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RECENT RESULTS FROM EXPERIMENTS WITH LIGHT IONS AT THE CERN ISR

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RECENT RESULTS FROM EXPERIMENTS WITH LIGHT IONS AT THE CERN ISR

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Recent results from the light-ion runs at the CERN Intersecting Storage Rings (ISR) are shown: the longitudinal momentum distribution of leading protons in aa collisions, the total neutral energy distribution in the central rapidity region, the particle composition at medium-high p_T , and the π^0 yields as a function of p_T , in the central rapidity region.

1. INTRODUCTION

The prediction of the deconfinement phase transition by lattice QCD at finite temperature and the rapid theoretical progress in the last years towards an understanding of the properties of this transition have raised much new interest in experimental investigations of nuclear collisions at very high energy. Even those investigations which were started prior to these new developments are now sometimes subordinated to the key questions: What are the best experimental conditions and what are the signatures for producing a quark-gluon plasma (QGP) in nuclear collisions?

In this review some recent results from the light-ion experiments at the CERN Intersecting Storage Rings (ISR) are reported; these results, although quite heterogeneous at first sight, can indeed be connected by the key questions. Firstly, data are shown on the longitudinal momentum (p_L) distribution of leading protons which can be associated with the transparency or stopping power of nuclear matter. The next results deal with the summed energy (E_{tot}) distribution of produced particles. The third group of data provides information on the particle yield and composition at medium-high transverse momentum (p_T). The first two sets of data contribute partial and complementary answers to the question of best experimental conditions for QGP production as they illustrate quantitatively how the energy of the incoming nucleons is transferred to produced particles. The latter data are relevant to the problem of proving the deconfinement, since changes of particle composition and yield at high p_T are among the expected signatures of QGP formation.

The data shown in this review are partly late results from the first run with alpha particles in 1980, and partly early results from the second and last runs in 1983. The 1983 runs were even more successful with respect to the accelerator performance than the first run. The Proton Synchrotron Booster (PSB) (bypassed in 1980) was used and led to an expected increase of the beam currents by a factor of 3. The maximum currents stored in the ISR were 13 A for the alpha beam and 25 A for the deuteron beam (compared to 40 A peak currents for protons in the last year of ISR life). The initial luminosities were $4 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ for aa (4×10^{28} in 1980) and $4 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ for dd (6×10^{29} in 1977) in normal intersections. The c.m. energy $\sqrt{s_{NN}}$ per nucleon-nucleon collision was chosen to be equal to 31 GeV for aa , ap , and dd collisions.

Five experiments took data simultaneously:

Experiment R110 in Intersection I1 applied single-particle (π^0 , γ), jet, total energy, and pair triggers using electromagnetic calorimeters (Pb-glass and Pb/scintillator-sandwich) covering the central rapidity region $|y| < 1$.

Experiment R210 in I2 measured elastic and inelastic interactions using a non-magnetic detector, in order to obtain the total and elastic cross-sections, multiplicity distributions, inclusive pseudorapidity distributions, and particle correlations.

Experiment R418 measured normal inelastic and high- p_T interactions using the Split-Field Magnet (SFM) detector. The apparatus had been upgraded at small angles with respect to the beams by the addition of two new multiwire proportional chambers and two calorimeters for neutron detection.

Experiment R608 triggered on diffractive and inelastic interactions in order to study the excitation of nucleons (p and n) and of nucleon clusters (p+p, n+p, ...) using the forward double-septum magnetic spectrometer.

Experiments R807 and R808 in I8 applied various calorimeter triggers (single-particle, jet, E_T , electron, and photon), a glueball, and an elastic trigger using the final Axial-Field Spectrometer (AFS) featuring C-type magnet, cylindrical drift chamber, 2π fission-compensated uranium calorimeters, NaI walls, and a muon filter.

Clearly a lot of new data will be added in the near future to the data from the 1980 run. Since most of the results from the previous run have been published by now, this talk focuses on a selection of the latest results.

2. THE STOPPING POWER OF ALPHA PARTICLES

The momentum, energy, or rapidity the incoming nucleons lose during the interaction is often associated with the "stopping power", "transparency", or "opaqueness" of nuclei; these notions are perhaps misleading. The projectile energy goes mainly into pions (by bremsstrahlung, loss of constituents or break-up of colour strings), and only a small portion of the lost energy is absorbed in the target¹.

The main previous experimental data for the momentum distributions of the final state protons in pp and pA collisions at Fermilab, CERN Super Proton Synchrotron (SPS), and ISR energies are briefly summarized in the following three paragraphs.

Erné² has compiled x_F distributions ($x_F = 2p_T/\sqrt{s}$) of protons (antiprotons subtracted) in inelastic pp collisions at different ISR energies and for two values of p_T (see Fig. 1a). One recognizes the tail of the diffraction peak at $x_F = 1$ and an approximately flat distribution from $x_F \approx 0.6$ down to $x_F = 0$.

FIGURE 1a

Inclusive differential cross-section for $pp \rightarrow (p - \bar{p}) + X$ versus x_F for four ISR energies and two values for p_T .

FIGURE 1b

Invariant inclusive cross-sections for $pA \rightarrow pX$ as a function of x_F for various targets, for fixed $p_T = 0.3 \text{ GeV/c}$.

For pA collisions no comparable data were available until recently. Comparing the rapidity (y) or pseudorapidity (η) distributions of all (usually unidentified charged) particles produced in pA with those in pp collisions it was often concluded that nuclear matter is very transparent to the high momentum components of the incoming nucleon. The reason was that particle densities at high y were found to depend only weakly on A . Indeed some experiments³ observed no decrease at high y ; however, others observed a sometimes significant depletion⁴⁻⁶. One has to realize that the high x_F or y part of the distribution depends very critically on the trigger bias, i.e. on how many diffractive or elastic events are contained in the data sample. This may be partly responsible for the discrepancy between different experiments.

In a recent experiment at Fermilab⁷ the x_F distribution of identified protons was measured in pp and pA interactions (see Fig. 1b). Busza and Goldhaber⁸ concluded from these data that the stopping power of nuclei is very large. Extrapolating the observed A dependence they estimated that the median rapidity loss of the incoming proton is -2.4 for a central collision on lead. Weak points of this conclusion are perhaps that it is based on fixed p_T data — the p_T distribution at large x_F depends very likely on A — and that the loss of protons by charge exchange $p \rightarrow n$ may also depend on A .

The p_L distribution of leading protons was measured in $\alpha\alpha$ collisions at the ISR with the SFM detector⁹. This was possible by subtracting negative from positive tracks, assuming the yields of π^+ and π^- , and of created p and $\bar{p}$, are equal and assuming that the difference of K^+ and K^- yields is negligible. Figure 2a shows the fully inclusive distribution of the difference $dn_+/dp_L - dn_-/dp_L$. The peak at 15 GeV/c (equal to the incoming momentum per nucleon, i.e. $x_F = 1$) corresponds to spectator protons and diffractively scattered protons. The small peak at 31 GeV/c contains mostly deuterons (also some alpha particles, because their rigidity p/z is 31 GeV/c) but this second peak does not reflect the real number of d's; d's and alphas are lost in the beam pipe for p_T below 0.2 and 0.4 GeV/c, respectively, and their p_T distribution below this p_T is unknown, so their number cannot be corrected.

FIGURE 2a
Inclusive p_L distribution $\langle Qdn/dp_L \rangle = \langle dn_+/dp_L - dn_-/dp_L \rangle$ (leading protons) in $\alpha\alpha$ interactions⁹.

FIGURE 2b

The p_L distribution of leading protons in $\alpha\alpha$ inelastic interactions for various multiplicity bins. The distributions are shifted upwards by units of 0.1 for increasing multiplicity. The inset shows the frequency of events as a function of the multiplicity n_c of charged vertex tracks in the central rapidity region $|y| < 2$. The integral over each distribution is shown at the right edge—it corresponds to the total positive excess charge seen⁹.

The distribution of leading protons which have interacted inelastically in $\alpha\alpha$ collisions ($p_L < 15$ GeV/c in Fig. 2a) can be *qualitatively* compared with the x_F distribution of leading protons in pp collisions shown in Fig. 1a, although the latter is at fixed p_T and the vertical scales are different.

The assumption of equal π^+ and π^- yields does not hold true for pp interactions [at high x_F the ratio $\sigma(\pi^+)/\sigma(\pi^-)$ increases up to a value of 5]. Therefore a *quantitative* comparison of the p_L distribution in Fig. 2a with pp data taken with the same trigger and the same detector is not possible. However, instead of comparing p_L distributions for different nuclei one can change the nuclear thickness by varying the impact parameter for a fixed nucleus. We assume that varying the multiplicity of produced particles is a way of

achieving this. A priori one expects i) a decrease of the number of spectator or diffractive protons and ii) a shift of the spectrum towards lower p_L as the multiplicity increases. In Fig. 2b the p_L distributions of protons in aa collisions are shown for different bins of the multiplicity n_c of charged vertex tracks in the central rapidity region $|y| < 2$. The second expectation (ii) is clearly satisfied; however, the peak at 15 GeV/c does not show the expected decrease except at the highest n_c . Looking at the integral over the Qdn/dp_L distributions which represents the total number of observed protons (shown at the right edge of the plot) one realizes that towards lower n_c an increasing number of the 4 incoming protons is lost. The possible explanation is that in peripheral (low-multiplicity) interactions protons are carried away by heavier fragments (d, t, ^3He) and are thus lost in the beam pipes.

3. TRANSVERSE ENERGY DISTRIBUTION

Total transverse energy triggers using large solid angle calorimeters have been applied in several recent experiments at Fermilab, SPS, ISR, and the CERN Sp $\bar{p}$ S Collider in order to observe unbiased jets from hard parton scattering events. Only at the highest ISR energy ($\sqrt{s} = 63$ GeV) and at the p $\bar{p}$ Collider ($\sqrt{s} = 540$ GeV) these triggers were a clear success. At lower energy they failed to isolate the wanted events with the properties of hard parton scattering; these events are buried under a background of events with a large number of tracks nearly isotropic in azimuthal angle. However, with respect to the search for the QGP these background events are interesting because they are candidates for high local energy densities or thermalized energy.

In the last light-ion run, R110¹⁰ has measured the total energy (E_{tot}^0) of neutral pions in the central rapidity region ($|y| < 1.1$ for most of the azimuthal angle). Figure 3 shows the distributions for pp, dd, and aa interactions, all at $\sqrt{s_{\text{NN}}} = 31$ GeV. The cross-section falls by 10 orders of magnitude over the measured range in E_{tot}^0 for aa interactions! The integrated luminosities which led to these remarkable plots were $5.3 \times 10^{35} \text{ cm}^{-2}$, $4.2 \times 10^{35} \text{ cm}^{-2}$, and $1 \times 10^{35} \text{ cm}^{-2}$ for pp, dd, and aa respectively.

The curves shown in Fig. 3 correspond to one-, two-, four-, and five-fold convolutions of the E_{tot}^0 distribution for pp collisions. It can be seen that the E_{tot}^0 distribution for dd collisions—only the tail of which had been measured—has the same slope as the two-fold convolution. However, the slope of the E_{tot}^0 distribution for aa collisions at E_{tot}^0 larger than 17 GeV is flatter than the four-fold convolution which corresponds to the superposition of four independent pp collisions. Since four independent nucleon-pair collisions is the maximum possible number of multiplicity-producing collisions in the so-called “wounded nucleon” model, this observation leads to the conclusion that the wounded nucleon model fails at very high E_{tot}^0 . In the framework of “wounded quark” models, where more than one constituent of each nucleon can produce multiplicity in the central rapidity region, the flatter slope at high E_{tot}^0 could presumably be accommodated. For instance, in the additive quark model, the maximum number of convolutions which has to be included in a multiple-inelastic interaction expansion would be 12 (for 3×4 independent quark-quark interactions).

It should be mentioned that the transverse energy E_T distribution of charged particles has been measured previously (in 1980) in the AFS¹¹ for aa and ap collisions. The conclusions then were that these distributions can be quantitatively reproduced by a convolution of the experimental inclusive single-particle p_T distribution and the multiplicity distribution of charged particles. In other words, the information contained in the E_T distribution is equivalent to the combined information contained in p_T and multiplicity distributions.

4. PARTICLE COMPOSITION AT MEDIUM-HIGH p_T

One of the expected signatures for QGP formation is a change of the particle composition; in particular, an increase of the yield of strange hadrons has been predicted¹². Hadrons in the intermediate- p_T range (2–5 GeV/c) are believed by some authors to be evaporated from a hot initial QGP even in pp

FIGURE 3

The total neutral energy spectra for pp, dd, and aa interactions at $\sqrt{s_{NN}} = 31$ GeV. The curves represent the E_{tot}^0 spectra produced by one, two, four, and five simultaneous pp collisions. All curves are normalized to the pp cross-section¹⁰.

collisions at ISR energies¹³ — this view contrasts with the more widely accepted view that one needs heavy nuclei for QGP formation. Nonetheless, the intermediate- p_T range seems to be an interesting place to look for changes of the particle composition as a function of the mass of the incoming nuclei (or of the impact parameter in nucleus-nucleus collisions).

By means of threshold Cherenkov counters the ratio of the yield of heavy particles ($K^\pm + p^\pm$) to pions in pp, dd, and aa collisions at $\sqrt{s_{NN}} = 31$ GeV was determined at the SFM detector in three angular regions: around 45° , 20° , and 10° in the p_T range from 1 to 3.5 GeV/c¹⁴. In Fig. 4a the ratios $R^\pm = [\sigma(p^\pm) + \sigma(K^\pm)]/\sigma(\pi^\pm)$ are shown for a p_T around 2.5 GeV/c. The choice of the horizontal scale $(A^{1/3})^2$ should be

FIGURE 4a

The ratios of the yields $R^{\pm} = \sigma(K^{\pm} + p^{\pm})/\sigma(\pi^{\pm})$ at a p_T around 2.5 GeV/c for pp, dd, and $\alpha\alpha$ collisions for two polar angles $\vartheta_{cm} = 45^{\circ}$ and $\vartheta_{cm} = 20^{\circ}$ as a function of $A^{2/3}$.

FIGURE 4b

The same ratios as in the previous figure for pA collisions ($E_{lab} = 400$ GeV, $p_T = 3.08$ GeV/c, $\vartheta_{cm} = 90^{\circ}$) versus $A^{1/3}$.

FIGURE 4c

The $K^{\pm}/\pi^{\pm}$, p/π^{+} , and $\bar{p}/\pi^{-}$ ratios for pp and pW interactions as a function of p_T .

considered as arbitrary. One observes a significant rise of the positive ratio R^+ at both angles; the negative ratio is constant within error bars for $\theta = 45^\circ$ and it rises at $\theta = 20^\circ$ from dd to aa. It is evident that the ratios depend also very strongly on the polar angle θ in all cases.

A theoretical explanation for these interesting strong changes of the particle ratios, which had already been indicated in the 1980 run¹⁵, is not available at present. Unfortunately, the experiment did not distinguish between (anti)protons and kaons. However, a comparison with pA data from Fermilab¹⁶ suggests that the observed rise of the positive ratio is mainly due to the fast increase of the proton yield at $p_T > 2 \text{ GeV/c}$ as a function of the mass number A. This is illustrated by Fig. 4b which shows the corresponding ratios as a function of $A^{1/3}$ for the data from the Fermilab experiment, and by Fig. 4c which shows the K/π and p/π ratios separately, for pp and pW interactions; clearly the increase of R^+ with A can be related to the very strong increase of the measured p/π^+ ratio. The $K^\pm/\pi^\pm$ ratios increase much more weakly with A and the $\bar{p}/\pi^-$ ratio is very small.

At the AFS the K/π ratio has been measured at lower p_T in aa collisions as a function of the multiplicity¹⁷. This ratio does not show any change for increasing multiplicity and it is equal to the ratio in pp interactions.

5. HADRON YIELD AT HIGH p_T

In the previous aa and ap runs in 1980, four experimental teams measured the inclusive cross-section of charged hadron and π^0 production in the central rapidity region as a function of p_T ¹⁸. The ratio of the

FIGURE 5

Ratio of inclusive cross-sections as a function of p_T . a) $R_{p_T}(ap/pp)$: the dashed line is an extrapolation from the measurement by the CP Collaboration¹⁶. b) $R_{p_T}(aa/pp)$: the dashed line is a prediction by Sukhatme and Wilk²⁰, the dotted line is one by Stasz and Wilk²¹. Old data from 4 experiments¹⁸ and new data from R808²².

measured cross-section with the corresponding cross-sections in pp interactions (at the same $\sqrt{s_{NN}}$ per nucleon-nucleon collision),

$$R_{p_T}(aa/pp) = [d\sigma(aa \rightarrow h)/dp_T^2]/[d\sigma(pp \rightarrow h)/dp_T^2],$$

showed a significant p_T dependence. For ap interactions the trend was less clear (see Fig. 5). An interpolation of the A dependence observed in the well-known Chicago-Princeton experiment¹⁶ at Fermilab was consistent with the ap data for p_T below 5 GeV/c (if one assumes energy independence of the effect)¹⁹; and a theoretical extrapolation to nucleus-nucleus interactions assuming multiple hard parton scattering as the cause for the A dependence observed in pA interactions was consistent with the p_T dependence measured in the aa interactions below 5 GeV/c²⁰.

However, above $p_T = 5$ GeV/c the ratio $R_{p_T}(ap/pp)$ was lower by about 20% than expected and $R_{p_T}(aa/pp)$ continued rising. [One has to keep in mind that the level of the ratios has an uncertainty of the order of 10% due to the uncertainty of the luminosity measurement, and that the rapidity ranges for ap and pp interactions were not equal owing to the asymmetric beam momenta in the former case]. Soon, calculations were published explaining the rise for aa interactions above $p_T = 5$ GeV/c in a model which includes multiple parton scattering and large momentum tails of the nucleons within the nucleus²¹. Despite this theoretical success, a confirmation of the experimental data seemed desirable.

The first data²² from the new run, obtained by experiment R807/808 (AFS Collaboration) are shown in Fig. 6 together with the old data and the mentioned calculations. It can be seen that only the data point at the highest p_T (5.5 GeV/c) disagrees with the old π^0 data of R110. It seems that a convincing confirmation or rejection of the previous results has to await further data.

6. OUTLOOK

In the near future, certainly many more results will be available from the past light-ion runs at the ISR, in addition to those shown in this talk and to older published results which have been reviewed recently¹⁹.

Meanwhile several Collaborations are preparing a new round of experiments at CERN requesting oxygen beams from the SPS. The first proposal by a GSI-LBL Collaboration intended to study strangeness production using a streamer chamber, and the target fragmentation using the plastic-ball detector, presently operating at the Bevatron (LBL), at the CERN Proton Synchrotron. GSI and LBL will provide the ion source and the pre-acceleration stage (an RFQ). Five more proposals have been submitted since then; their physics goals are measurement of strangeness production, of lepton and lepton-pair production, and of many other characteristics of oxygen-nucleus interactions. Except for the first one which has been approved the decision on all these proposals is pending. But clearly the unprecedented number of proposed experiments using high-energy ions at CERN reflects a very strong new interest in this kind of physics.

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