ANNUAL PROGRESS REPORT
ON
DEEXCITATION PROCESSES IN NUCLEAR REACTIONS:
THE STUDY OF HOT HADRONIC MATTER

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During the past year, our research program has involved continuing analysis of Fermilab E-735, search for quark-gluon plasma (QGP) in $\bar{p}$ -p collisions; experiments on multifragmentation using reverse kinematics at the Bevalac; continuing study of target fragments produced in the interaction of copper with intermediate-energy heavy ions; and detector R&D for the STAR detector at RHIC.

A. Search for QGP in $\bar{p}$ -p Collisions at the Tevatron

Fermilab E-735, a Duke-Fermilab-Iowa State-Notre Dame-Purdue-Wisconsin collaboration, is designed to search for the formation of QGP in $\bar{p}$ -p collisions at $\sqrt{s} = 0.3$ -1.8 TeV. The experimental observables are the transverse momenta ($p_t \leq 1.5$ GeV/c) of centrally produced mass-identified particles ($\pi^\pm$, $K^\pm$, $\bar{p}$) as a function of charged particle multiplicity. Some information has also been obtained on photons and on neutral particles that decay to two or more charged particles. Continuing effort has been devoted this past year to the analysis of the data obtained in a year-long experiment performed in 1988-89.

The collaboration has performed an analysis of photons emitted in $\bar{p}$ -p collisions at $\sqrt{s}$ 1.8 TeV. Figure 1 shows a plan view of the detector as configured for the study of inclusive photon production. The detector differs from the normal configuration (1) in that the magnet was turned off, the TOF counters and magnet tracking chambers were removed, and an electromagnetic calorimeter was added. The calorimeter was made from 36 hexagonal NaI (Tl) crystals, 6 in. in diameter and either 10 or 20 radiation lengths deep. The crystals were stacked in a rectangular array 61 cm high and 106 cm wide, located 2 m from the beam line, and subtending the azimuthal interval $1.0^\circ \leq \phi \leq 18.1^\circ$ and the pseudorapidity interval $-0.16 \leq \eta \leq 0.37$. Data were taken

Figure 1. A plan view of the E735 apparatus. ($\bar{P}TH/PTH$: $\bar{p}$ and p trigger hodoscopes, UBH/DBH : upstream and downstream barrel hodoscopes, ECH : endcap hodoscopes, CTC : central tracking chamber, ECC : endcap chambers, VC : vertex chamber, SM : spectrometer magnet, STC : straw tube chambers, NaI : electromagnetic calorimeter).

during a two month period of our run and approximately 1.7 million events were obtained.

The energy deposited in each NaI crystal was determined with the help of a calibration curve and the crystals were clustered into showers. With the aid of a Monte Carlo simulation of the detector response the observed showers were ascribed to photons (47%) or to converted photons, and charged or neutral hadrons. The photon spectrum included additional background from these other sources, which was removed with the help of the simulation and various cuts on the data. A special store, in which some of the p or $\bar{p}$ bunches in the collider were missing, allowed us to estimate the contamination from beam-related background.

Figure 2 displays the inclusive photon differential cross sections between $p_t = 0.03-5$ GeV/c. If a quark-gluon plasma (QGP) is formed, one expects an enhanced yield of soft photons from the bremsstrahlung of quarks accelerating in the color field confining the plasma (2). To search for such an enhancement, it is necessary to determine the photon spectrum expected from the electromagnetic decay of hadrons, which should be the dominant component in the p_t range of interest. We have estimated the photon spectrum expected from the decay of π^0 , η mesons, and sigma hyperons on the basis of our previous measurements of p_t spectra of various hadrons (1,3) and the use of isotopic spin symmetry considerations and several additional assumptions. The curve in Fig. 2, which has been normalized to the number of photons in the data, is the spectrum predicted by the above hadron decay model. The predicted photon spectrum is in good agreement with the data, permitting us to set an upper limit of 15% for any excess contribution of photons with p_t between 30 and 100 MeV/c.

Figure 2. The measured inclusive photon differential cross-section from minimum bias $p\bar{p}$ collisions compared to the prediction of the empirical E-735 model.

Another new result from E-735 obtained this past year is the spectrum of ϕ^0 mesons and its dependence on charged particle multiplicity, N_c . Enhanced production of the ϕ^0 relative to non-strange mesons has been suggested as a possible signature of QGP formation (4).

We analyzed $\sim 10^7$ events obtained in our standard operating mode. The detector differed from that depicted in Fig. 1 in that the NaI calorimeter was replaced by two TOF walls located at 2 and 4 m from the beam line, the spectrometer magnet was turned on, and additional tracking chambers were placed at the entrance and exit of the magnet. The ϕ^0 decays to a $K^\pm$ pair with a mean decay length of only $\sim 10^{-12}$ cm, much smaller than the vertex resolution. Our procedure was therefore based on a search for $K^\pm$ pairs originating at a common vertex, and included a tight vertex cut. Figure 3a shows the invariant K^+K^- mass distribution; the ϕ^0 peak is clearly visible above background. The background was estimated using K^+K^+ and K^-K^- pairs. A polynomial was fit to the background in the region above the ϕ^0 mass peak. The background-subtracted ϕ^0 peak is shown in Fig. 3b and corresponds to 1144 ± 34 ϕ^0 , where the error is statistical.

The ϕ^0 p_t spectrum is displayed in Fig. 4. As for most of the other particles detected in our experiment, the spectrum is exponential. An $e^{-p_t/T}$ fit yields $T = 0.35 \pm 0.11$ GeV, which is comparable to the value from the $\bar{p}$ spectrum. A calculation based on the PYTHIA code (5) is in good agreement with the data, as shown in the figure.

In order to examine the dependence on multiplicity, the data were divided into five multiplicity bins. Values of $\langle p_t \rangle$ were obtained from each of the spectra and the dependence of $\langle p_t \rangle$ on N_c is displayed in Fig. 5a. We observe that $\langle p_t \rangle$ is independent of N_c within the limits of error, a result that is consistent with the very slight increase with N_c predicted by PYTHIA. Since

Fig. 3. (a) Invariant mass distribution of K^+K^- pairs. The dotted line shows the fit to the like sign kaon background. (b) ϕ^0 peak after background subtraction.

Figure 4. Momentum distribution of ϕ^0 . The histogram is from the PYTHIA Monte Carlo.

Figure 5. (a) Average p_t and N_c correlations and histogram obtained from PYTHIA. (b) Ratio of the number of ϕ^0 mesons to the total number of charged tracks per event plotted for regions of charged multiplicity N_c .

we have reported similar results for π^+ , K^+ , and $\bar{p}$ (3), we can determine the ratio of ϕ^0 to charged particles, N_{ch} . The variation of this ratio with N_c is shown in Fig. 5b. The ratio has a constant value of 0.10 ± 0.01 . The lack of an increase at large N_c , where one expects a contribution from the QGP, argues against QGP formation in these collisions.

B. Exclusive Multifragmentation Studies at the Bevalac

The EOS collaboration (Catania-GSI-Kent State-LBL-Purdue-Texas A&M-UC Davis) is working on an exclusive study of heavy ion reactions at the Bevalac using the EOS time projection chamber as the central detector in a multi-detector system. The experiments include studies of flow effects in both symmetric and asymmetric collisions and multifragmentation of heavy projectiles using reverse kinematics, which is the primary interest of our group.

The goal of the multifragmentation experiment is to detect and identify all the charged particles emitted in the breakup of the projectile on an event-by-event basis. As shown by Campi (6), and confirmed by Bauer (7), correlations between various single event moments of the fragment distribution and their scaling with the size of the fragmenting system give significant insight into the nature of the fragmentation mechanism. If multifragmentation is viewed in the context of a critical phase transition, the moments can be used to extract the critical indices and thereby determine the nature of the phase transition (8).

The experiment was performed during three running periods in 1992 terminating in mid-December, just a few weeks before the final shutdown of the Bevalac. The integrated running time was ≈ 15 weeks (≈ 15 shifts/week). Figure 6 shows a lego plot of the number of events accumulated for a particular projectile-target combination at various bombarding energies. The experiments

Figure 6. Lego plot of the number of events recorded for a particular projectile-target combination at a specific beam energy during the 1992 EOS runs.

involving Ca + Be, Ni + Be, Kr + C, La + Be, La + C, and Au + C at an energy of 1 GeV/nucleon provide the main data sets for the multifragmentation study. Approximately 3×10^5 events were written to tape for each of these combinations, which should provide good statistics for the desired analysis. The entire data set occupies ~1000 8 mm tapes with a capacity of 1 Gbyte.

The experimental layout has been described in detail in our last annual progress report (9). Briefly, the charged fragment detection system consists of three main detectors: the EOS time projection chamber (TPC), followed by a multiple sampling ionization chamber (MUSIC II), and followed in turn by a time-of-flight wall (TOF). Under normal operating conditions the TPC can identify fragments with $Z = 1-6$, MUSIC II can identify fragments with $Z \geq 8$ all the way up to at least gold, and TOF is most useful for bridging the gap between the TPC and MUSIC II, although it can detect fragments over a broad range of charges.

Since the end of the run we have begun to analyze the data. We are concentrating on the MUSIC II and TOF detectors, while the TPC data is being analyzed at Berkeley. The initial pass through the MUSIC II data involved the determination of various quantities that are needed for tracking and charge identification, and that can vary from run to run. These include the pedestal values and the electron drift velocity. Algorithms to determine these quantities have been written and a first pass through the data is in progress.

The initial stage of TOF analysis involves calibration of the 98 scintillator slats that comprise the wall. The calibration was provided by sweeps of the various beams across the wall. Figure 7 shows the response of the ADC's to the incident charge for a few typical slats. (Each slat is viewed by two phototubes and the geometric mean of the ADC's is plotted.) The response is linear, as expected for $Z \geq 10$. For lower charges, the ADC response is

Figure 7. Pulse height vs projectile charge for attenuated ADC's in 4 typical slats of the TOF walls.

expected to vary as Z^2 . The calibration at low Z has been checked with a ^4He beam. (The phototube amplitude signals were output to two ADC's: an ADC with an attenuated input for fragments with $Z \geq 10$ and an unattenuated input for fragments with $Z \leq 10$. The data in Fig. 7 are for the attenuated ADC. Analysis of the unattenuated ADC data is in progress.)

The results shown in Fig. 7 cannot be applied directly to data runs because they were obtained for an idealized situation: the beam was swept across the midpoint of the 1 m long slats. In contrast, fragment hits will be scattered over the slats and the output signals will therefore be subject to much larger time slewing. The timing signals from the two phototubes will be used to correct for this effect.

C. Target Fragments from the Interaction of Copper with 90 MeV/nucleon ^6Li Ions

We have previously examined the evolution of the reaction dynamics in the intermediate energy regime by studying the variation with projectile energy between 15 and 90 MeV/nucleon of the mass yield distribution (MYD) and longitudinal velocity transfer (LVT) in the interaction of copper with ^{12}C ions (10-12). In the present work we examine the dependence of these observables on projectile mass by studying target fragments from the interaction of copper with 90 MeV/nucleon ^6Li . The availability of similar data for incident protons, ^3He , and α -particles (13-16) permits us to study the mass dependence of the MYD and LVT over a significant range of projectile masses.

Figure 8 shows our experimental MYD. The distribution exhibits a broad peak at $A \sim 60$ and the yields decrease at lower masses, the decrease being exponential over most of the observed mass region. The MYD curve is compared with similar curves obtained for copper plus ^{12}C and ^{22}Ne in Fig. 9a. Results

Figure 8. Mass yield distribution for the interaction of copper with ${}^6\text{Li}$ ions. The solid curve represents a 3-parameter fit to isobaric yield. The points are experimental yields corrected for unmeasured products at a given mass number. The different symbols reflect the fractional contribution of the experimental cross sections to a given isobar: (•) >50%, (Δ) 20-50%, and (*) <20%. The dashed line is an estimate of the dropoff in yields above $A = 64$.

are shown for 45 MeV/nucleon ^{12}C (11) and 25 MeV/nucleon ^{22}Ne (16), which have comparable total kinetic energy, and for 90 MeV/nucleon ^{12}C (12), with the same energy per nucleon. Although all the curves have similar overall shape, several significant differences between ^6Li and the heavier projectiles may be noted. Thus, the peak in the ^6Li curve is shifted to a larger mass by 3 to 6 mass units. This difference suggests that, at comparable total kinetic energies, preequilibrium emission may be more extensive for the heavier projectiles. Furthermore, the increase in the yields of the lightest products, $A \leq 30$, observed for ^{12}C and ^{22}Ne is not evident for ^6Li , indicating that fragmentation is more important for the heavier projectiles. Figure 9b shows a comparison of the ^6Li mass yield curve with that obtained for lighter projectiles (13,14). All three curves have very similar shape, indicating that ^6Li is more akin to a light than a heavy ion as far as the shape of the mass yield is concerned. Note that differences in total reaction cross section, σ_R , have not been taken into account so that differences in vertical scale are expected.

The longitudinal velocity of the target residue, v_l , expressed as a fraction of the velocity of the putative compound nucleus, v_{CN} , can be obtained from the range data and is plotted in Fig. 10 vs mass loss from the target ΔA . The values of LVT exhibit a nearly linear increase with increasing mass loss terminating in a leveling off for products farthest removed from the target, which has been attributed to central collisions (17). Figure 10 also includes LVT results for both lighter and heavier projectiles (11,12,15). Two important trends may be noted: First, for a given projectile, an increase in energy leads to a marked decrease in the LVT over the entire product range. This trend points both to the increasing dominance of peripheral interactions

Figure 9. Mass yield distribution for the interaction of copper with (a) 90 MeV/nucleon ^{6}Li (—), 45 MeV/nucleon (— • —) and 90 MeV/nucleon (— — — — —) ^{12}C and (• • • • •) 25 MeV/nucleon ^{22}Ne ; (b) 90 MeV/nucleon ^{6}Li (—), 720 MeV α (— — — — —), and 590 MeV protons (— • • —).

Figure 10. Fractional velocity transfer for the interaction of copper with 90 MeV/nucleon ${}^6\text{Li}$ ions vs mass loss from the target, ΔA . The various curves show the trends in similar results for the interaction of copper with ${}^{12}\text{C}$ at 45 (— • • —) and 90 (—) MeV/nucleon, and ${}^3\text{He}$ at 86 (— — —), 117 (— • —), and 303 (— — —) MeV/nucleon.

at higher beam energies and to the greater importance of nucleon-nucleon collisions at higher energies, and thus to increasing transparency (18). Second, for a given energy per nucleon, the LVT decreases with increasing projectile mass. This trend supports previous work showing that light projectiles are more efficient in transferring their momentum than heavier projectiles (12,17,18,19). However, for a given total kinetic energy, the trend is reversed and the LVT now increases with projectile mass, although the variation is smaller than that seen in the comparison for a given energy per nucleon. The above trends are also evident in a comparison of the mean longitudinal momentum transfer.

We have compared our results with the intranuclear cascade-evaporation simulation ISABELLE-EVA (20,21) as well as with the BUU transport equation (22) coupled with the GEMINI deexcitation code (23). The comparisons are shown in Figs. 11-14. The cascade-evaporation model appears to predict the overall shape of the MYD fairly well although several discrepancies may be noted (Fig. 11). Thus for near-target products the calculation overpredicts the cross sections while for the low mass products it underpredicts them. However, the slope of the exponential region of the distribution is adequately reproduced. The underestimation of those products farthest removed from the target is a consequence of binary fragmentation of the target residue, a process that is not incorporated in the evaporation code. The overestimation of the yields of near-target products indicates a problem with the treatment of peripheral interactions, possibly resulting from approximations in the nuclear density distribution in the surface region (20). This model also adequately predicts the shape of the LVT distribution (Fig. 12) although the velocities of near-target products are substantially underestimated.

Figure 11. Comparison of the experimental (curve) and ISABELLE-EVA (O) calculated mass yield distribution for 90 MeV/nucleon ${}^6\text{Li} + \text{Cu}$. The uncertainties in the calculated cross sections reflect the number of events leading to a particular product.

Figure 12. Comparison of the experimental (•) and ISABELLE-EVA calculated (◊) fractional velocity transfers.

Figure 13. Comparison of the experimental (—) and BUU-GEMINI mass yield distribution for (a) an intermediate EOS and $t_{\text{stop}} = 90$ fm/c (— • —) and a soft EOS and $t_{\text{stop}} = 60$ fm/c (•••); (b) a soft EOS (— • —) and stiff EOS (- - - - -) at $t_{\text{stop}} = 90$ fm/c; (c) a soft EOS and $t_{\text{stop}} = 60$ fm/c with the nucleon-nucleon cross sections scaled to $\sigma_{\text{NN}/2}$ (•••••) and $2\sigma_{\text{NN}}$ (—•—•—).

Figure 14. Comparison of the experimental ($\bullet$) and BUU ($\circ$) fractional velocity transfer for (a) an intermediate EOS and $t_{stop} = 90$ fm/c ($\circ$); (b) a soft EOS and $t_{stop} = 60$ fm/c ($\circ$).

The MYD is compared with BUU-GEMINI in Fig. 13. Results are shown for various choices of parameters in the BUU code. None of the calculated curves adequately fit the data. The predicted LVT distribution also has a different shape than the experimental curve (Fig. 14). These discrepancies may reflect the fact that BUU is an ensemble-averaged theory which does not properly include fluctuations (24).

D. R&D for STAR

During the past year, we have been heavily engaged in R&D for the STAR collaboration at the Relativistic Heavy Ion Collider (RHIC). The STAR detector is shown in Fig. 15. The main component is a cylindrical time projection chamber (TPC) with an inner radius of 0.5 m, an outer radius of 2 m, and a length along the beam direction of 4.2 m. The TPC will measure track position and energy loss, dE/dx , for particles emitted in the pseudorapidity interval $|\eta| \leq 1$.

Our R&D efforts have focussed on the expected performance of the TPC. Electrons produced by ionization drift towards the readout endcaps, which are divided into 48 sectors. Owing to the high multiplicity expected in Au + Au collisions at RHIC (~2000 charged particles/interaction) some novel features had to be incorporated into the TPC design in order to ensure adequate two-track resolution. Thus two sizes of pads are planned for the readout sector. The size of these pads is $2.85 \times 11.5 \text{ mm}^2$ for the inner sectors and $6.2 \times 19.5 \text{ mm}^2$ for the outer sectors. While the use of the large-sized pads has become fairly common in TPC's, the small pads have not been used before. In addition, the gap between the anode wires and the pad plane has been reduced from 4 mm for the outer sectors to 2 mm for the inner ones. This new geometry requires extensive testing for gain variation as well as measurements of the

Figure 15. The STAR detector.

pad response function. Our R&D efforts have involved these measurements, including setup of an appropriate test facility.

The tests were performed on a small prototype chamber built at LBL, a top view of which is shown in Fig. 16. Figure 17 is a schematic of the chamber showing the four planes of interest: drift plane/gas window, ground grid, anode/field, and pad plane. The chamber was tested with both a ^{55}Fe radioactive source and a laser. Separate gas windows could be used for these two tests. A three-axis positioning system above the drift plane moved the source or laser in known increments.

The data acquisition system, sketched in Fig. 18, is a copy of the LBL-EOS acquisition system and uses the EOS stick electronics to read out the pads. A SUN Sparc 10 (from the Purdue High-Energy Nuclear Physics group) is used to control data taking, display events, and run auxiliary programs. The signals on the anode wires were read out by use of a multichannel analyzer as well as a digital scope.

The ^{55}Fe source was used to measure the gas gain of the chamber, which has to be uniform throughout the chamber volume for proper functioning. In turn, gas gain depends on such geometrical factors as uniformity in wire placement, wire tension, inter-plane distances, and planarity; the effect of these factors was investigated. For example, Fig. 19 shows the relative gain measured along a particular wire. Measurements of this type for all the wires give a gain variation of $\sim 1.5\%$, well below design tolerance.

The pad response function (PRF) of the TPC pads must be known accurately in order to determine the spatial coordinates of the various hits associated with a particular track. The PRF is mapped out by scanning across a pad in both x and y directions using a focussed laser pulse to generate a localized ionization. The theoretical PRF is shown schematically in Fig. 20. Note that

Mini-Pad Prototype: Cover Removed

Top View

All Dimensions In Inches

Figure 16. Top view of prototype chamber. Note the curved pad rows.

Drift Plane: ◇ For Fe 55 Measurements - Mylar window with conductive TiO on inside

◇ For Laser - Quartz Window with Al coating on inside -250 V

Field Wires: Ground Potential $\phi = 125 \mu\text{m}$, Be-Cu

Anode Wires: +HV, $\phi = 20 \mu\text{m}$, gold-plated tungsten

Pad Plane: 2.85 X 11.5 mm Pad
3.35 mm pitch
Curved Pad Rows

Gas: 90% Ar - 10% Methane

Figure 17. Pictorial view of prototype chamber showing the various planes.

Experimental Set-Up

Figure 18. Schematic diagram of the data acquisition setup.

Figure 19. Relative gain measured at various locations along a particular anode wire.

Figure 20. Theoretical pad response function (PRF) in x and y .

the PRF has steps corresponding to the individual anode wires (4 mm pitch) in the x direction and is Gaussian in y.

Figure 21 shows the result of an x and y laser scan taken at the end of the pad row, where the pads are virtually straight. Observe that the x scan shows the expected step behavior while the y scan demonstrates the (nearly) Gaussian shape of the PRF in this direction. Similar measurements have been made for pads in the curved section of the pad row.

Figure 21. Experimental PRF vs x (top) and y (bottom). The y scan covers 5 pads.

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