DOE/ER/40571--1

DOE/ER/40571--1

DE92 003434

NOV 13 1991

DOE Award DE-FG03-90ER40571

Investigation of Rare Particle Production in Relativistic Heavy Ion Collisions

Henry J. Crawford and Jon Engelage, UCSSL

Performance Report

During FY91 we began our investigation of rare particle production in relavistic nuclear collisions at the Brookhaven National Laboratory. We were funded for a period of one year to perform the initial experimental search, E858, to determine the level of antideuteron ($\bar{d}$) production in Si+Au collisions at the AGS. We accomplished this goal with the discovery of two $\bar{d}$'s in the June 1990 run. We describe below the experiment performed and the results obtained.

We performed our rare particle search at the A-1 line of the AGS. We instrumented the line with a four time-of-flight (TOF) detectors, two high pressure gas Cerenkov (Ck) detectors, and four drift tube (DT) tracking detectors. The TOF detectors achieved time resolution of better than 100ps leading to a mass resolution of <15 MeV at 1 GeV. The Ck detectors were used both to suppress the large π^- signal and in π/K separation at high rigidities (>6GV). The DT system provided particle trajectories for all of the particles passing the trigger requirements.

In this experiment we measured the π^-, K^-, and $\bar{p}$ momentum spectra at 0° for rigidities from 2 to 8 GV to a statistical accuracy of 1-3% at all settings. We found that the $\bar{p}$ yield as a function of target did not show any evidence for reabsorption within the interactio volume. We also found two $\bar{d}$'s, the first observation of complex antinuclei produced in nucleus-nucleus collisions. The $\bar{d}$ yield is at least an order of magnitude smaller than prediced using a simple coalescence model based on the d/p ratio from E802 and the $\bar{p}$ spectrum measured in our experiment. This suggests a larger production volume for antinuclei, and may indicate a significant hadronization time for heavy particles, an idea we will pursue in our new program.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOV 1 2 1991

Summary

High energy nucleus-nucleus collisions produce an environment that is not possible to make with any other process, and may thus produce new forms of matter that would not have been observed previously. We seek support for a three year program to investigate particle production in this high energy nuclear collision environment. The program includes measurements of π and K correlations in Si+A collisions and of general properties of particle production in Au+Au interactions, with major emphasis on the production of antinuclei and rare particles in Si+A and Au+A collisions. Our goal is to provide a firm experimental foundation for understanding the space-time evolution of the particle production process through measurement of the yield of antinuclei, and to determine with high sensitivity whether any new types of particles emerge from this environment. The rare particle experiment is a follow on to our E858 program in which we made the first observation of antideuteron production in A+A collisions and set significant new limits on the production of new particles in this environment.

In our first year we will measure the 0° momentum spectrum of both $\bar{p}$ and $\bar{d}$ from Si+Au collisions at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS) in experiment E878. We will also measure the $\bar{d}$ yield from Al and possibly Cu targets to help understand the hadronization process. The E878 proposal is included here as Appendix 1. We expect to follw this in the second year with a measurement using the Au beam at the AGS to study antinucleus production as well as to continue our search for new particles. In the third year we expect to continue our participation in the existing E866 particle production program as well as to begin a program to search for short lived particles produced in nucleus-nucleus collisions.

Investigation of Rare Particle Production in High Energy Nuclear Collisions

Henry J. Crawford and Jon Engelage, UCSSL

I. Introduction

High energy nucleus-nucleus collisions provide a new environment in which to study details of the particle production process. The extent of the interaction region and the number of simultaneous elementary interactions occuring in the region make this a very different environment than that found in p-nucleus collisions and it may well lead to the formation of new states of hadronic matter. We seek support to continue our study of particle production from relativistic nuclear collisions. Our program includes participation in three ongoing experiments at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS) to study the particle production process and the space-time development of the production region in nucleus-nucleus collisions.

The major part of our program will be in performing E878, an experiment whose goals are to provide high statistics measurements of the π, K, and $\bar{p}$ yields at 0° from Si +A and Au+A interactions, to determine the momentum distribution of $\bar{d}$ production and its target and projectile dependence, and to search for new particles such as the multi-hyperon nuclei (Schaffner 91; Dover 91) or the strangelets (Chin 79; Liu 84) that may be produced in this complex environment. The E878 proposal is included here as Appendix 1. Results of our initial experimental investigation of rare particle production, E858, are given in Appendix 2 and 3. Here we summarize the E858 results and discuss our motivation for continuing the search.

The yield of antinuclei is sensitive to the space-time development of the particle production process (Heinz 86; 89; Ellis 89; Gavin 90). Antinuclei provide a possible signature of the interaction having passed through a quark-gluon (QG) phase before evolving to a hadron gas phase. In the QG phase the relative antiquark content will increase leading to enhanced yields of anti particles upon hadronization. Entropy considerations at the transition boundary obscure this effect, however. Because of antibaryon reabsorption in the hadron phase, it is expected that the yield of antinucleons as a function of rapidity will provide a sensitive measure of the

interaction evolution (Jahns 91) In E878 we will cover rigidities from 1 GV to 15 GV, equivalent to rapidities from 0.8 to 3.5 for $\bar{p}$'s. The rapidity of the Si beam is 3.5 (3.3 for the Au beam), and of the cms is 1.7 (1.6 for Au) This broad range of rapidity coverage at 0° takes us well into the rapidity regions of both the target and projectile frames, and covers the midrapidity region completely.

In our previous experiment, E858, we detected 2 $\bar{d}$'s at a rigidity of 6 GV, the position at which their production is expected to peak. This represents a yield that is well below what we had predicted from our coalescence model calculation which used the d/p ratio from E802 (Sarabura 91) and the $\bar{p}$ spectrum we measured as input. However, the yield far exceeds that expected from any "subthreshold" process that relies on the Fermi momentum of both projectile and target nuclei. One of our first goals is to verify the $\bar{d}$ production level from Si+Au interaction, taking enough data to get a significant number of $\bar{d}$'s at three or more rigidities. We also plan on measuring the $\bar{d}$ signal from at least two and hopefully three targets as a probe of the reabsorption and hadronization time questions.

It has long been known that a double-focusing spectrometer system can be set up to provide a very sensitive tool for searching for new and rare particles from high energy interactions. Our E878 spectrometer, a mirror image of our E858 system, is expected to have sensitivity to better than 1 part in 10^{12} π's, making it an excellent tool for a new particle search. We expect to attain sensitivities on this order for a wide variety of rigidity settings in our mapping of the $\bar{d}$ signals. Our sensitivity to short lived particles is significantly reduced by the 53m flight path of our spectrometer, and it is our intention to begin planning and perhaps even executing a search for short lived particles within the time span of this proposal.

Our role in both experiments E859 and E866 is relatively modest although important, in that we are responsible for providing the TOF start signal and beam monitor system for cross section determination. It was interesting to find that the focus on the Si beam is so good at our target area, stable to within a spot ~$2mm^2$, that we produced significant radiation damage to a Bicron 418 scintillator 0.25mm thick at dose levels of 10^{11} beam particles. Our problem for E859 is to provide a solid signal that is immune to this radiation damage for the next run. Our task for E866 is to provide a beam counter system that will reliably count the Au beam at intensities up

to 10^6 per spill, and signal when an interaction has occured, ie, be sensitive to $\Delta Z=1$ processes in the target.

II. State of the Field of Investigation

E858 was the first high sensitivity experiment to study particle spectra, reflected in the fact that we were the first to observe an $\bar{d}$. The experimental layout for both E858 and E878 is shown in Figure 1. The results of this experiment are summarized in Appendix 2, a paper being submitted on our results, and shown here as Figure 2. The performance of the experiment is described in Appendix 3, the shell of a NIM article. Our investigations overlap the antiproton measurements of E802, E859, and E866 in rapidity, although those measurements are at larger $p_\perp$. We note that we agree within errors with the extrapolation of the midrapidity $\bar{p}$ data from E802 to 0 $p_\perp$ (Costales 91). We also overlap the range of $\bar{p}$ momenta studied in E814 although in all cases our statistics are significantly better.

One of the major issues arising from all three of these experiments (E802, E814, and E858) concerns the issue of reabsorption of the $\bar{p}$'s in the interaction region. As described in Appendix 2, we investigate this question in a study of the target and rapidity dependence of the production cross section. We fit the data to a simple function,

$$\frac{d^3\sigma}{dydp_\perp^2}(\mathrm{Si+At}\rightarrow\bar{p}+x) \propto \sigma_{TOT}^{\alpha},$$

where σ_{TOT} is the total nuclear interaction cross section (3.7 b for Si+Au), and α is the fitting parameter. We show in Figure 3 the results of this fit as a function of rapidity for the π^-,K^-, and $\bar{p}$ data from Si+Au collisions. We agree in this analysis with the conclusions reached by Dorfan (Dorfan 65) and by Marmer (Marmer 69) that there is no evidence for significant reabsorption of the $\bar{p}$'s seen in the target dependence. The conclusion from E802 is that there is no compelling evidence in their $\bar{p}$ yield for significant reabsorption of the antibaryons (Abbott 91) The results from E814, in which the $\bar{p}$ yield is investigated as a function of transverse energy created within the event, suggest that reabsorption may become important in collisions with

the heaviest targets (Greene 91), although the evidence is not compelling. We will be able to address this issue in E878 with the addition of the centrality detector.

In describing our $\bar{d}$ yield in Appendix 2, we discuss the coalescence model at some length. Basically we find that a wide variety of both d and $\bar{d}$ data can be described in terms of the p and $\bar{p}$ yield through the simple relation

$$\left(\frac{d^3N}{dy\,dp_t^2}\right)_d = B_A\left(\frac{d^3N}{dy\,dp_t^2}\right)_p^2.$$

where B_A is a constant whose value ranges from 0.009 to 0.022 over a range of experiments from the Bevalac for Au+Au to FNAL for p+W. A similar value, B_A=0.015, describes the bulk of the data from E802, although the value decreases significantly when considering only the highest multiplicity events. If the value for antinuclei is as low as is indicated by our E858 data, this could mean that we are sensitive to the real hadronization time for heavy particles. We intend to investigate this function in E878 with implementation of our new centrality detector, E_T, described in Appendix 4, and with a thorough study of the target dependence in $\bar{d}$ production. If the B_A reflects an increase in the production volume for antibaryons, then the size may be dominated by an effective hadronization length, rather than by the nuclear sizes of the target and projectile. By measuring the 0° yield of p, d, $\bar{p}$, and $\bar{d}$ for at least two and hopefully three targets in the Si+A program, we should be able to answer this question.

We also investigated whether our $\bar{d}$'s could be arising in individual nucleon-nucleon collisions. Note that the beam energy at the AGS, 14.6 A GeV, is below the threshold for producing a d $\bar{d}$ pair in an elementary nucleon-nucleon collision. However, it is well known that the nucleons inside nuclei possess significant Fermi momentum. We located a study of $\bar{d}$ production in pAl/Be interactions as a function of energy (Johnson 89) that allowed us to perform the double Fermi momentum production calculation shown in Figure 4. We find that this process yields a value for the $\bar{d}/\bar{p}$ ratio of 5×10^{-8}, compared to our value of 10^{-5}. We conclude from this that the production mechanism is through a coalescence of the $\bar{p}$ and $\bar{n}$ formed in different

nucleon-nucleon collisions. We would like to have more than our 2 $\bar{d}$'s on which to base this important conclusion, however.

Special care must be taken in performing a rare particle search, and it is important that the apparatus provide many levels of redundancy in the particle identification. Rare particles are required to pass stringent cuts to be classified as real particles, including the following:

1. TOF consistency between TOF3-TOF1 and TOF4-TOF2. Note that these four detectors are spaced to provide two independent and high resolution measurements of particle velocity, thereby eliminating decays in flight and contamination from interactions in the upstream portions of the spectrometer.

2. Charge consistency in all detectors. The charge resolution of our TOF detectors is excellent, typically $\sigma_Z<0.05$ e^-.

3. Valid trajectories pointing through the spectrometer to the target. This is a powerful cut that eliminates any scattering from pole tips or other interaction sites.

4. Consistent Ck signals. Heavy particles in the spectrometer, being slower at a given rigidity, will typically not fire the Ck detectors, so any evidence of a hit in the Ck detectors would cause the event to be suspect.

We show in Figure 4 of Appendix 2 the search levels we attained in E858 as a function of Z/A of the particles. We expect to improve these to a level of 10^{-11} over a broad range of Z/A in E878. We expect the AuAu interaction environment to have a much better chance at producing new states of matter because of its larger size and the commensurate increase in the number of strange quarks produced.

III. Program Description

A. First year

As shown in the proposal timeline of Figure 5, we will setup our experiment E878 on the A-3 line at the AGS and begin data taking in the first year of the program.

The apparatus is described in detail in Appendix 3 and 4. Detector systems are being fabricated at UCSSL, LBL, BNL, Waseda, and JHU. These are to be completed in time for a test run at the LBL Bevalac in November 1991, in a parasitic program. They will then be installed at BNL in early December 1991 in preparation for the Si beam which is to run between Jan and Mar 1992.

We have been approved for a total fluence of 10^{13} SiAu interactions in E878. We expect it to take a significant portion of the Si run to integrate that number of interactions in our spectrometer. We have budgeted enough time at BNL to cover a long run of E878 as well as to meet our responsibilities to E859.

Data analysis will be performed primarily at Berkeley, and we expect to bring our two students out for a portion of each year. We expect this to take about 6 months for the full analysis of the Si run, although we will have preliminary results online. This is essential since we will be presenting a program review to the AGS PAC in their Spring meeting. At the same time that we are analysing the Si data we will be performing the simulations needed to interpret this data and to prepare for the Au beam.

B. Second year

We will analyse all of the data from the preceding year's run and publish the 0° momentum spectra for Si+Au-> $\bar{d}$ + X and the relative yield as a function of target A. This will be accompanied by a study of the question of reabsorption and the question of hadronization length. We will then concentrate on preparing for the expected Au run at the AGS in Winter 1993. We will be involved in both E866 and E878 at this time, necessitating a presence at BNL throughout the winter.

In addition to this we hope to test the concept for our short lived/neutral detection experiment during the first Au beam. We expect this test to involve the MPS group and facility and to lead to a full experiment proposal in the third year of our program.

C. Third year

We will complete the analysis of the preceding year's Au run and publish the particle spectra as a function of target and raidity from that run.

We will continue our investigation with either a lower sensitivity search for neutral and short lived new particles, or a further investigation of anti-nucleus production. We will also be taking data with E866.

References

Abbott, A., for BNL E802 Collaboration, Phys.Rev.Lett. 64, 487, 1990.

Abbott, A., for BNL E802 Collaboration, submitted to Phys.Rev.Lett. 1991Butler,S.T.

Chin, S.A. and A.Kerman, PRL 43, 1292, 1979.

Costales, J. MIT PhD. Thesis, 1991.

Cronin.J.W., H.J.Frisch, M.J.Sochet, J.P.Boymond, P.A.Piroue, and R.L.Sumner, Phys.Rev.D11, 3105, 1975.

Dorfan, D.E., J.Eades, L.Lederman, W.Lee, and C.C.Ting, PRL 14, 1003, 1965.

Dover, C., U.Heinz, Ekkard Schnedermann, and Josef Zimanyi, BNL TCP-90-60, 1991.

Ellis, John, U.Heinz, and Henryk Kowalski, Phys.Lett.B 233, 223, 1989.

Gavin, S., M.Gyulassy, M.Plumer, and R.Venugoplan, Phys.Lett.B 234, 175, 1990.

Greene, V. for E814 Collaboration, Bul.Am.Phys.Soc., 1991.

Greiner, Carsten and Horst Stocker, Frankfurt Preprint 1991, submitted to Phys.Rev.D.

Heinz, U., P.R.Subramanian, H.Stocker, and W.Greiner, J.Phys.G 12, 1237, 1986.

Heinz,U., Kang S. Lee, and Ekkard Schnedermann, Regensberg Preprint TPR 89-13, 1989.

Jahns, A. H.Sorge, H.Stocker, and W.Greiner, Frankfurt Preprint, 1991.

Johnson,C.D., and T.R.Sherwood, in "Hyperfine Interactions" V44, 65, 1989.

Liu, H.C. and G.L.Shaw, Phys.Rev D30, 312, 1984.

Marmer,G.J., K.Reibel, D.M.Schwartz, A.Stevens, R.Winston, D.Wolfe, C.J.Rush, P.R.Phillips, E.C.Swallow, and T.A.Romanowski, Phys.Rev. 179, 1294, 1969.

Sarabura, M., MIT PhD.Thesis, 1991.

Schaffner, J., H.Stocker, and C.Greiner, Frankfurt Preprint 1991.

Figure Captions

1. Experimental layout showing the beamline spectrometer. The time-of-flight counters consist of 5mm thick scintillator viewed at both ends by photomultiplier tubes. The 3 atm.gas Freon-12 Cherenkov detectors are used to veto π^-'s in the trigger, as well as in supplementing the PID capabilities at high and low momentum. The four drift tube arrays provide acceptance and particle trajectory information. E858 was performed oin the A-1 line; E878 will be performed on the A-3 line.

2. Particle distributions: $Ed^3\sigma/dp^3$ for π^-, K^-, $\bar{p}$ from Al, Cu, and Au targets; the $\bar{d}$ prediction from coalescence model calculation , and the 90%CL upper limit to the invariant cross section from our data, as well as our 2 $\bar{d}$ data point at 6.1 GeV/c. To compute the number of interactions sampled at each setting, multiply the upper limit values by $10^{-5}p^3/E$ assuming a deuteron mass particle.

3. Target dependence showing values of parameter "α" obtained in fits to equasion #2:

$$\frac{d^3\sigma}{dydp_\perp^2}(Si+At\rightarrow\bar{p}+x) \propto \sigma_{TOT}^{\alpha},$$

High rapidity points are π^-, lowest are $\bar{p}$'s with K^- in the middle.

4. a) Experimental $\bar{d}/\bar{p}$ production ratios from p-nucleus experiments at AGS, CERN, and Serpukov [collated by C.D.Johnson in "Hyperfine Interactions 44, 65, 1989]

b) Ratio of $\bar{d}/\bar{p}$ from direct production in central collisions of 14.6 A GeV/c Si on Au. Curve is the product of the $\bar{d}/\bar{p}$ ratio obtained in p-nucleus collisions and the Fermi momentum probability for ^{28}Si boosted to 14.6 GeV/c. A total integrated $\bar{d}/\bar{p}$ value of 5×10^{-8} is obtained when signa and direction are taken into account.

5. Experiment timeline showing the major milestones for the project.

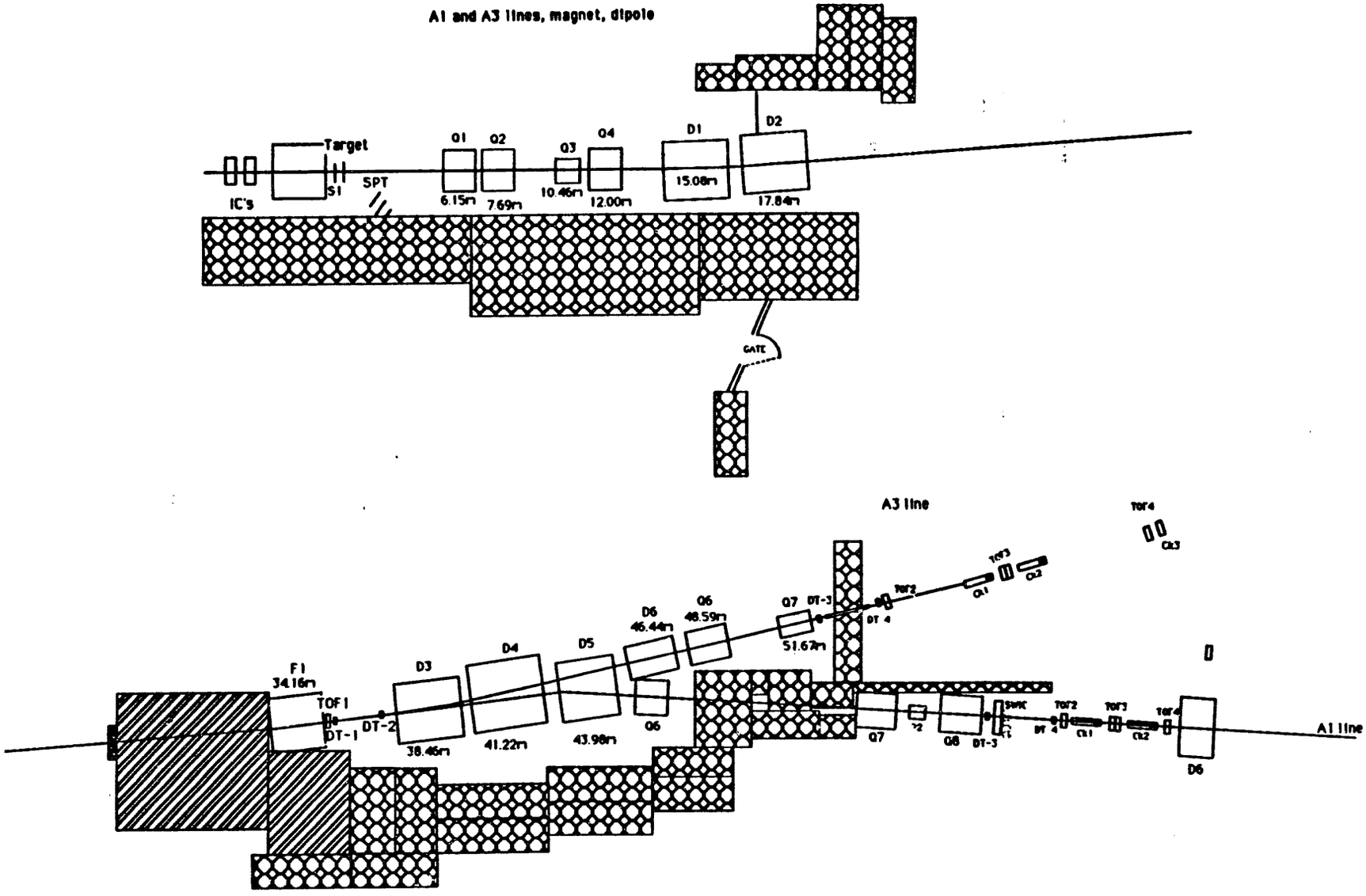

A1 and A3 lines, magnet, dipole
Target
IC's
S1
SPT
Q1
Q2
Q3
Q4
D1
D2
6.15m
7.69m
10.46m
12.00m
15.08m
17.84m
GATE
A3 line
A1 line
F1
34.16m
TOF1
DT-1
DT-2
D3
D4
D5
D6
Q6
Q7
Q8
38.46m
41.22m
43.98m
46.44m
48.59m
51.67m
DT-3
DT 4
TOF2
TOF3
TOF4
CL1
CL2
CL3
D6

Figure 1

Particle Production @0° in Si+A 14.6 A GeV/c

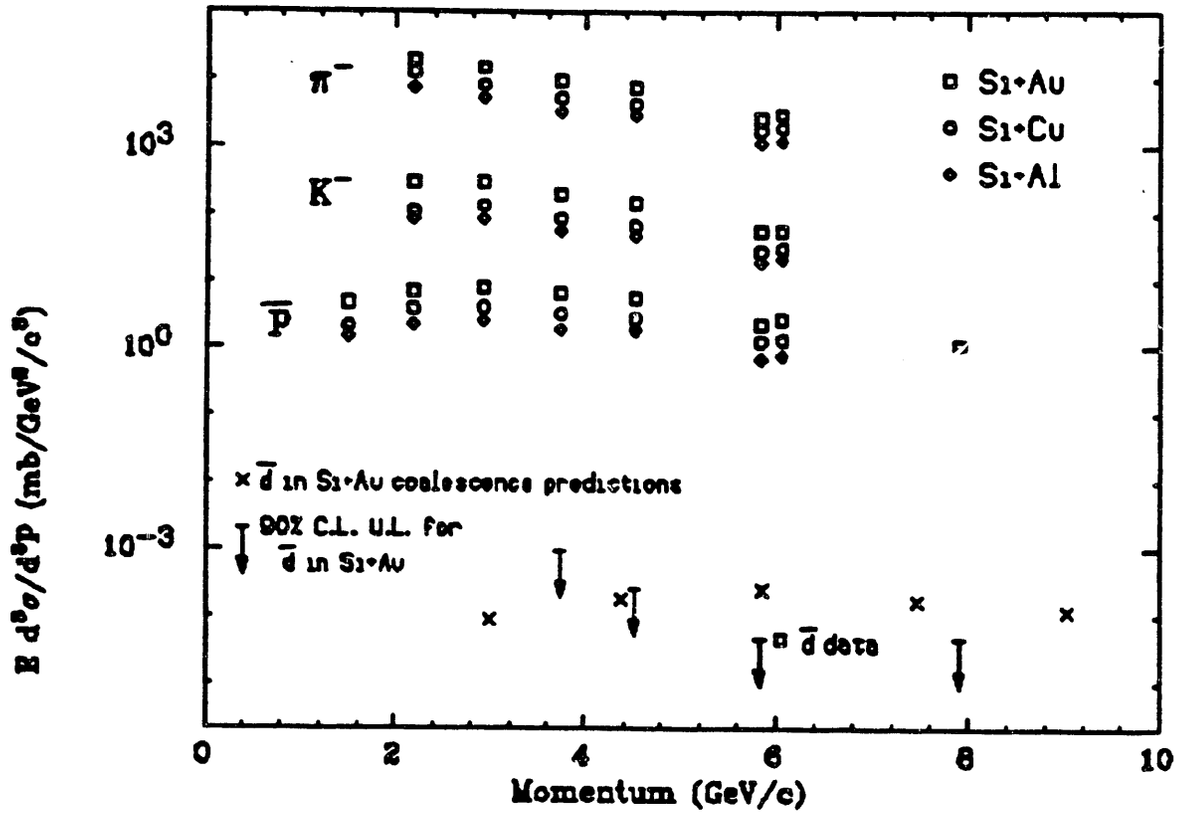


Figure 2

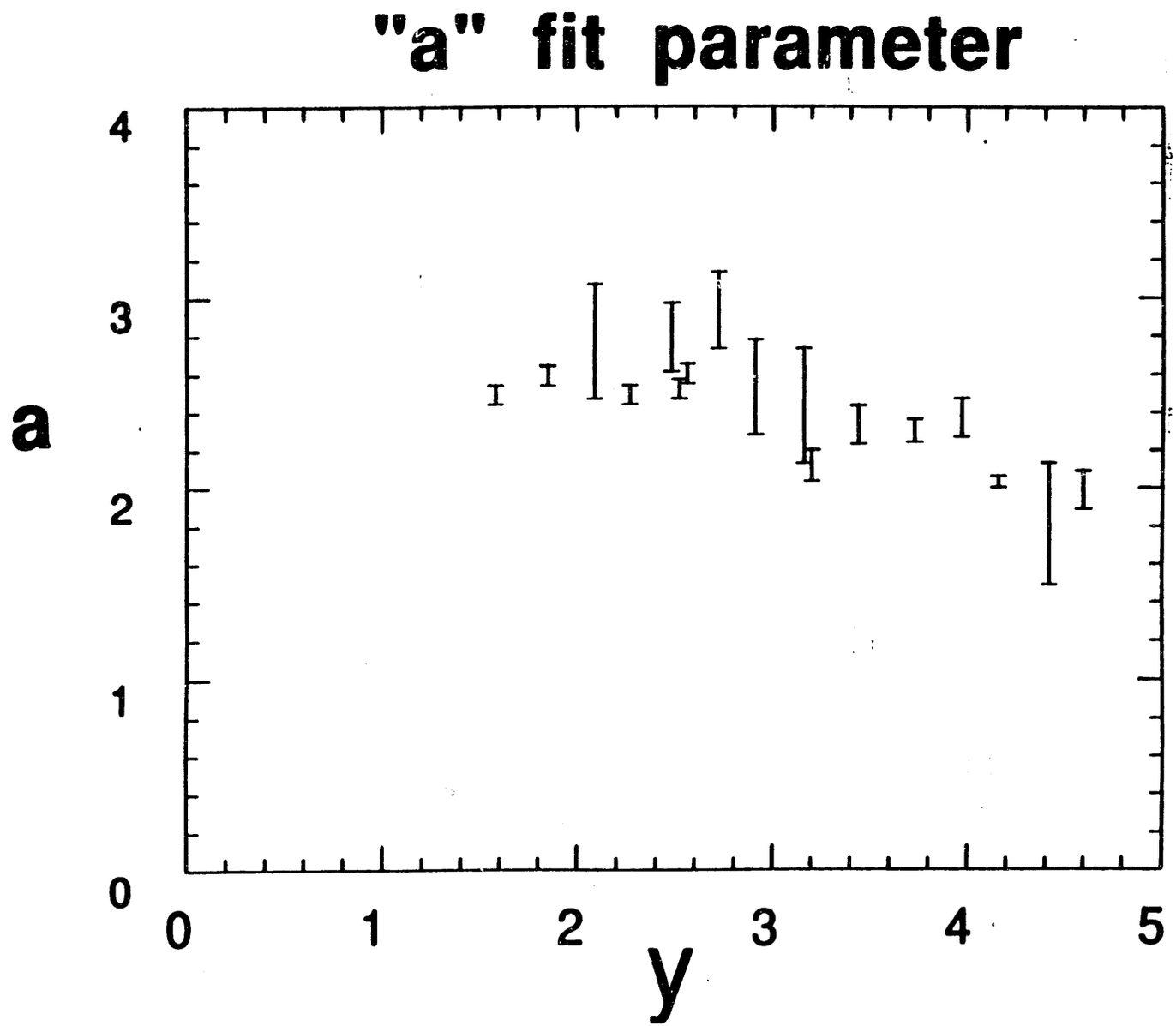


Figure 3

C.D. Johnson, T.R. Sherwood / Antideuterons at CERN

Experimental antideuteron/antiproton production ratios

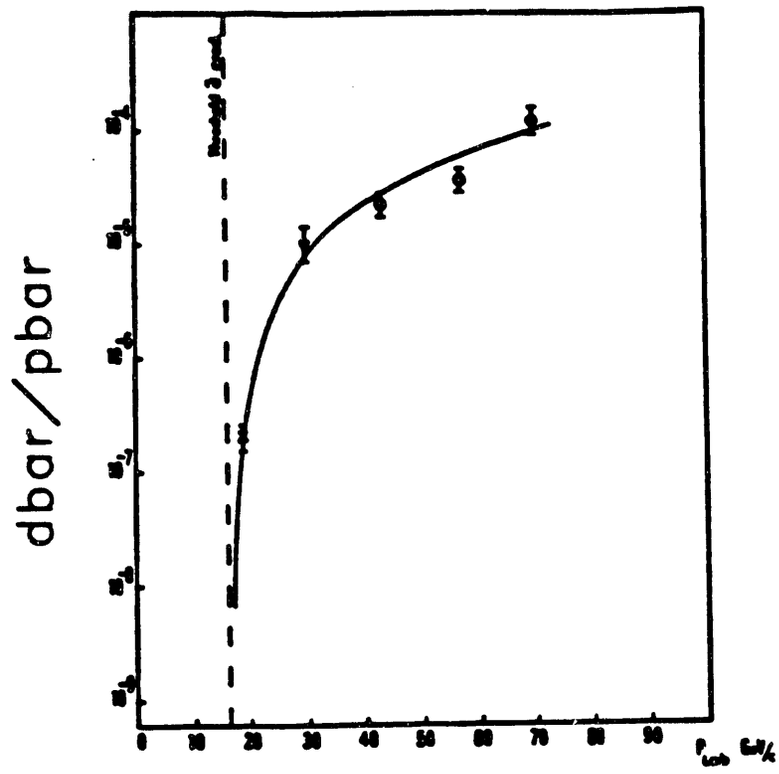
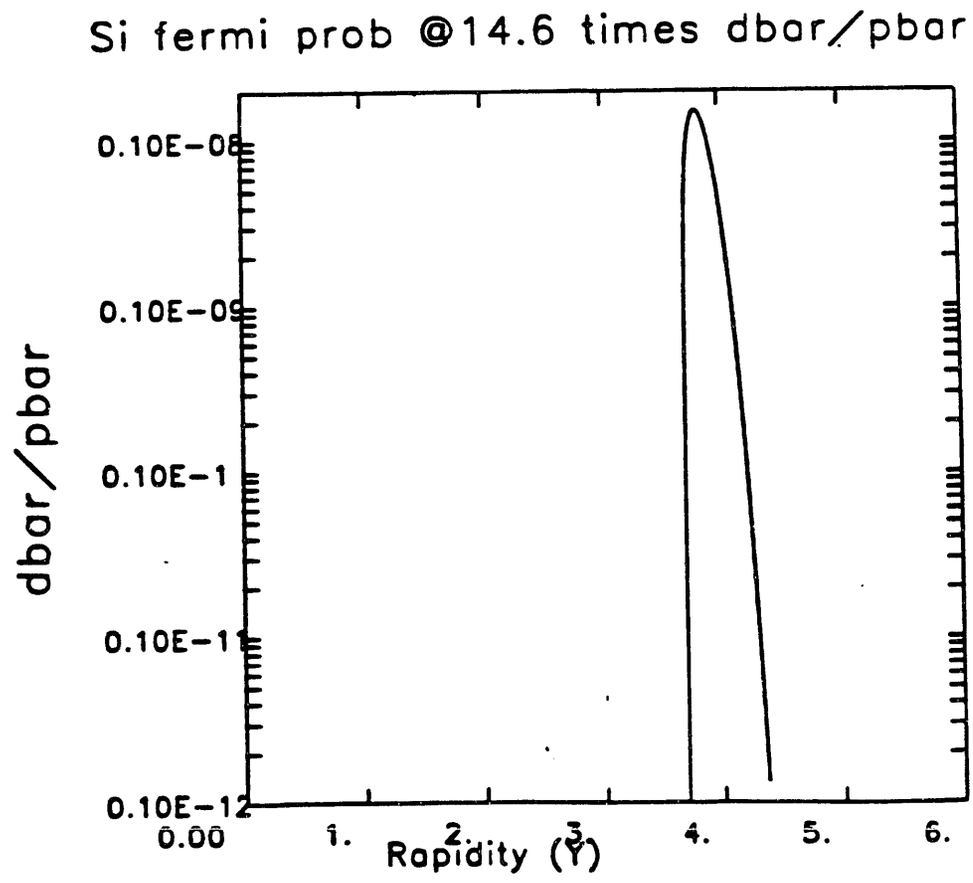


Figure 4

a)



b)

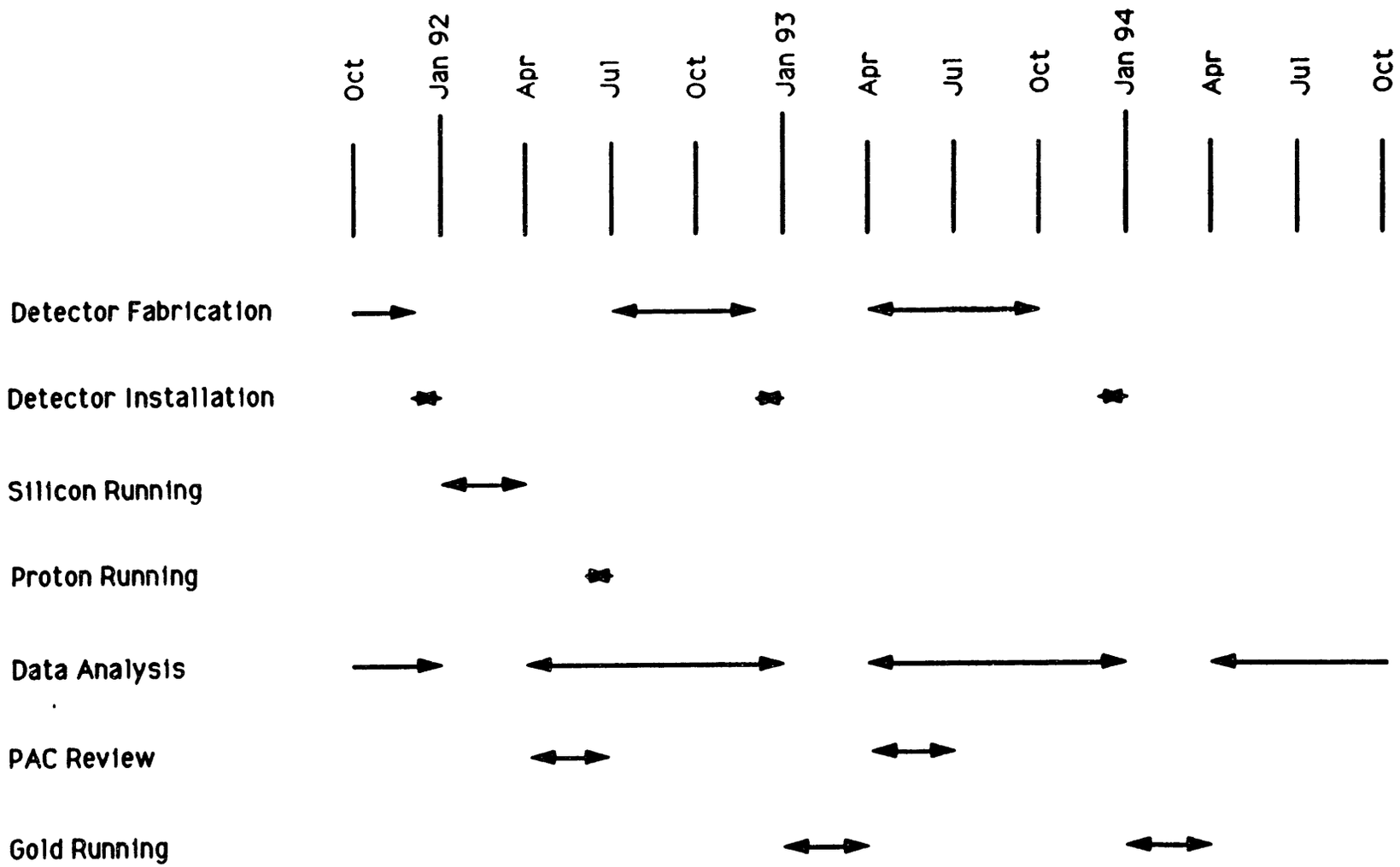

Oct
Jan 92
Apr
Jul
Oct
Jan 93
Apr
Jul
Oct
Jan 94
Apr
Jul
Oct
Detector Fabrication
Detector Installation
Silicon Running
Proton Running
Data Analysis
PAC Review
Gold Running

Figure 5

IV. Principal Investigator

Henry Joseph Crawford
2410 Spaulding Street
Berkeley, CA 94703
(415) 548-0111

Employment

10/71–present:	**Space Sciences Laboratory** **University of California, Berkeley**
10/89 - present:	Research Physicist II
10/86 - 9/89:	Associate Research Physicist
1/80 - 9/86:	Specialist
10/79 - 12/80:	Assistant Research Physicist
7/76 - 9/79:	Assistant Specialist
1/76 - 6/76:	Junior Specialist
6/73 - 12/75:	Research Assistant
10/71 - 6/73:	Staff Research Associate
6/65–6/71:	**Laboratory of Astrophysics and Space Research** **University of Chicago**
1/70 - 6/71:	Staff Research Assistant
7/68 - 12/69:	Graduate Student Research Assistant
6/65 - 6/68:	Research Assistant

Research

1. At BNL AGS on production of antinuclei and new states of matter.

2. With G. Guzik, J. Wefel, J. Waddington, W. Webber, on measurement of nuclear fragmentation for Cosmic Ray propagation.

3. With O. Hansen and S. Nagamiya, measuring strange particle production in relativistic nuclear collisions.

4. With D. Greiner, H.H. Heckman, and P. Lindstrom, on dynamics of nuclear interactions in relativistic heavy ion collisions using a large superconducting magnetic spectrometer system.

5. With J.O. Rasmussen, investigating γ-ray correlation with nuclear fragmentation using Ge and Si(Li) detectors.

6. With P.B. Price, G. Raisbeck, D. Greiner, and H.H. Heckman, on electron capture and loss and energy-loss phenomena for high energy heavy nuclei using a magnetic spectrometer.

7. With B. Cartwright and D. Greiner, on isotopic composition of galactic cosmic rays using balloon and satellite instruments consisting of scintillator-Cherenkov-range and Si(Li) telescopes.

8. With P.B. Price, on solar particle composition and acceleration using plastic track detector techniques.

9. With J. Wang and J. Simpson, developing spherical shell Si detectors to measure p spectra in Jupiter radiation belts using detection of proton-induced fission of U foil.

10. With K.C. Hsieh, on solar modulation of galactic cosmic rays.

11. With J. Simpson and J.D. Sullivan, on solar and galactic cosmic ray composition and acceleration using IMP satellites.

12. With A. Tuzzolino and A. Turkevich on an α backscatter experiment to analyse lunar surface composition and development of solid state Si(Li) detectors.

Education

Ph.D.,	Physics,	University of California, Berkeley, May 1979.
M.A.,	Physics,	University of Chicago, December 1969.
B.A.,	Physics,	University of Chicago, June 1968.

Attached is a complete list of publications.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Publications

Journal Publications:

1. Sullivan, J.D., Price, P.B., and Crawford, H.J. "Composition and Energy Spectra of Heavy Nuclei with 1<E<40 MeV/nuc in 1971 January 24 Solar Flare", *Bulletin of the American Astronomical Society* **4**, 1972, p. 393.

2. Crawford, H.J., Price, P.B., and Sullivan, J.D. "Composition and Energy Spectra of Heavy Nuclei with 0.5<E<40 MeV/nuc in the 1971 January 21 and September 24 Solar Flares", *Astrophysical Journal Letters* **175**, 1972, p. 3.

3. Sullivan, J.D., Crawford, H.J., Price, P.B., and Whitehead, M. "Fragments with 6 <Z <15 Emitted from Au Bombarded with 2.1 GeV/nuc ^{16}O Ions and 2.1 GeV Protons", *Physical Review Letters* **30**, 1973, p. 136.

4. Crawford, H.J., Price, P.B., Cartwright, B.G., and Sullivan, J.D. "Solar Flare Particles: Energy Dependent Composition and Relationship to Solar Composition", *Astrophysical Journal* **195**, 1975, p. 213.

5. Crawford, H.J., Price, P.B., Stevenson, J., and Wilson, L.W. "Very High Energy Fragments from Relativistic Heavy Ion Reactions", *Physical Review Letters* **34**, 1975, p. 329.

6. Lindstrom, P.J., Crawford, H.J., Greiner, D.E., Hagstrom, R.T., and Heckman, H.H. "Evidence Against Copious Sub-Threshold Pion Production in Heavy Ion Collisions", *Physical Review Letters* **40**, 1978, p. 93.

7. Heckman, H.H., Crawford, H.J., Greiner, D.E., and Lindstrom, P.J. "Central Collisions Produced by Relativistic Heavy Ions in Nuclear Emulsion", *Physical Review C* **17**, 1978, p. 1651.

8. Viyogi, Y.P., Symons, T.J.M., Doll, P., Greiner, D.E., Heckman, H.H., Hendrie, D.L., Lindstrom, P.J., Mahoney, J., Scott, D.K., van Bibber, K., Westfall, G.D., Wieman, H., Crawford, H.J., McParland, C.P., and Gelbke, C.K. "Fragmentation of ^{40}Ar at 205 MeV/nuc", *Physical Review Letters* **42**, 1979, p.33.

9. Symons, T.J.M., Viyogi, Y.P., Westfall, G.D., Doll, P., Greiner, D.E., Faraggi, H., Lindstrom, P.J., Scott, D.K., Crawford, H.J., and McParland, C.P. "Observations of New Neutron-rich Isotopes by Fragmentation of 205 MeV/nuc Ar Ions", *Physical Review Letters* **42**, 1979, p. 40.

10. Westfall, G.D., Wilson, L.W., Lindstrom, P.J., Crawford, H.J., Greiner, D.E., and Heckman, H.H. "Fragmentation of Relativistic ^{56}Fe", *Physical Review C* **19**, 1979, p. 1309.

11. Westfall, G.D., Symons, T.J.M., Greiner, D.E., Heckman, H.H., Lindstrom, P.J., Mahoney, J., Schotter, A.C., Scott, D.K., Crawford, H.J., McParland, C.P., Awes, T.C., Gelbke, C.K., and Kidd, J.M. "Production of Neutron-rich Nuclides by Fragmentation of 212 MeV/amu ^{48}Ca", *Physical Review Letters* **43**, 1979, p. 1859.

12. Olson, D.L., Berman, B.L., Greiner, D.E., Heckman, H.H., Lindstrom, P.J., Westfall, G.D., and Crawford, H.J. "Electromagnetic Dissociation of ^{16}O Nuclei", *Physical Review C* **24**, 1981, p. 1529.

13. Murphy, M.J., Symons, T.J.M., Westfall, G.D., and Crawford, H.J. "Beta-decay Half-lives of Isotopes Produced in Projectile Fragmentation", *Physical Review Letters* **49**:7, 1982, p. 455.

14. Hoang, T.F., Cork, B., and Crawford, H.J. "Space Structure of a Fireball and the Pion Radius", *Zeitschrift fur Physics C* 12, 1982, p. 345.

15. Crawford, H.J., and Lindstrom, P.J. "LULU Analysis Program", *IEEE Transaction in Nuclear Science, NS-30* 5, 1983, p. 3842.

16. Olson, D.L., Berman, B.L., Greiner, D.E., Heckman, H.H., Lindstrom, P.J., and Crawford, H.J. "Factorization of Fragment-produced Cross Sections in Relativistic Heavy Ion Collisions", *Physical Review C* 28, 1983, p. 1602.

17. Gould, H., Greiner, D.E., Lindstrom, P.J., Symons, T.J.M., and Crawford, H.J. "Electron Capture by U^{91+} and U^{92+} and Ionization of U^{90+} and and U^{91+}", *Physical Review Letters* 52, 1984, p. 180.

18. Symons, T.J.M., Baumgartner, M., Dufour, J.P., Girard, J., Greiner, D.E., Lindstrom, P.J., Olson, D.L., and Crawford, H.J. "Charge Changing Reactions of Secondary Fragments Produced in High-energy Heavy Ion Collisions", *Physical Review Letters* 52, 1984, p. 982.

19. Greiner, D.E., Crawford, H.J., Lindstrom, P.J., Kidd, J.M., Olson, D.L., Schimmerling, W., and Symons, T.J.M. "Uranium Nuclear Reactions at 900 MeV/ Nucleon", *Physical Review C* 31, 1985, p. 416.

20. Hoang, T.F., Cork, B., and Crawford, H.J. "Cross Sections of High Energy Nuclear Reactions", *Zeitschrift fur Physik C* 29, 1985, p. 611.

21. Doke, T., Crawford, H.J., Gruhn, C.R., Hitachi, A., Kikuchi, J., Masuda, K., Nagamiya, S., and Shibamura, E., and Tamada, S. "Scintillation Yields by Relativistic Heavy Ions and the Relation Between Ionization and Scintillation in Liquid Argon", *NIM* A235, 1985, p. 136.

22. Tomasch, A., Ahlen, S.P., Bower, C., Price, P.B., Salamon, M., Tarle, G., Musser, J., Crawford, H.J. "Response of High Resolution Drift Tubes to Relativistic Heavy Ions", *NIM* A241, 1985, p. 265.

23. Engelage, J., Baumgartner, M., Greiner, D.E., Lindstrom, P.J., Olson, D.L., Wada, R., Crawford, H.J., and Webb, M.L. "A Quasi Exclusive Measurement of ^{12}C (^{12}C, 3α) X at 2.1 GeV/nucleon", *Physics Letters B* 173, 1986, p. 34.

24. Waddington, C.J., Crawford, H.J., Lindstrom, P.J., and Heckman, H.H. "Stopping of Relativistic Heavy Ions in Various Media", *Physical Review A* 34, 1986, p. 3700.

25. Crawford, H.J., Flores, I., Lindstrom, P.J., Krebs, G. "Report on TOF for 900 MeV/nuc Au Ions", *NIM* A245, 1986, p. 100.

26. Crawford, H.J., Doke, T., Hitachi, A., Kikuchi, J., Lindstrom, P.J., Masuda, K., Nagamiya, S., and Shibamura, E. "Ionization and Scinitillation from Relativistic La Ions in Liquid Argon", *NIM*, A256, 1987, p. 47.

27. Christie, W.B., Romero, J.L., Brady, F.P., Tull, C.E., Castenada, C.M., Barasch, E.F., Webb, W.L., Drummond, J.R., Crawford, H.J., Flores, I., Greiner, D.E., Lindstrom, P.J., Sann, H., and Young, J.C. "A Multiple Sampling Ionization Chamber (MUSIC) for Measuring the Charge of Relativistic Heavy Ions", *NIM* A255, 1987, p.466.

28. Shibamura, E., Crawford, H.J., Doke, T., Engelage, J.M., Flores, I., Hitachi, A., Kikuchi, J., Lindstrom, P.J., Masuda, K., Ogura, K. "Ionization and Scintillation Produced by Relativisitic Au, He, H Ions in Liquid Argon", *NIM* A260, 1987 p. 437.

29. Wienands, U., Hessey, N., Barnett, B.M., Rosen, F.M., Roser, H.W., Altman, A., Johnson, R.R., Gill, D.R., Wiedner, C.A., Manley, D.M., Berman, B.L., Crawford, H.J., and Grion, N. "Elastic and Inelastic Scattering of 50-MeV Pions on ^{28}Si and ^{30}Si", *Physical Review C* 35, 1987, p. 708.

30. Webb, M., Baumgartner, M., Crawford, H.J., Engelage, J., Greiner, D.E., Lindstrom, P.J., Olson, D.L., and Wada, R. "Probing the Direct Step of Relativistic Heavy Ion Fragmentation - ^{12}C, ^{11}B+p at 2.1 GeV/nuc", *Physical Review C* 36, 1987, p. 193.

31. Brady, F.P., Christie, W.B., Romero, J.L., Tull, C.E., McEachern, B., Webb, M.L., Young, J.C., Crawford, H.J., Greiner, D.E., Lindstrom, P.J., Sann, H. "Large p_t from the Fragmentation of 1.2 Gev/nuc ^{139}La Nuclei", *Physical Review Letters* 60 1988, p. 1699.

32. Abbott, T., et al., E802 collaboration. "Measurement of Energy Emmission from O+A and p+A Collisions at 14.5 GeV/nuc with a Lead Glass Array", *Physics Letters B* 197, 1988, p. 285.

33. Kidd, J.M., Lindstrom, P.J., Crawford, H.J., Woods, G. "The Fragmentation of ^{12}C Ions at 250 MeV/n", *Physical Review C* 37, 1988, p. 2613.

34. Berg, H., Dorner, R., Kelbch, C., Kelbch, S., Ullrich, J., Hagmann, S., Richard, P., Schmidt-Bocking, H., schlachter, A.S., Prior, M., Crawford, H.J., Engelage, J.M., Flores, I., Loyd, D.H., Pedersen, J., Olson, R.E. "Multiple Ionization of Rare Gases by High-Energy Uranium Ions", *J. Physics B* 21, 1989, p. 3929.

35. Hoang T.F., Crawford, H.J. "Characteristics of π^-, $\bar{p}$, and Antinuclei from pp Collisions", *Zeitschrift fur Physik C Particles and Fields*, 43 1989, p. 215.

36. Cole, A.J., Lindstrom, P.J., Crawford, H.J., Harvey, B.G. "Peripheral Reactions Induced by a 2.1 GeV/nucleon ^{12}C Beam on a C Target Using a Simple Combinatorial Model", *Physical Review C* 39, 1989, p. 891.

37. Harvey, B.G., Crawford, H.J., Lindstrom, P.J., Cole, A.J. "Statistical Decay of Fragments from C + ^{12}C, 2.1 GeV/nucleon", *Physical Review C* 39, 1989, p. 841.

38. Ziock, K.P., Hailey, C.J., Stewart, R.E., Lupton, J.H., Crawford, H.J. "A Dopplar Tuned spectrometer for Precision Measurement of Transition Energies in High Z Ions", submitted to *NIM*, 1989

39. Perelygin, V.P., Stetsenko, S.G., Crawford, H.J., Symons, T.J.M. "Analysis of the Results of Calibration Meteoritic Olivine Crystals with ^{238}U Nuclei at the Bevalac Accelerator", submitted to *Zeitschrift fur Physik*, 1989

40. Engelage, J., Baumgartner, M.E., Beleal, E., Berman, B.L., Bieser, F., Brady, F.P., Bronson, M., Carroll, J.B., Crawford, H.J., Flores, I., Greiner, D.E., Greiner, L., Hashimoto, O., Igo, G., Kadota, S., Kirk, P.N., Lindstrom, P.J., McParland, C.P., Nagamiya, S., Olson, D.L., Porter, J., Romero, J.L., Ruiz, C.L., Symons, T.J.M., Tanihata, I., Wada, R., Webb, M.L., Yamada, J., Yee, H. "Design of the Bevalac Heavy Ion Spectrometer System and Its Performance in Studying ^{12}C Fragmentation", *NIM* A277, 1989, p. 431.

41. Hof, M., Isbert, J., Mathis, K.D., Simon, M., Guzik, T.G., Mitchell, J.W., Wefel, J.P., Crawford, H.J. "A Drift Chamber Telescope for Heavy Ion Track Detection with High Spatial Resolution", *NIM* A276 1989,

p. 628.

42. Abbott, T., et al., E802 Collaboration, "Results from the BNL E802 Spectrometer for 14.5 GeV/C per Nucleon Silicon Beams", *Nuclear Physics* A498 1989, p.67c

43 Abbott, T. et al., E802 Collaboration, "Kaon and Pion Production in Central Si+Au Collisions at 14.6 A GeV/c", *Phys.Rev.Lett.* 64

44 Hoang,T.F. and H.J.Crawford, "Multiparticle Production in p-Nuclus and Nucleus-Nucleus Collisions" *Phys.Rev.* D42 1990, p45

45 Abbott,T. et al., E802 Collaboration, "A Single Arm Spectrometer Detector System for High Energy Heavy Ion Experiments", *NIM* A290 1990, p.41

46 Golden,R.L., for the WIZARD Collaboration, "Wizard - A Program to Measure Cosmic-Ray Antiprotons and Positrons, and Search for Primordial Antimatter", *Nuovo Cimento* B105 1990, p.191

Conference Proceedings and Other Publications:

1. Sullivan, J.D., Crawford, H.J., and Price, P.B. "Relative Abundance of Nuclei with $2<Z<26$ in Solar Flares", in *Proceedings of the XIII International Cosmic Ray Conference, Denver, Colorado* SP, 1973, p. 1522.

2. Price, P.B., Chan, J.H., Crawford, H.J., and Sullivan, J.D. "Systematics of Heavy Ion Enhancements in Solar Flares", in *Proceedings of the XIII International Cosmic Ray Conference, Denver, Colorado* SP, 1973, p. 1479.

3. Ahlen, S.P., Cartwright, B.G., Crawford, H.J., Price, P.B., and Tarle,G. "The University of California Iron Isotope Experiment", in *Proceedings of the XIV International Cosmic Ray Conference, Munich* T, 1975, p. 3256.

4. Heckman, H.H., Crawford, H.J., Greiner, D.E., Lindstrom, P.J., and Wilson, L.W. "Non-peripheral Collisions of Heavy Ions in Nuclear Emulsion", *LBL-6562*, 1978.

5. Crawford, H.J. "Single Electron Attachment and Stripping Cross Sections for Relativistic Heavy Ions", *LBL-8807*, 1979.

6. Crawford, H.J., Gould, H., Greiner, D.E., Lindstrom, P.J., and Symons, T.J.M. "Equilibrium Charge States of Uranium at Relativistic Energies", *LBL-16241*, 1983.

7. Olson, D.L., Baumgartner, M., Dufour, J.P., Girard, J.G., Greiner, D.E., Lindstrom, P.J., Symons, T.J.M., and Crawford, H.J. "A Cherenkov Detector for Heavy Ion Velocity Measurements", *LBL-18259*, 1984.

8. Dufour, J.P., Olson, D.L., Baumgartner, M., Girard, J.G., Lindstrom, P.J., Greiner, D.E., Symons, T.J.M., and Crawford, H.J. "A Cherenkov Particle Identifier for Relativistic Heavy Ions", *LBL-18643*, 1985.

9. Guzik, T.G., Wefel, J., Crawford, H.J., Greiner, D.E., Lindstrom, P.J., Schimmerling, W., and Symons, T.J.M. "Implications of New Cross Section Measurements from ^{16}O Fragmentation", in *Proceedings of the XIXth ICRC, La Jolla, California*, volume 2, 1985, p. 80.

10. Betts, R., and the E802 collaboration. "First Encounter with 14.5 GeV/A ^{16}O Beam", *Prodeedings of the XI International Conference on Particles and Nuclei (PANIC) Kyoto, Japan*, 1987.

11. Abbott, T., et al., E802 Collaboration, "Measurement of Energy and Charged Particle Emission in the Central Rapidity Region from O+A and p+A Collisions at 14.5 GeV/c per Nucleon and Preliminary Results from Si+A Collisions", *Quark-Matter*, 1987

12. Guzik, T.G., Mitchell, J.W., Wefel, J.P., Crawford, H.J., Lindstrom, P.J. "The Fragmentation of ^{16}O Nuclei in the Laboratory and in the Galaxy", *Proceedings of the XX International Cosmic Ray Conference, Moscow, Russia*, OG 7.2-7, 1987

13. Crawford, H.J., Smoot, G.F. "Technical Aspects of a Germanium Calorimeter for Space-borne Gamma-ray Detection", *LBL-25514*, 1988

14. Crawford, H.J., Engelage, J., Flores, I., Lindstrom, P.J. "The Bevalac Beam 40 Spectrometer", *LBL-25621*, 1988

15. Doke, T., Crawford, H.J., Engelage, J.M., Flores, I., Kashiwagi, T., Kikuchi, J., Masuda, K., Nishijima, K., Shibamura, E., Symons, T.J.M. "A Liquid Argon Calorimeter for Investigating High Energy Heavy Ion Reaction", *Bulletin of Science and Engineering Research Laboratory*, Waseda University, No. 123, May, 1989

16. Isbert, J., Crawford, H.J., Guzik, T.G., Hof, M., Mathis, K.D., Mitchell, J.W., Neuhaus, J., Simon, M., Wefel, J.P. "A Drift Chamber for High Z Particles", *Proceedings of the XXI International Cosmic Ray Conference, Adelaide, Australia*, OG 10.5-18, 1990

17. Crawford, H.J., Engelage, J., Guzik, T.G., Isbert, J., Lindstrom, P.J., Mitchell, J.W., Pitts, J.J., Schimmerling, W., Simon, M., Wefel, J.P. "The Fragmentation of ^{28}Si", *Proceedings of the XXI International Cosmic Ray Conference, Adelaide, Australia*, OG 8.3-10, 1990

18. Crawford, H.J., Engelage, J., Ferrando, P., Guzik, T.G., Jones, F.C., Lindstrom, P.J., Mitchell, J.W., Soutoul, A., Waddington, C.J., Webber, W.R., Wefel, J.P. "A Database of Fragmentation Cross Section Measurements Applicable to Cosmic Ray Propagation Calculations", *Proceedings of the XXI International Cosmic Ray Conference, Adelaide, Australia*, OG 8.3-14, 1990

Invited Talks:

1. "Study of ^{12}C Interactions at HISS", presented at the Symposium on Detectors in Heavy Ion Physics, Hahn-Meitner Institute fur Kernforschung, Berlin, West Germany, October 6-8, 1982. Published by Springer-Verlag.

2. "Characteristics of High Energy Nuclear Fragmentation", Colloquium at Louisiana State University, November, 1986.

3. "Totally Active Ge Calorimeter for Gamma-ray Astrophysics", workshop on high resolution Electromagnetic Calorimetry, Sigtuna, Sweden, 1989.

4 "Results from the E858 Rare Particle Search", AGS Users Association Meeting, Brookhaven National Laboratory, April, 1991.

5 "Search for Antinuclei and New Particles in Si+A and Au+A Interactions", workshop on Strange Matter in Physics and Astrophysics, Aarhus, Denmark, 1991.

Contributed Papers:

1. Crawford, H.J., Price, P.B., Stevenson, J., and Wilson, L.W. "Very Energetic Heavy Fragments from Relativistic Heavy Ion Reactions", *Bulletin of the American Physical Society* 20, 1975, p. 40.

2. Crawford, H.J., Lindstrom, P.J., Greiner, D.E., Shibata, T., Ioannou, J., Bowman, H., Nakai, K., Chiba, J., and Rasmussen, J.O. "Target-projectile Excitation Correlations in Relativistic Heavy Ion Collisions", *Bulletin of the American Physical Society* 22, 1977, p. 594.

3. Crawford, H.J., Cork, B., Greiner, D.E., Heckman, H.H., Lindstrom, P.J., and Wilson, L.W. "Isotope Production Cross Sections from ^{14}N and ^{15}N at 2 GeV/nuc", *Bulletin of the American Physical Society* 23, 1978, p. 27.

4. Crawford, H.J., Greiner, D.E., Heckman, H.H., Lindstrom, P.J., Wilson, L.W., and Raisbeck, G.M. "Electron Attachment and Loss by Relativistic Nuclei", *Bulletin of the American Physical Society* 23, 1978, p. 93.

5. Crawford, H.J., Baumgartner, M., Gelbke, C.K., Greiner, D.E., Heckman, H.H., Lindstrom, P.J., Olson, D.L., Schotter, A., Scott, D.K., Symons, T.J.M., Westfall, G.D., Wilson, L.W. "Fragmentation Cross Sections for Argon between 100 MeV/nuc and 1.8 GeV/nuc", abstract in *Proceedings of the XVI International Cosmic Ray Conference, Kyoto Japan*, 1979.

6. Crawford, H.J., Engelage, J., Flores, I., Baumgartner, M., Beleal, E.E., Bieser, F., Bronson, M., Greiner, D.E., Lindstrom, P.J., McParland, C.P., Olson, D.L., Porter, J., and Wada, R. "Destruction Cross Sections for Off-stability Isotopes", presented at the American Physical Society Meeting, Washington, D.C., Conference on Radioactive Beams, April 27, 1984.

7. Crawford, H.J., Engelage, J., Flores, I., Baumgartner, M., Beleal, E.E., Bieser, F., Bronson, M., Greiner, D.E., Greiner, L., Lindstrom, P.J., McParland, C.P., Olson, D.L., Porter, J., and Wada, R. "Fragmentation Channel Population for ^{12}C Breakup at 2.1 GeV/nuc", presented at Washington D.C. APS meeting, April, 1986.

END

DATE FILMED

12/24/91