Search for abnormal-nucleus production in heavy-ion collisions

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In 1.0×10^9 collisions of $11.4A$ GeV ^{197}Au on a 1.27-cm Pb target we found no nuclear products with charge >84 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 for abnormal nuclei with lifetime $\geq10^{-9}$ s.

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The possibility that stable or metastable abnormally dense nuclei might exist in nature or might be created in high-energy heavy-ion collisions has been suggested, as a theoretical speculation, by several authors [1–7]. In a particular version of the theory, Lee and Wick [3] proposed a model in which an abnormal nucleus would have a density several times that of normal nuclei, a large volume binding energy ($\sim130A$ MeV), and a large atomic number, $Z\approx A/2\gg10^2$. To create abnormal nuclei they suggested compressing nuclear matter to a high density in a relativistic nucleus-nucleus collision. Several attempts to find a trace abundance of abnormal nuclei in nature [8,9] and to produce them at the Lawrence Berkeley Laboratory Bevalac [10,11] led to negative results. In collisions of ^{40}Ar on Pb at $1.1A-1.6A$ GeV and of ^{40}Ar on Ca and U at $0.1A-0.45A$ GeV at the Bevalac, upper limits of ~50 and ~100 nb have been placed on the production cross section of nuclei with $Z\geq26$ and lifetime $\geq10^{-9}$ s [10,11]. Since then, interest has shifted away from searches for abnormal nuclei in heavy-ion studies, due partly to the experimental evidence against the model and partly to theoretical criticism of the model [12]. In a recent calculation for finite normal and abnormal nuclei, Zhang and Li [13] claim that nuclei with $A\geq86$ may have bound abnormal states and nuclei with $A\geq165$ may have bound abnormal nuclei with binding energies larger than those of corresponding normal nuclei.

The availability at the Brookhaven Alternating Gradient Synchrotron of very heavy projectiles ($Z=79$, $A=197$) with energies one order of magnitude greater than at the Bevalac led us to consider the possibility of forming a system with an energy density ~1.5 GeV fm^{-3} [14] which might evolve into an abnormally dense nuclear object.

To carry out this experiment we exploited one of the useful features of the BP-1 phosphate glass track-etch detector [15]: its sensitivity can be tuned by a suitable choice of chemical etchants [16]. With its uniquely high 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 [17–20]. When a charged particle passes through the glass, a process occurs in which a large fraction of the bound ions within ~50 Å of the particle's trajectory in the glass is permanently displaced as a result of the energy deposition associated with the ionization rate of the particle [21]. When etched in a suitable chemical reagent, etching occurs along the trajectory of a particle with charge Z and velocity βc at a rate $v_T(Z,\beta)$ that exceeds the general etch rate v_G, producing a pair of conical etch pits 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 a measure of the etch rate ratio $s\equiv v_T/v_G$ given by

$$s=\frac{1+(b/G)^2}{1-(b/G)^2}\frac{1}{\sin\theta}\,, \qquad (1)$$

where b is the semiminor axis of an elliptical fit to an etchpit mouth, θ is the zenith angle, and G is the thickness of material removed on one side of the glass plate during the etch.

Figure 1 shows, for four different etchants, the dependence of the etch rate ratio on the quantity Z/β, which is, to a good approximation, a measure of the ionization rate. In order of decreasing sensitivity the etchants are 48% fluoboric acid at 50 °C, 49% hydrofluoric acid at 20 °C, 6.25 normal sodium hydroxide at 70 °C, and 1 normal sodium hydroxide at 70 °C. The curves are fits to data obtained using heavy-ion beams with various energies at a track density of ~800 cm^{-2}. Points at $Z/\beta=56-80$ were obtained from $11.4A$ GeV ^{197}Au and fragments; the point at $Z/\beta=99$ was from $0.7A$ GeV ^{197}Au; and the points at $Z/\beta=106-125$ were from ^{197}Au at various energies below $0.47A$ GeV. For each etchant, the reduced etch rate $(s-1)$ is a sensitive function of the ionization rate in a given dynamic range. With our system, measurements of elliptical mouths are best made when values of $s-1$ are within the range ~0.02 to ~6. Thus, one sees from Fig. 1 that an etchant can be chosen with optimum response anywhere in the region $Z/\beta\approx60-130$, depending on the problem of interest.

In the present experiment we used 1N NaOH at 70 °C. For this etchant the threshold is at $Z/\beta=84$, as a consequence of which only nuclear fragments with $Z/\beta>84$ are detectable, whereas the surviving beam ($Z/\beta=79$) and projectile fragments with $Z/\beta<79$ are invisible.

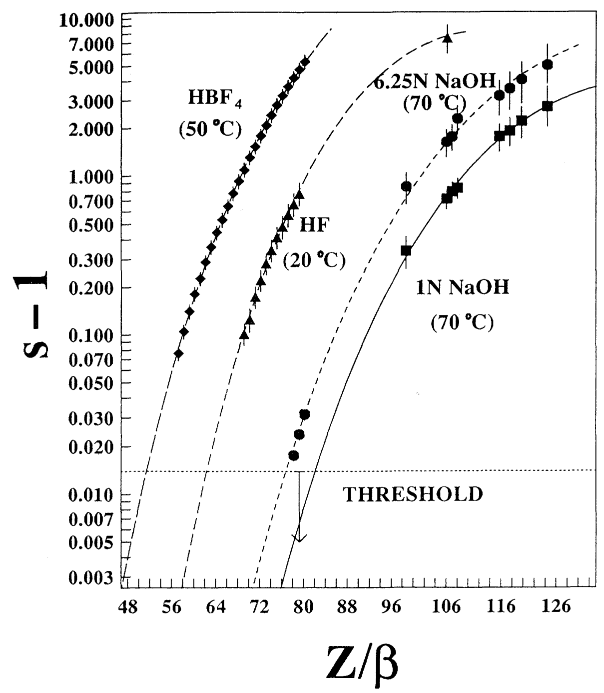

FIG. 1. The calibrated response curve of BP-1 detector in various etchants: HBF_4 at 50 °C, HF at 20 °C, 6.25N NaOH at 70 °C, and 1N NaOH at 70 °C. The reduced etch rate $(s-1)$ is shown as a function of Z/β. The threshold for 1N NaOH is at $Z/\beta=84$.

With this threshold we were able to search for products with $Z/\beta>84$ emitted in a rather large forward cone and with lifetime sufficient to survive the flight path through target+detector.

Our experimental setup consisted of a 1.27-cm lead plate as a target and 17 sheets of BP-1 glass, each with dimensions 5 cm×5 cm×0.074 cm, as detectors. The thickness of the Pb target was ~35% of the interaction length at this energy [16], so ~30% of the beam particles was expected to interact with target nuclei. Two of the BP-1 sheets were placed in front of the stack and 15 of them were placed downstream, in contact with the target. With the two front sheets we could veto beam particles and fragments which had energies much different from the beam energy and with $Z/\beta>84$ before reaching the target. With the 15 downstream sheets we looked for central collisions leading to a product with $Z/\beta\geq 84$ emitted from the Pb target within an angle of 140 mrad along the beam direction. We expect that a candidate for an abnormally dense nucleus would have to be produced in such a central collision, with a charge definitely greater than the projectile $Z>80$ *and* with an initial velocity at least as large as the center-of-momentum velocity $\beta_{\text{c.m.}}=0.915$, which would result from a completely inelastic collision of two nuclei of roughly equal masses. We therefore establish the event criterion of a candidate for an abnormally dense nucleus as $Z>80$ *and* $\beta>\beta_{\text{c.m.}}$ in our experiment.

The target-detector stack was exposed to a beam of $11.4A$ GeV ^{197}Au ions at normal incidence at the Brookhaven Alternating Gradient Synchrotron. The beam profile was characterized by a full width at half maximum (FWHM) in the horizontal direction of 1.2 cm and a FWHM in the vertical direction of 0.8 cm, after having passed through the exit window of the beam pipe and ~1.5 m of air. We used a remote-controlled two-dimensional translation stage to uniformly "paint" the beam spot on the stack over an area of 6 cm×6 cm. The beam intensity was recorded by an on-line beam counter and the entire exposure process was monitored. A fluence of 3.5×10^9 particles passed through the 5 cm×5 cm target-detector assembly.

To verify that the BP-1 detectors would record highly ionizing reaction products while traversed by beam particles up to a density of 1.4×10^8 cm^{-2}, we irradiated a 1-cm^2 area of two BP-1 sheets from this stack with fission fragments both before and after the Au exposure. The fission tracks produced both before and after the exposure had the same appearance, from which we concluded that the Au beam did not adversely affect the recording properties of the glass. We also etched one sheet in a more sensitive etchant (6.25N NaOH at 70 °C) for a short time and observed tracks corresponding to the beam and fragments at a density consistent with the on-line electronic counts.

The BP-1 glass was scanned with an automated scanning microscope system [18] after a 6-h etch in 1N NaOH at 70 °C. In the two sheets placed in front of the target, we found two tracks with $Z/\beta\geq 84$ aligned nearly parallel to the Au beam. Their charges and energies were $Z=56\pm1$, $E=0.15\pm0.01A$ GeV, and $Z=78\pm1$, $E=0.54\pm0.02A$ GeV. In the sheets downstream from the target we found two categories of etch pits. The first consisted of tracks at a density of ~100 cm^{-2}, a broad distribution of zenith angles, and ranges less than 100 μm, so that they did not penetrate even one sheet of BP-1. These tracks, due to target fragmentation, were of no interest in the present search and were rejected by requiring a coincidence measurement on both sides of a BP-1 sheet.

The second category consisted of tracks of highly ionizing particles that penetrated at least one sheet of BP-1. Nine such events were found within the fiducial area of 5 cm×5 cm. We also made an independent manual scan of two selected sheets using a stereomicroscope to search for penetrating tracks and found the same nine events. All of the nine events ranged out in the stack. Figure 2 and columns 2 and 3 of Table I give the results of our measurements of the elliptical mouths of these events on all of the surfaces of glass until the ends of range of the particles were reached. Using the calibration curve for 1N NaOH in Fig. 1 and an ionization rate code, we determined the charge and energy of the nine events at the point they exited the target by minimizing χ^2 of the fits to the data in Fig. 2. The fitting curves are shown in Fig. 2 as solid lines and the best-fitted charge (Z) and energy (E), together with χ^2/ν, are listed in the fourth, fifth, and sixth columns of Table I. None of the events had a value of Z/β large enough that they could have been detected

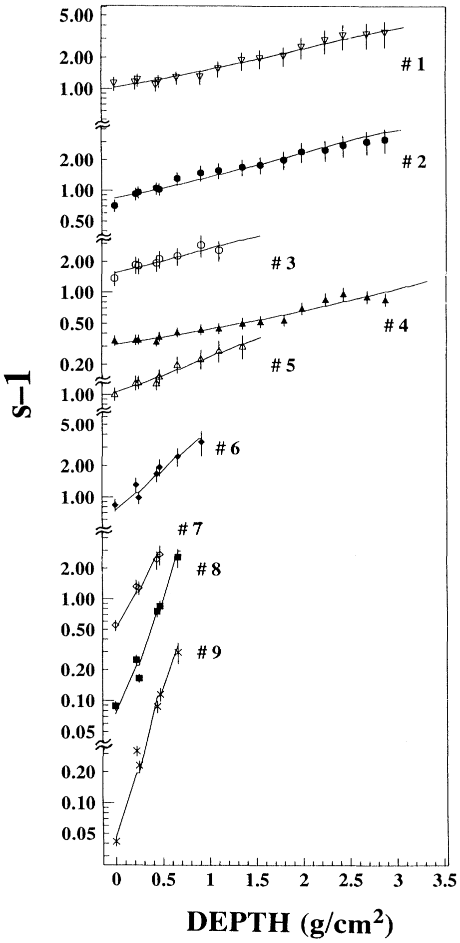

FIG. 2. The detected signal $(s-1)$ measured at various depths downstream from the target in the BP-1 stack for the nine events. The solid curves are best-fitted results corresponding to charge and energy listed in Table I.

TABLE I. Measured parameters of nine events found in this experiment.

Event	θ (mrad)	φ (deg)	Z	(E GeV) E	χ^2/ν	(A GeV) E_0
1	12.9	178	82±2	0.48±0.04	0.52	1.07
2	5.8	189	79±2	0.45±0.03	0.47	1.04
3	8.8	311	79±2	0.36±0.03	0.24	0.97
4	15.2	212	78±1	0.59±0.02	0.52	1.14
5	6.7	270	73±2	0.32±0.02	0.23	0.90
6	35.9	258	60±1	0.20±0.01	0.65	0.75
7	46.1	70	49±1	0.13±0.01	0.64	0.64
8	8.6	34	43±1	0.13±0.01	4.15	0.60
9	13.5	42	39±1	0.11±0.01	5.02	0.56

in the two glass plates in front of the target. Thus, it could not be established whether they were created in the Pb target or within the beam pipe.

None of the nine events satisfied our criteria of a candidate for an abnormally dense nucleus: $Z>80$ *and* $\beta>\beta_{\rm c.m.}$. Like the two events that stopped in the two sheets upstream of the target, they were probably created in interactions of beam particles that scraped the beam pipe. Their small angular dispersion in the beam direction (Table I, columns 2 and 3) is consistent with this hypothesis. Assuming that no charge-changing interactions occurred while the particles were passing through the target, we calculated the energies they would have had just before reaching the target, E_0, as listed in the last column of Table I. From these relatively low energies we infer that the particles were produced either as 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.

Even if the nine events were produced at the very front of the Pb target, they would have had too small an initial energy E_0 to be considered as candidates for abnormally dense nuclei. This null result allows us to set an upper limit of $\sim$20 nb at 90% confidence level on the production cross section for composites of abnormally dense matter. We should note that, if we had succeeded in detecting events with Z definitely greater than 80 and with $\beta>\beta_{\rm c.m.}$, a further experiment would then be required in order to establish whether such events were due to normal or abnormal nuclei.

In summary, we have performed a high-statistics experiment to search for production of metastable nuclear objects, either normal or abnormal, in interactions of 11.4A GeV ^{197}Au with a Pb target. Based on null observation of products with $Z>80$ *and* $\beta>\beta_{\rm c.m.}$, we have placed an upper limit of $\sim$20 nb on the production cross section for abnormal nuclei with lifetime larger than 10^{-9} s. Another 1–2 orders of magnitude improvement in sensitivity can be achieved with this technique when a more intense Au beam becomes available.

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