71**, 1160 (1993).

1993d **Interactions of 11.4 A GeV ^{197}Au in various targets.** P. B. Price and Y. D. He, Proc. 23rd Intern. Cosmic Ray Conf., Calgary, Canada, **2**, 199 (1993).

1994a **First measurement of charge-changing cross sections for 11.4 A GeV ^{197}Au in various targets.** Y. D. He and P. B. Price, Nucl. Phys. A **566**, 363c (1994).

1994b **Response of BP-1 phosphate glass track-etch detector to relativistic heavy ions.** Y. D. He, A. J. Westphal, and P. B. Price, Nucl. Instr. Meth. B **84**, 67 (1994).

1994c **Apparent binary microscopic response to relativistic ions of a large class of track-etch detectors.** A. J. Westphal, Y. D. He, and P. Wojdowski, Nucl. Instr. Meth. B **86**, 317 (1994).

1994d **Nuclear and electromagnetic fragmentation of 2.25-TeV ^{197}Au.** Y. D. He and P. B. Price, Z. Phys. A **348**, 105 (1994).

1994e **Atomic-force-microscopic study of etched nuclear tracks at extremely short distance scale.** M. Drndic, Y. D. He, P. B. Price, D. P. Snowden-Ifft, and A. J. Westphal, Nucl. Instr. Meth. B **93**, 52 (1994).

1994f **Sensitivity of BP-1 glass detectors etched in methanesulfonic acid.** Y. D. He and M. Solarz, Nucl. Instr. Meth. B **94**, 113 (1994).