Title
EXPERIMENTS WITH HEAVY BEAMS AT THE BERKELEY BEVALAC

Permalink
https://escholarship.org/uc/item/3s77d1sf

Author
Schroeder, L.S.

Publication Date
1984-10-01

LBL-18309

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Invited talk given at the VII International Seminar on High Energy Physics Problems--Multiquark Interactions and Quantum Chromodynamics, JINR, Dubna, USSR, June 19-23, 1984

EXPERIMENTS WITH HEAVY BEAMS AT THE BERKELEY BEVALAC

L.S. Schroeder

October 1984

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-18309

EXPERIMENTS WITH HEAVY BEAMS AT THE BERKELEY BEVALAC*

L.S. Schroeder

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

EXPERIMENTS WITH HEAVY BEAMS AT THE BERKELEY BEVALAC*

L.S. Schroeder

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

1. Introduction

I will be presenting some of the early results obtained with heavy beams ($A \gtrsim 100$) at the Bevalac. My intention is to give you a flavor of the research program that has developed in the early 1980's with the capability of accelerating nuclei spanning the full periodic table. For additional information on results with heavy beams see talks by Löhner (on GSI/LBL Plastic Ball experiments stressing collective features) and Nagamiya (single-particle information) elsewhere in this proceedings.

2. Physics with $A \leqslant 40$

Before discussing the results from heavy beam studies, it is worth recalling the major elements of the research program at the Bevalac in the 1970's and early 1980's with nuclear beams having $A \leqslant 40$. These were:

Research	*Physics Interest*
a) Reaction Studies < 200 MeV/N	• Liquid → gas phase transition • Hydrodynamics
b) Projectile Fragmentation	• Measure nuclear Fermi momenta • Production of neutron-rich nuclei • Anomalons
c) Light Fragment Production	• Coalescence (freeze-out density) • d/p ratio as measure of entropy
d) Pion Production	• Production beyond kinematic limits (cooperative effects) • Two-pion interferometry (Hanbury-Brown/Twiss)—measure source size • Pionic instabilities
e) Photons	• π° production • Nuclear levels excited in heavy-ion collisions • Decay of anomalons
f) Strange Particles ($K^\pm, \Lambda^\circ$)	• Sensitive probe of reaction mechanism
g) Extreme Conditions	• High T, ρ nuclear matter • Nuclear equation of state

---

*This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

The initial trend involved single-particle inclusive measurements. However, with time we have realized that single-particle observables often only tell us about average properties of the produced system. The clear need for more exclusive measurements involving as many particles in the final state as possible has led to the development and use of a class of nearly 4π detectors like the streamer chamber,[1] the GSI/LBL Plastic Ball,[2] and the heavy-ion spectrometer system (HISS).[3]

3. *The Uranium Capability Project*

The primary goal of the Bevalac research program was, and continues to be, the study of nuclear matter under extreme conditions of high temperature (T) and baryon density (ρ). In order to achieve these extreme values of T and ρ, the largest nuclei are needed to guarantee that the maximum number of participating nucleons are involved in a central nucleus-nucleus collision. Thus, it was clear from the earliest days of the Bevalac that one wanted to extend the range of available projectiles for research all the way up the periodic table to uranium. This "uranium capability" was realized in 1982 after the addition of a third injector at the SuperHILAC (to provide the heaviest beams) and the improvement of the Bevatron's vacuum from the range of 10^{-7} torr to about 10^{-10} torr. The improved vacuum was necessary to allow partially stripped ions to survive acceleration in the Bevatron without suffering catastrophic losses through interactions with residual gas atoms. With this improvement the Bevalac became the first accelerator to provide beams of uranium ions at relativistic energies of about 1 GeV/nucleon.

Table 1 below indicates some of the available beams with associated intensities.

TABLE 1. Bevalac Ion Species and Intensities.

Ion	Intensity*	Ion	Intensity*
proton	2×10^9	^{55}Mn	1×10^6
deuteron	1×10^9	^{56}Fe (24^+)	2×10^8
alpha	3×10^9	^{84}Kr	1×10^7
^{12}C	5×10^9	^{93}No	2×10^6
^{16}O	6×10^9	^{128}Xe	3×10^6
^{20}Ne	1×10^{10}	^{139}La (57^+)	7×10^5
^{27}Al	5×10^8	^{139}La (32^+)	8×10^7
^{38}Si	6×10^9	^{197}Au (62^+)	1×10^5
^{40}Ar	1×10^9	^{197}Au (37^+)	1×10^7
^{40}Ca	4×10^7	^{238}U (68^+)	1×10^6
^{48}Ca	1×10^7	^{238}U (40^+)	1×10^7

*Particles per pulse in external beam lines (10–15 pulses per minute depending on beam energy).

The maximum energy for ions with e/m = 1/2 is 2.1 GeV/nucleon, dropping to about 1 GeV/nucleon for uranium.

A natural first question to ask is whether the upgrade to uranium beams was worth the effort. The answer is certainly yes! I cite two examples to illustrate this point. The first, shown in Fig. 1, indicates the multiplicity of charged particles (M) observed in the GSI/LBL Plastic Ball for Au + Au collisions at 1.05 GeV/nucleon (equivalent to 0.234 GeV/nucleon in c.m. for this systematic target-projectile system). The lower portion of the figure corresponds to the multiplicity associated with their central collision trigger. The peak is near $M \approx 160$, indicating that the majority of the target-projectile nucleons have participated in the collisions. The more participants, the higher the probability of achieving the extreme conditions of T and ρ that we wish to probe for in these violent collisions. Figure 2, again from Plastic Ball data,[4] shows contours of summed parallel and perpendicular momentum components in the c.m. system. If isotropy is present in these collisions, then the data would fall along the dashed line indicated in Fig. 2. This is not quite true for the lighter Ca + Ca system, but is for the heavier Nb + Nb. Thus, we are able to achieve isotropy in the central collisions of these heavier beams. In these multiplicity selected collisions, the incident longitudinal momentum is completely randomized and the final state particles are emitted isotropically. These two statements, taken together, indicate that the two colliding nuclei in effect "stop" each other in the c.m. system. Although isotropy is observed for these heavy beam central collisions, this is only a necessary, but not sufficient condition, to guarantee an equilibrated system being formed. To conclude, clearly the much heavier systems now available at the Bevalac do provide a better environment for studying extreme conditions in nuclear matter.

4. First Results with Uranium Beams

One of the first things that was done with the uranium beams when they exited the Bevatron in September 1982 was to pass the 960 MeV/nucleon uranium ions through an emulsion stack. Figure 3 shows a characterization of the different types of interactions observed.[5] From top to bottom these include: (a) "clean" fission event—this type accounts for ~4–5% of all events, (b) example of "dirty" fission event—some accompanying fragments of both target and projectile, (c) $N_h = 0$ event—projectile fragmentation with one heavy fragment, (d) $N_h = 0$—with only light projectile fragments, (e) "star" or semi-central event presumably occurring on either Ag or Br—these account for ~9–10% of all events, and (f) example of "ternary" fission ($Z = 92 \rightarrow 14+43+35$)—one event observed.

D. Greiner et al.[6] have measured the nuclear cross sections for uranium at 900 MeV/nucleon on a variety of targets (H, C, Al, Si, Cu, Ta, Pb) using the solid state detector array shown in Figure 4(a). The response of the detector is shown in Fig. 4(b), where they are able to identify categories they associate with "fission" and "central collision" events. Cross sections for these different processes are then obtained for each of the targets used. Figure 5 shows their measured cross sections as a function of target mass. The fission cross section is found to be $\sigma_F \propto A_T^{0.37}$, suggestive of peripheral collisions, as one would expect. Whereas the cross section for central collisions is found to go like $\sigma_c \propto A_T^{1.02}$, i.e., varying as the number of participants, again as one would expect. For uranium-uranium central collisions their data predict a cross section of 2.5 barns.

The UC Riverside group has begun a study of uranium interactions using the 4π geometry of the LBL streamer chamber.[7] For their studies, they have placed the uranium target at the entrance of the streamer chamber, rather than inside of it. This helps avoid problems associated with having the high-Z uranium ions passing through the active volume of the chamber (e.g., flares, sagging of the voltage on the chamber due to high density of ionization left by passage of uranium ions). Figure 6 shows an example of a fully measured and reconstructed uranium-uranium event at 960 MeV/nucleon. They have observed and measured events with up to 120 charged tracks. Approximately ten negative tracks (those with counterclockwise bends) are observed in Fig. 6, these are negative pions. From a sample of 185 minimum bias events, they have observed $<M_{\pi^-}> = 3.4$. They have fit both the overall pion distribution (dn/dp_{cm}) and the pion p_t distribution (dn/dp_t) in order to extract a "temperature" for the pions. They find $T_\pi = 53 \pm 3$ MeV by fitting the overall pion distribution, and $T_\pi = 41 \pm 2$ MeV by fitting the pion p_t distribution. They plan to continue these studies and will be looking for fluctuations in the pseudo-rapidity distributions, comparing their results with intranuclear cascade calculations for indications of unusual phenomena.

5. *Subthreshold Pion Production with Lanthanum Beams*

My group in association with Louisiana State University, Michigan State University, Clermont-Ferrard II University, and GSI have utilized one of the arms of our two-arm spectrometer system (TASS) to study subthreshold pionic production in La + La collisions at 246 MeV/nucleon.[8] The motivation for this experiment was to test a theoretical speculation point forward by Gyulassy[9] of an enhancement in the yield of pions due to the formation of a pion instability in central nucleus-nucleus collisions. The instability would manifest itself by an increased yield of pions at $\Theta_{cm} = 90°$ for momenta around $\approx (2-3)m_\pi c$ at low incident energies to suppress the yield of pions from incoherent processes. Recently, Nagamiya et al.[10] measured the inclusive negative pion distribution at 183 MeV/nucleon for the A = 20 projectile-target combination (Ne + NaF). They found only an exponentially falling spectrum, with no hint of an enhanced yield. However, Gyulassy has stressed the need to do the measurement with the heaviest possible system in order to maximize the amount of participant matter. Therefore we have used an intense ^{139}La beam to make our measurements. The preliminary results are shown in Fig. 7. The invariant cross section falls exponentially over four decades in cross section with no evidence of a bump or break in the spectrum at the level of $\lesssim 2\%$. Therefore it appears that the formation of a pion condensate is ruled out. However, since we are only measuring the inclusive cross section which is necessarily an average over impact parameters, the door cannot be completely closed on this subject yet. We are now preparing a 120 element multiplicity array to help select very central collisions and will be continuing these measurements (with approximate impact parameter selection) in early 1985.

For information on inclusive pion production by La beams at 800 MeV/nucleon, please consult the talk by S. Nagamiya at this conference.

6. *Atomic Physics with Heavy Beams*

A final point concerns the physics potential with heavy beams. One of the mature areas of science which will surely find new avenues to explore with highly stripped heavy ions is that of atomic physics. In particular, QED in the presence of external fields can be further tested by studying hydrogen-like (U^{91+}) and helium-like (U^{90+}) uranium.

H. Gould et al. have studied electron capture by U^{91+} and U^{92+} and ionization of U^{90+} and U^{91+} at the Bevalac.[11] These studies were done by accelerating U^{68+} in the Bevatron, extracting and stripping the uranium ions to the desired charge state and measuring them with a magnetic spectrometer and its associated detectors. Figure 8 shows the equilibrium charge-state distributions obtained for different target materials at two different energies. Note that U^{91+} is made in large enough quantities at 437 MeV/nucleon to be used for QED tests. For future heavy ion colliders, one will only store fully stripped uranium ions. From the information in Fig. 8, uranium ions would have to be accelerated to several hundred MeV/nucleon and stripped before they could be sent off for eventual storage in collider rings.

7. *Future Experiments*

Before ending, I want to briefly indicate what can be expected in the near future from some other Bevalac experiments. Both light and heavy beams will continue to be used:

a) Streamer Chamber (enhanced by ~300 element forward hodoscope (dE/dx + TOF) for identifying and matching particles tracked through the streamer chamber)
  - energy dependence of $La + La \rightarrow n\pi^- + X$
  - Λ° production in central Ca + Ca collisions

b) Hanbury-Brown/Twiss Interferometry with Fe and La Beams

c) Neutron Production with Heavy Beams

d) Subthreshold Kaons ($K^\pm$), $\bar{p}$'s and Fractional Charge Search

e) Subthreshold $\pi^\pm$ Angular Distributions with Associated Multiplicity

f) Direct $e^\pm$ Production in pA Collisions, Study of Low Mass Anomalous e^+e^- Pairs in pA and AA Collisions

g) Conventional Nuclear Physics
  - radiochemical studies
  - low energy (<100 MeV/nucleon) reaction mechanism studies

h) Projectile Fragmentation with Heavy Beams
  - Production of radioactive beams and measurements of their reaction cross sections

8. Acknowledgments

My thanks to S.Y. Fung (UC Riverside), Harvey Gould (LBL), Doug Greiner (LBL), Harry Heckman (LBL), and members of the TASS collaboration for being allowed to show results from their Bevalac experiments. Particular thanks to Prof. Baldin and the other members of the Organizing Committee for inviting me to give this talk.

References

1. A. Sandoval et al., Nuclear Physics *A400*, 365 (1983).
2. A. Baden et al., Nucl. Instr. and Meth. *203*, 189 (1982).
3. D.E. Greiner, Nuclear Physics *A400*, 325 (1983).
4. H.-A. Gustafsson et al., Phys. Lett. *142B*, 141 (1984).
5. E.M. Friedlander et al., Phys. Rev. *C27*, 2436 (1983).
6. D.E. Greiner et al., LBL-18468 (Oct. 1984), submitted to Phys. Rev. C.
7. S. Fung (University of California at Riverside), private communication (1984).
8. G.F. Krebs et al., LBL-18267 (Nov. 1984), to be submitted to Phys. Lett.
9. M. Gyulassy, Nucl. Phys. *A345*, 377 (1981).
10. S. Nagamiya et al., Phys. Rev. Lett. *48*, 1788 (1982).
11. H. Gould et al., Phys. Rev. Lett. *52*, 180 (1984).

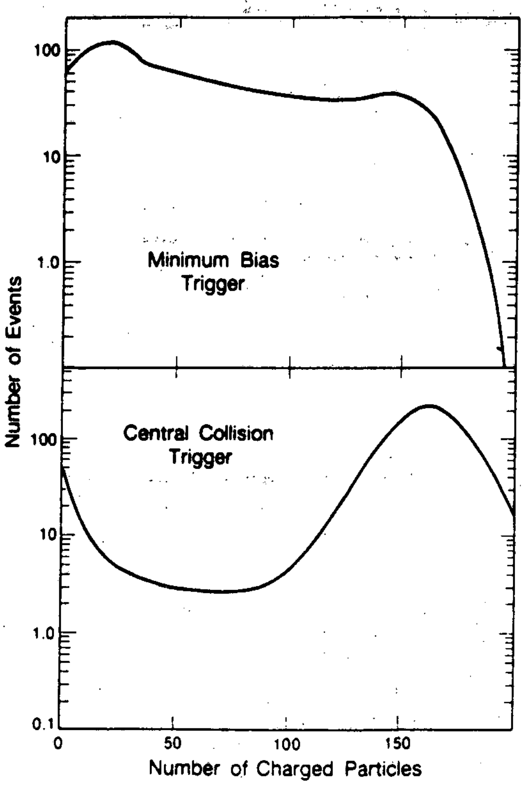

Fig. 1. Charged particle multiplicity distribution for Au + Au collisions studied by the GSI/LBL Plastic Ball collaboration at the Bevalac.

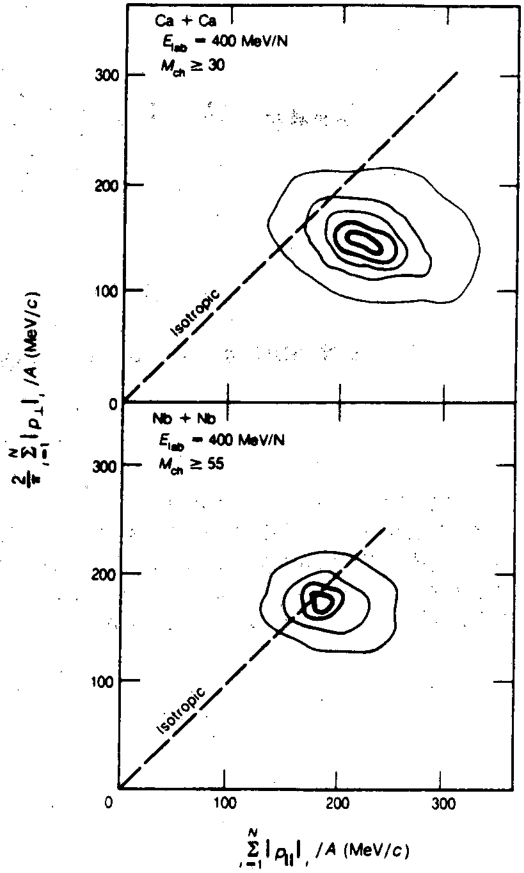

Fig. 2. Contour plots of the average particle momentum components in the c.m. frame perpendicular and parallel to the beam axis for Ca + Ca (top) and Nb + Nb (bottom) at 400 MeV/nucleon. The diagonal lines correspond to isotropic events.

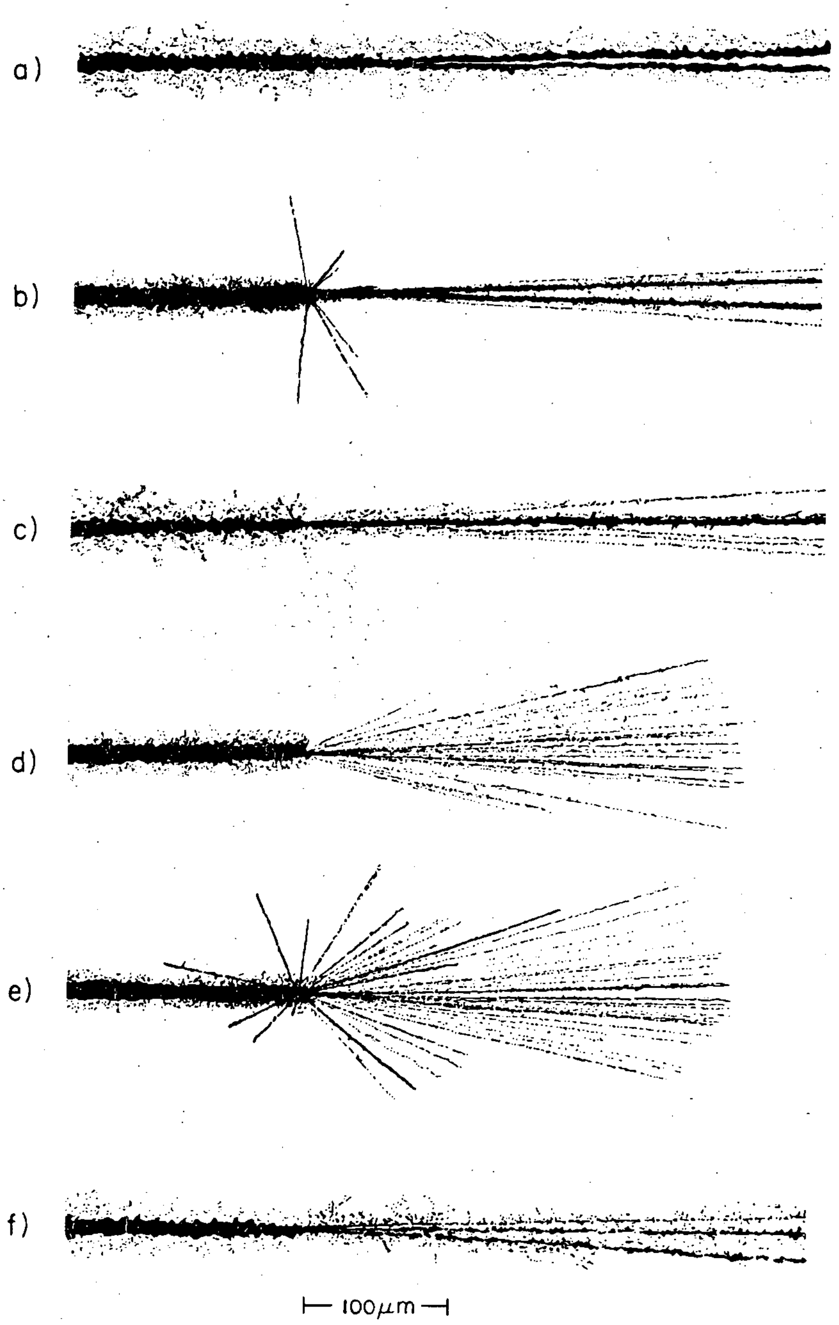

Fig. 3. Microprojection drawings of ~0.9 GeV/nucleon uranium interactions in nuclear emulsion. (a) "Clean" fission. (b) "Dirty" fission (with both target and additional projectile fragments). (c) $N_h = 0$ event with one heavy projectile fragment. (d) $N_h = 0$ event with only light projectile fragments. (e) "Star" induced in a (Ag-Br) target nucleus. (f) "Ternary" fission.

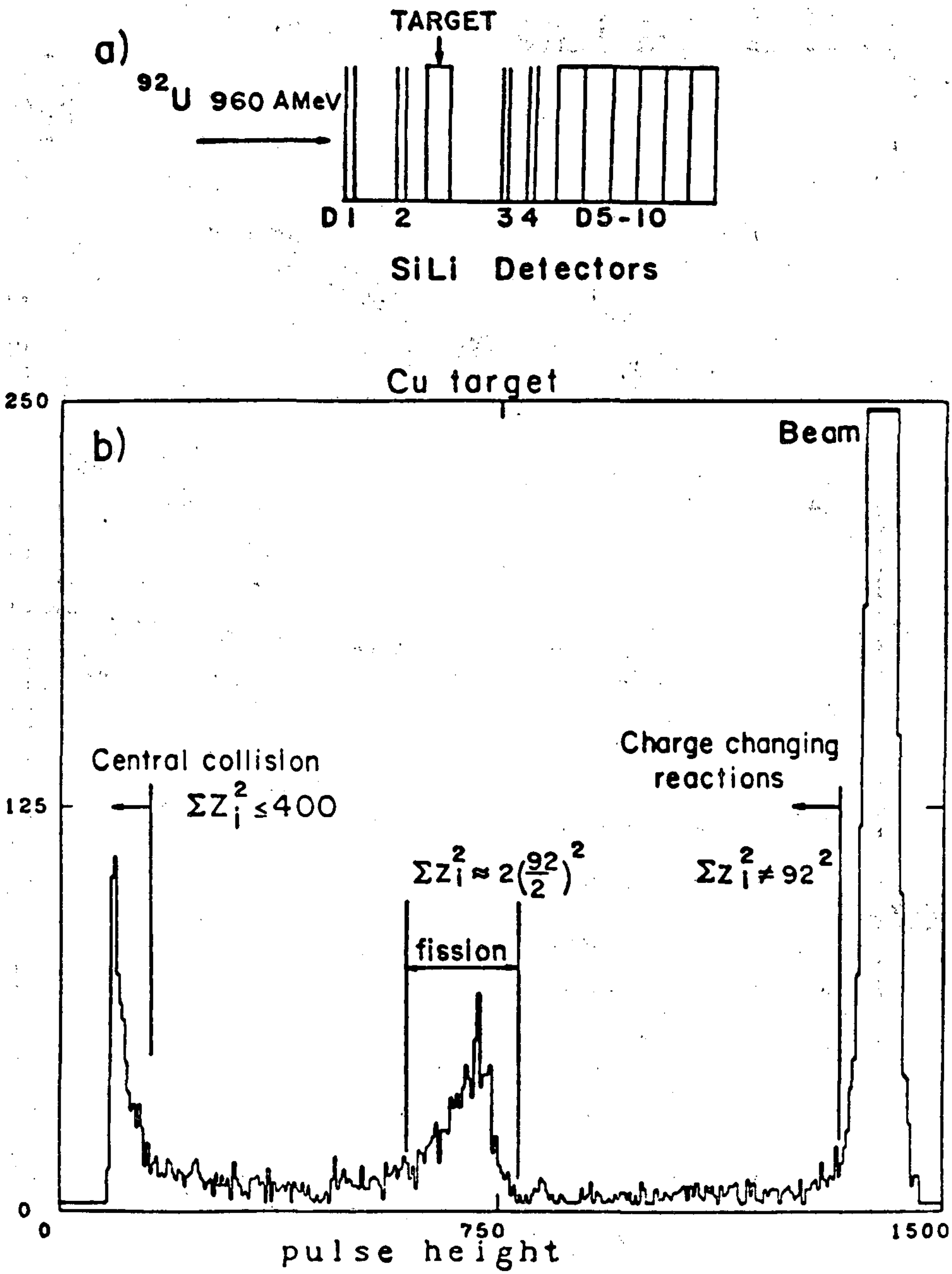

Fig. 4. (a) Experimental apparatus: Detectors D1–4 are 1.02 mm thick, position sensitive solid state detectors with resistive read out. Detectors D5–10 are 4.72 mm thickness solid state detectors. The detectors down stream of the target subtend an opening angle of 21 degrees. (b) Typical pulse height spectrum for detector D3 with the Cu target in place. The features common to all targets are: the large peak of un-interacted beam, the fission peak near dE/dX = half of the beam value, and the central collision peak occurring at low dE/dX indicating loss of most of the highly charged particles in the forward direction. The cuts to determine the charge changing, fission, and central cross sections are shown.

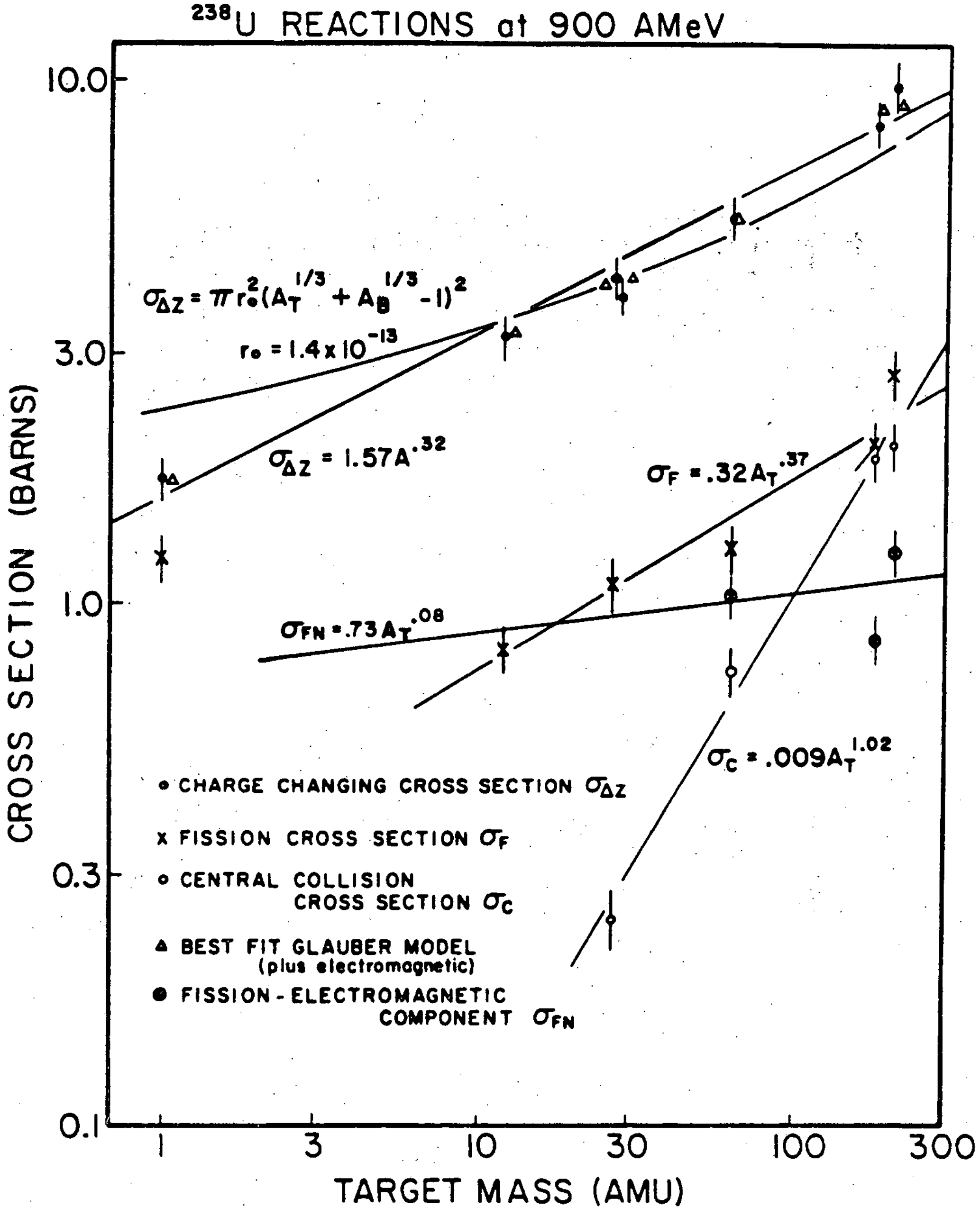

Fig. 5. Charge changing ($\sigma_{\Delta Z}$), fission (σ_F), and central collision (σ_C) cross sections plotted as a function of target mass for a uranium projectile at 900 MeV/nucleon. Open triangles indicate the calculated charge changing cross section using the closed form optical model plus electromagnetic corrections. Labeled curves are geometric and power law fits to the data. The nuclear part of the fission cross section is indicated by the circled x points. The central collision component rises as A_T and reaches 20% of the measured cross section for the lead target.

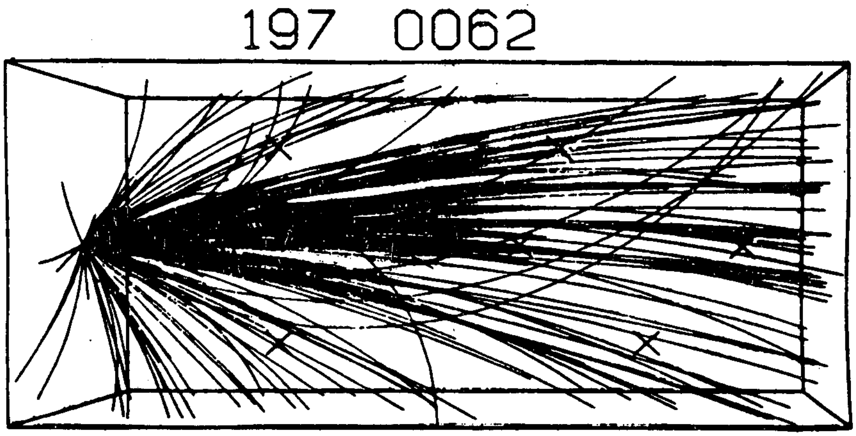

Fig. 6. Schematic of the reconstruction of a 960 MeV/nucleon U + U central event in the LBL streamer chamber. The event was measured by the UC Riverside group and contains over 100 charged tracks.

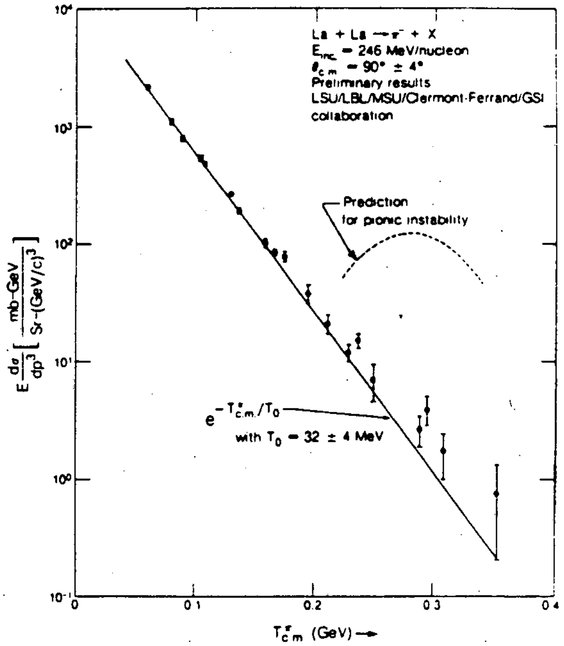

Fig. 7. The invariant cross section vs. the c.m. kinetic energy for the La + La $\rightarrow \pi^- + X$ inclusive reaction at 90° c.m. The incident energy is 246 MeV/nucleon. T_0 is the inverse slope parameter when the cross section is parameterized by $\exp(-T^{\pi}_{c.m.}/T_0)$. A least square fit using this parameterization is shown as a solid line. The dashed curve is the expected cross section for the pionic instability. Error bars are statistical.

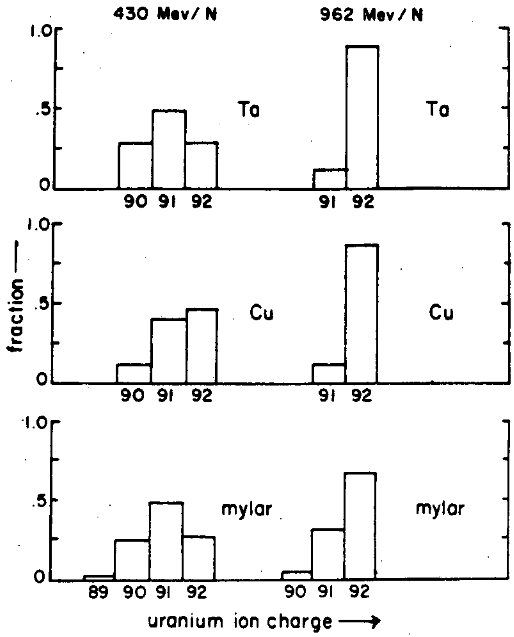

Fig. 8. Equilibrium charge state distributions of 430 MeV/N and 962 MeV/N uranium from mylar ($Z \approx 6.6$), copper ($Z = 29$), and tantalum ($Z = 73$) targets.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720