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VOLUME AND TEMPERATURE IN αp AND $\alpha\alpha$ COLLISIONS AT VERY HIGH ENERGY

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VOLUME AND TEMPERATURE IN αp AND $\alpha\alpha$ COLLISIONS AT VERY HIGH ENERGY

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Abstract: Two special runs with α particles in the CERN Intersecting Storage Rings allowed the study of collisions of nuclei at the highest accelerator energies. The data obtained simultaneously by five experiments give an impression of the richness of this novel field. Results for elastic αp and $\alpha\alpha$ scattering, for quasi-elastic interactions of nucleons, for hard scattering of constituents of nucleons, and for inelastic interactions are reported. The relevance of interaction volume and temperature is discussed. The modest increase of complexity of their interactions as compared to pp interactions compensates the small size of ^4He nuclei. Collisions of ultrarelativistic light nuclei may thus provide a bridge between the well-explored field of high-energy pp collisions and the unexplored field of high-energy nucleus-nucleus collisions.

1. Introduction

Two years ago two exceptional runs took place at the CERN Intersecting Storage Rings (ISR). Beams of α particles were stored for the first time. In the first run, two α beams circulated for 60 h and collided at a c.m. energy of 125 GeV in the intersections of the rings. In the second run of 60 h an α beam (momentum 63 GeV/c) in one ring collided with a proton beam (momentum 31.7 GeV/c) in the other ring at a c.m. energy of 88 GeV. These c.m. energies represent world-record energies at accelerators for collisions of nuclei.

In four intersection regions the detectors were switched on for data taking. They were very sophisticated and powerful second or later generation detectors which have been developed during 10 years of pp experiments at the ISR. Since, in addition, the beam luminosities were very satisfying, it was possible to obtain a large variety of data during the relatively short α runs. What were the physics goals for these unusual runs?

Our primary goal was to investigate various phenomena of the strong interaction with the help of nuclei. The nucleus serves as the microlaboratory to induce multiple interactions of nucleons or constituents of nucleons within very short space- and time-intervals. The most essential property of the nucleus for this purpose is the high density of nuclear matter. However, it should be mentioned that some of our results -- like the differential elastic cross-section -- also reveal great sensitivity to details of the ^4He wave function.

Results have been obtained for elastic scattering; for quasi-elastic scattering of nucleons or larger constituents of the nucleus; for production of particles with large transverse momenta -- this phenomenon is commonly understood as hard scattering of constituents of nucleons ("partons"); and for normal "soft" inelastic interactions. Since I have to discuss widely differing processes when presenting the results I will use the relevant interaction volumes as a guideline.

Thermodynamic concepts were applied in the very first¹⁾ and in later²⁾ attempts to describe the strong interaction at high energy. ("High energies" are defined here as energies far above the threshold for pion production, i.e. incoming energies higher than about 10 GeV.) The thermodynamic language has recently regained popularity in the widely-explored field of heavy-ion collisions at incoming energies of a few GeV per nucleon³⁾ and more recently in the -- only theoretically explored -- field of high-energy heavy-ion collisions⁴⁾. For some cases I will extract a "temperature" from our data, but will not attempt to interpret the results systematically in thermodynamic terms.

2. Experimental technique and data taking

One example for the three large solid-angle detectors which were operating during the α runs is shown in fig. 1. This is called the Split-Field Magnet (SFM) detector. It consists of a magnet which produces fields of opposite directions on both sides of the beam intersection. The maximum magnetic field is 1 T and the useful magnetic volume is 30 m³. This volume is filled with planar multiwire proportional chambers. The total number of sensitive wires is 70,000, of the same order of magnitude as the number of sensory cells in the human ear. As for the human ear, pattern recognition is one of the major problems to solve; it has been solved for the SFM detector during its 10 years of history.

The following numbers may serve to illustrate the conditions of the data taking and the data analysis. The rates of $\alpha\alpha$ (αp) interactions "seen" by the detector were 7,500 (80,000) per second, corresponding to luminosities of 3×10^{28} (8×10^{29}) cm⁻² s⁻¹ and visible cross-sections of 250 (100) mb. For minimum-bias triggers, which are mostly inelastic events, the data-acquisition speed is of the order of 20 events per second (the average number of 16-bit words per event recorded on tape amounts to about 3,000). Thus a tape with 30,000 minimum-bias events is written in 25 minutes and corresponds to only a few seconds (or less for αp) of open detector time. A million minimum-bias events were written on tapes in a small fraction of the available beam time. The largest part of the beam hours was spent triggering simultaneously on rare events or events for which the detector efficiency is small, such as elastic scattering, nuclear break-up of the α particle without pion production, or large- p_T inelastic interactions.

It takes 10 s of computer time (IBM 168) to reconstruct one inelastic $\alpha\alpha$ event (with, on the average, 10 charged particles) and 30 s to reconstruct a large- p_T $\alpha\alpha$ event (average 20 tracks). Therefore only a limited number (about 100,000 in total) of minimum-bias events could be reconstructed, given the limited number of available computer hours. Samples of rare triggers, such as elastic or pure nuclear break-up triggers or events with a trigger particle having large transverse momentum, have been reconstructed completely; here we were limited by the number of beam hours.

3. Elastic nuclear scattering

The gross structure of the differential elastic scattering cross-section of hadrons and nuclei reflects the size of the interaction region. According to the geometrical scaling law⁵⁾ the slope and height of the diffraction cone (momentum transfers above the Coulomb region and up to the first diffraction minimum) can be deduced from the effective radius of the interaction.

Various models have been proposed to explain the structure of the elastic hadron-nucleon cross-sections at higher momentum transfers (beyond the first diffraction minimum), but the gold-plated final theory has not yet been arrived at⁶⁾. The analogous structures in the case of pA or AA collisions, where A is a light nucleus, have been most convincingly explained by the Glauber model as a consequence of interference between single- and multiple-scattering terms of the constituents of A -- the nucleons. Thus, for instance, the first diffraction minimum results from the destructive interference between the single- and the double-scattering amplitude⁷⁾.

Figure 2 shows the elastic-scattering cross-section as a function of the Mandelstam variable t , the invariant four-momentum transfer squared in (GeV/c)². The data are from two experiments; the points below and up to about the diffraction minimum were obtained by the CERN-MIT-Naples-Pisa-Stony Brook Collaboration⁸⁾ with a non-magnetic detector in intersection 2, and the points above the first dip were obtained by the CERN-Heidelberg-Lund Collaboration with the SFM detector⁹⁾. The curves are calculations by Proriot et al.¹⁰⁾. The dashed line corresponds to a pure Glauber-model calculation with an effective radius of 1.66 fm. The continuous line includes a correction for intermediate inelastic states in the double-scattering term. Such a correction is believed by many authors¹¹⁾ to be necessary

Fig. 1 An artist's view of the Split-Field Magnet (SFM) detector. The upper iron yoke and part of the multiwire proportional chamber are removed.

Fig. 2 Differential elastic αp (a) and $\alpha\alpha$ (b) cross-sections. Data from experiments R210 (ref. 8) and R418 (ref. 9) and calculations from refs. 10 and 12.

at high energies. In between two scatterings the proton may get excited as long as it returns to the ground state before it leaves the nucleus and if the nucleus is not destroyed by the momentum transfer needed to excite the proton. This process increases the double-scattering amplitude, which has a negative sign, and hence the cross-section in the region dominated by double-elastic scattering [$0.2 < -t < 0.8$ (GeV/c)²] is expected to decrease.

The correction just described seems, at a first glance, like an unwanted complication arising from the use of nuclear targets. Taking a second look one learns that the nucleus reveals the complicated structure of the projectile. The intermediate states are quantum fluctuations of the projectile, identical to the ones leading also to diffractive dissociations. As intermediate inelastic states they are "prepared" in quite a specific way. Thus one has an independent test for models of the diffractive dissociation⁶⁾.

Unfortunately, the precision of the data and the general agreement with the calculations are not good enough to decide between the two calculations which differ only by about 20% (fig. 2a).

The results from the two experiments^{8,9)} for the $\alpha\alpha$ elastic cross-section are shown in fig. 2b. Again, two Glauber-model calculations are shown, one without, the other one with intermediate inelastic states¹²⁾. Here the latter correction is large in the region above the second diffraction minimum, but unfortunately the disagreement between the two experiments in the overlap region is so large that it prevents us from drawing any firm conclusions until it is decided which data are correct. Assuming that above 0.2 (GeV/c)² the SFM data are correct, the comparison with the calculation would tell us that indeed inelastic intermediate states are needed in $\alpha\alpha$ elastic scattering.

4. Quasi-elastic scattering of the nucleons

In the Glauber model, elastic interactions of nuclei are expressed in terms of single or multiple elastic and even inelastic interactions of nucleons where, at the end, target and projectile emerge in their ground state. Next we consider quasi-elastic interactions of nucleons which leave the nucleons in their ground state but break up the α particle. With the SFM detector charged nuclear fragments p, d, t, and ³He can be distinguished by their energy loss measured in a scintillation counter and by their total momentum. The trigger required 1 or 2 high-momentum charged tracks on either side of the intersection and vetoed on low-momentum particles, which are mostly pions. Most of the events are incomplete owing to the acceptance hole at small angles (< 7 mrad) caused by the beam tube and because neutrons were not detected at all. But the inclusive distribution, i.e. the momentum spectrum of a specific fragment (p or d, etc.), regardless of the other emitted particles, already contains some valuable information.

The fragments are either spectators or participants -- in the latter case they acquire a momentum kick in addition to the Fermi motion. It can be shown¹³⁾ that the inclusive distribution of fragments in the longitudinal momentum p_L (component parallel to the incoming beams) reflects mainly the Fermi motion, whereas the distribution in transverse momentum (p_T) contains information on both Fermi motion and quasi-elastic momentum transfer. In fig. 3 the p_L and p_T distributions are shown for proton and deuteron fragments in the rest system of the incoming α particle. Indeed, the width of the p_L distribution is consistent with Fermi motion for protons ($\sigma_p \approx 110$ MeV/c); for deuterons it is higher than expected in a simple model¹⁴⁾ ($\sigma_d \approx 180$ MeV/c). We assume that this is a consequence of our p_T cut which is $p_T > 0.2$ GeV/c for deuterons. The tail of the proton distribution at the negative p_L side is likely due to inelastic channels where the produced particle (e.g. a π^0) was not detected; both distributions are centred at slightly negative values of p_L , i.e. the fragments are decelerated. This shift can probably be explained by the negative Q-value of the reaction and by the finite p_T of the observed fragments. The p_T distributions, shown in fig. 3b have larger widths ($\sigma \approx 250$ MeV/c for protons and ≈ 230 MeV/c for deuterons) in agreement with the qualitative expectation that the recoil from quasi-elastic scattering should show up in the p_T rather than in the p_L distribution.

Fig. 3 a) Longitudinal and b) transverse momentum distribution of proton and deuteron fragments in α break-up reactions. The longitudinal momentum is given in the rest system of the incoming α particle. Preliminary data from the SFM detector (CERN-Heidelberg-Lund Collaboration).

Fig. 4 Inclusive t -distribution of the scattered beam proton in $p\alpha$ break-up reactions compared with the slope for elastic pp collisions. Preliminary data of the CERN-Heidelberg-Lund Collaboration.

The inclusive t distribution ($t \approx p_T^2$) of the proton in $p\alpha$ elastic and nuclear break-up reactions is expected to reflect all processes from elastic $p\alpha$, quasi-elastic $p^3\text{He}$, pt , pd to pn and pp reactions, each process having a characteristic slope in t . Figure 4 shows the inclusive p_T distribution of the observed scattered beam proton in the $p\alpha$ fragmentation trigger. This trigger is not "fully inclusive" owing to the acceptance hole at small angles and the requirement of detecting at least one charged particle at each side. The fact that the slope $b = -7.8 \text{ (GeV/c)}^{-1}$ is close to the elastic pp slope tells us that quasi-elastic nucleon-nucleon (NN) collisions represent the dominant part of our fragmentation trigger. This observation was confirmed by a study of exclusive channels such as $p\alpha \rightarrow ppt$. Unfortunately, only few events of the exclusive type, which would be very interesting for more detailed investigations, have been obtained in the short α runs.

5. Hard scattering of constituents of nucleons

5.1 ANALOGY WITH NUCLEAR BREAK-UP

Trying to draw on analogies between the behaviour of nucleons as constituents of the nucleus and of partons as constituents of the nucleons is a major challenge. The problem is the confinement of the partons. We can only observe hadrons which are mostly decay products of other hadrons (resonances), which in turn are "fragments" or (re)combinations of partons. Nevertheless, there are valuable analogies. Recall from the previous section that the inclusive p_L distribution of nuclear fragments reflects their Fermi motion, whereas the p_T distribution measures the (additional) momentum transfer to the fragment. Since this is partly a simple consequence of relativistic kinematics, it is still true to some extent on the level of partons. The inclusive p_T distribution of hadrons is believed to be closely related to the intrinsic parton (quark) momentum distribution, at least at high values of the Feynman variable ($x_F = p_L^{\text{cm}}/p_{\text{inc}}^{\text{cm}} \geq 0.2$). On the other hand, the inclusive p_T distribution of hadrons reveals information on the momentum transfer to partons.

5.2 PRODUCTION OF PARTICLES WITH LARGE p_T

A large momentum transfer is a necessary condition for the interaction to be localized to a small volume. One may define "high p_T " such that the corresponding dimension is much smaller than the nucleon diameter, say by a factor of 10; thus one considers $p_T \geq 2 \text{ GeV/c} = 10\hbar/R_N$ as "high p_T ". Numerous experiments have strengthened the belief that the basic subprocess underlying events with high- p_T hadrons is hard, large-angle scattering of small constituents (i.e. the partons) followed by the fragmentation or recombination of the partons into hadrons.

Such processes are quite rare. This is demonstrated in Fig. 5a, which shows the inclusive invariant cross-sections $E d^3\sigma/dp^3$ for $\alpha\alpha \rightarrow h^-$ ^{15,16}, $\alpha\alpha \rightarrow \pi^0$ ¹⁷, and $pp \rightarrow h^-$ ^{16,18} as a function of p_T at fixed rapidities (or fixed polar angles $\theta_{\text{cm}} \approx 50^\circ$ and $\theta_{\text{cm}} = 90^\circ$ with respect to one of the incoming beams) and at equal c.m. energies $\sqrt{s_{\text{NN}}} = 31.5$ per nucleon-nucleon collision. Negative hadrons (h^-) at large p_T are mostly (about 70%) π^- . The p_T ranges from 0.2 to 5 GeV/c; the cross-section falls by 9 orders of magnitude.

Let us first consider the features common to the $\alpha\alpha$ and pp inclusive cross-section. For p_T up to about 1 GeV/c the invariant cross-section in pp collisions was found to decrease rapidly with increasing p_T ; the dependence is exponential with a slope $B \approx -6 \text{ (GeV/c)}^{-1}$ and does not depend on the incoming energy from 10 to 2000 GeV (on a fixed target). This feature of "limited transverse momentum" of the bulk of produced particles has been explained by the existence of a limited temperature equal to about the pion mass

$$T_{\text{max}} \approx \frac{C}{B} \approx m_\pi \text{ } ^2).$$

Obviously, above $p_T \approx 1 \text{ GeV/c}$ the shape of the cross-section changes, and at 3 GeV/c the yield of pions is more than a factor of 10 higher than expected by extrapolation of the low- p_T data (see fig. 5a); this deviation from the e^{-6p_T}

Fig. 5 a) Inclusive invariant cross-section for negative hadron and π^0 production in $\alpha\alpha$ collisions compared with pp collisions as a function of the transverse momentum p_T . b) Ratio of the negative hadron or π^0 yield in $\alpha\alpha$ interactions to that in pp interactions as a function of p_T . The curve is a prediction (ref. 28).

Fig. 6 a) Hard scattering of two partons out of two incoming protons. This process leads (ideally) to two large- p_T jets (trigger- and away-jet) in addition to two spectator-jets. b) Double hard scattering of one parton from an incoming proton on two partons from different nucleons N_1, N_2 . As a result two away-jets are expected.

dependence depends on the incoming energy as it is most dramatically demonstrated by the recent data from the CERN $\bar{p}p$ collider at c.m. energy $\sqrt{s} = 540 \text{ GeV}$ ¹⁹⁾. The discovery of this phenomenon, first made at the ISR ²⁰⁾, supported the evidence for a substructure of the nucleons and demonstrated that point-like partons ²¹⁾ act also in the strong interaction. Such a conclusion is analogous to the one by Rutherford on the existence of a "point-like" nucleus in the atom when he first observed larger-than-expected momentum transfers for scattered α particles.

5.3 TEMPERATURE VERSUS DIRECT PARTON-PARTON SCATTERING

Some authors explain the decreasing exponential slope as an indication of the occurrence of higher temperatures. They assume that hadrons with high p_T result from partons (quarks or gluons) emitted directly from a hot plasma, which was formed in the initial state of the collision, whereas the low- p_T hadrons are emitted after the plasma expanded and cooled down to the temperature $T = T_{\text{max}}$ at which partons turn into hadrons by condensation ²²⁾. Unfortunately, none of these thermodynamic models predicts more than the inclusive single-particle distribution. On the other hand, parton models which assume a direct parton-parton collision as a basic subprocess have led to a wide range of predictions which can be tested experimentally ²³⁾. These models are today incorporated into QCD and the mentioned predictions belong to a rich field of present high-energy physics which one may call "jetology". The basic rules of this game are easily understood. High-momentum partons, which are confined and hence not directly observable, decay into jets of hadrons. Thus, for instance, the hard scattering of a pair of partons out of two incoming nucleons results in four jets: two jets from the scattered partons and two jets from the spectator-partons (see fig. 6a). The jetology consists of establishing the existence and properties of the jets and of measuring correlations between jets.

5.4 LARGE- p_T HADRON PRODUCTION FROM NUCLEI

So far we have dealt with the interpretation of the inclusive p_T spectrum common to pp , αp , and $\alpha\alpha$ interactions. Next we shall look for differences. But let me first explain the origin of a prejudice as to what differences could be expected. The cross-section for scattering of a parton to large p_T is orders of magnitude lower than the total pp cross-section. That is to say the mean free path λ_{p_T} in nuclear matter is much larger than the thickness of hadrons or even nuclei. Pictorially speaking, for hard interactions of partons the two incoming nucleons behave like very rarefied gases of point-like partons. The probability P_0 for no such interaction to occur when the two gases penetrate each other is close to 100%, for one interaction (P_1) it is very small and for two or more ($P_{>1}$) it is negligible. Now adding more nucleons (volumes of parton gases of the same density) on either side would just multiply P_1 by the number of nucleons, but $P_{>1}$ would still be negligible.

Systematic measurements of large- p_T particle production from various nuclear targets, done some years ago at Fermilab, have revealed the prejudice as such ²⁴⁾. At p_T larger than about 2 GeV/c the yield of hadrons grows faster than linear with the nucleon number A . A similar, or perhaps the same, phenomenon has also been found comparing yields in $\alpha\alpha$ with those in pp interactions. The ratio of the inclusive cross-sections as a function of p_T

$$R_{p_T} \left(\frac{\alpha\alpha}{pp} \right) = \frac{d^3\sigma(\alpha\alpha)/dp^3}{d^3\sigma(pp)/dp^3}$$

is shown in fig. 5b. Here the data from four different experiments are compiled ^{15-17, 25)}. According to the prejudice which I tried to make plausible, the ratio $R_{p_T}(\alpha\alpha/pp)$ should be 16 at high p_T . It can be seen that it is higher than 16 at high p_T . Why is the expectation wrong?

5.5 THE POSSIBILITY OF MULTIPLE HARD PARTON SCATTERING

When we concluded in the previous subsection that $P_{>1}$ should be negligible, we forgot that the p_T distribution is rapidly falling with increasing p_T and that

physics on a steep slope often provides for surprises. I quote, in the following, an argument in slightly modified form, which was given by Jacob²⁶). The cross-section for a large- p_T scattering of a parton is $\sigma_0 R / \lambda_{pT}$, where σ_0 is the geometrical cross-section of the target, $R = r_0 A^{1/3}$ is the thickness of the target nucleus and λ_{pT} is the absorption length or mean free path in nuclear matter λ_{pT} . We assume for simplicity that the problem is one-dimensional, such that for double scattering the p_T add. Then the cross-section for a double scattering of the kind $(p_T/2 + p_T/2 \rightarrow p_T)$ is $[(\sigma_0/2)(R/\lambda(p_T/2))]^2$. We know λ_{pT} is rapidly increasing with p_T ; let us assume it increases as a power law p_T^N with $N=8$. Then $\lambda(p_T/2)/\lambda_{pT} = 2^8$. Therefore the ratio of the double to single scattering probability is

$$P_2/P_1 = 128 r_0 A^{1/3} / \lambda(p_T/2) .$$

Qualitatively, this estimate yields two results: the probability for double scattering is not negligible in the high- p_T region; it increases with $A^{1/3}$ and it vanishes with increasing p_T as $\lambda(p_T/2)$ increases.

More quantitative calculations have been performed, making it plausible that multiple hard parton scattering is at the origin of the enhanced yield at high p_T from nuclear targets²⁷). One such calculation is shown in fig. 5b²⁸). However, noticing that the data at the highest p_T are significantly higher than the calculation, one may wonder whether another mechanism is at work in $\alpha\alpha$ interactions. The decision should be done on the basis of jetologic studies. Although the three large solid-angle detectors at the ISR are specifically designed and tuned for such investigations and much work has already been done^{16,26,29,30}), I will only sketch the idea of one of these studies because the studies have not yet led to a firm conclusion on the mechanism causing the enhanced high- p_T particle yield from nuclei. If parton rescattering plays a role in large- p_T hadron production from nuclei, then one expects to see sometimes two jets instead of one on the side opposite to the trigger jet (fig. 6b). The analysis has, however, shown that the spectrum of particles recoiling against the trigger particle is within statistical errors identical in hard $\alpha\alpha$, αp , and pp interactions^{16,30}). One amusing conclusion from such an identity, if it were confirmed with higher precision, is that perhaps double scattering already plays an important role in hard pp interactions in the p_T range above 2 GeV/c.

6. Inelastic interactions

The progression from elastic nuclear interactions via quasi-elastic interactions of nucleons to hard scattering of partons and finally to this section calls for a definition of what is meant by "inelastic". Obviously the answer is: all that which is not (quasi-)elastic in the sense of the previous sections, i.e. those interactions where particles (mainly pions) are produced with only small transverse momenta -- the normal, "soft" inelastic interactions which are the most frequent of all high-energy hadron interactions. The average number of produced charged particles being 7.1 ± 0.2 and 8.6 ± 0.2 for pp interactions at $\sqrt{s} = 31$ and 44 GeV, is 12.5 ± 0.3 and 10.5 ± 0.3 for $\alpha\alpha$ and αp interactions, respectively (SFM results).

When one studies inelastic interactions of nuclei, the main goal is, of course, to find properties which cannot be trivially explained by a superposition of NN interactions, or to measure quantities which can serve to discriminate between different models for multiple NN interactions within very short space-time intervals. Predictions and experimental studies have so far focused on the gross properties of these interactions -- such as the multiplicity distribution of particles produced, the inclusive single-particle distribution in longitudinal phase space (rapidity y or longitudinal momentum p_L), inclusive two-particle correlations³¹), or correlations between forward-going and centrally-produced particles³¹). However, in this section we will confine ourselves to some aspects which can be related to temperature and volume of the interaction, and we will simply look whether we find any differences in pp , $p\alpha$, and $\alpha\alpha$ collisions for these two global properties.

Fig. 7 Average transverse momentum $\langle p_T \rangle$ of charged particles in the central rapidity region as a function of their number per unit rapidity. Comparison of $\alpha\alpha$ data at $\sqrt{s} = 125$ GeV and pp data at $\sqrt{s} = 63$ GeV with $\bar{p}p$ data at $\sqrt{s} = 540$ GeV.

6.1 TEMPERATURE AS A FUNCTION OF THE FINAL-STATE MULTIPLICITY

We mentioned already in the previous section the interpretation of the inclusive p_T spectrum at low p_T by a temperature $T_{\max} \sim (\text{slope})^{-1}$. This temperature represents the average over all events since it was obtained from the fully inclusive p_T distribution. We can ask the question whether the temperature changes for increasing multiplicity of produced particles. Higher multiplicity is related to higher entropy¹⁾ and, intuitively, to more central collisions (small impact parameter). In central collisions higher energy densities of the initial plasma are reached³³⁾ and hence higher initial temperatures are expected. An experimental investigation on the multiplicity dependence of the p_T distribution led to a negative result³⁴⁾. It was found that in the p_T range from 0.2 to 2.0 GeV/c the distribution scales with the total multiplicity for $\alpha\alpha$ at $\sqrt{s} = 125$ GeV as well as for pp interactions at $\sqrt{s} = 63$ GeV. The interpretation of this result seemed obvious: What we measure is the temperature of the pions at the time they are emitted, i.e. after the plasma has cooled down to the "condensation" temperature $T_{\max}$. However, very recently an interesting experimental fact has been added. At the CERN $p\bar{p}$ collider, at $\sqrt{s} = 540$ GeV, a significant dependence of the average $\langle p_T \rangle_n$ on the final-state multiplicity was found³⁵⁾. In fig. 7 we compare our result for $\alpha\alpha$ and pp collisions with their data in a plot $\langle p_T \rangle_n$ versus particle density per unit rapidity y in the central region. [Particles with absolute rapidities $|y| = \text{tgh}^{-1}(|v/c|)$ lower by about 1.5 units than the beam rapidities $|y_{\text{inc}}|$ (in the c.m.s.) are defined as central.] The absolute values of our $\langle p_T \rangle$ may have a systematic error; $\langle p_T'' \rangle$ was defined as $\langle p_T'' \rangle = 2/B$, where the slope B was fitted in the range 0.3 to 1.6 GeV/c; however, the information on the multiplicity dependence of $\langle p_T'' \rangle$ is quite reliable. For $\alpha\alpha$ at 125 GeV and pp collisions at 63 GeV $\langle p_T'' \rangle$ is equal and independent of the multiplicity. It will be interesting to learn how the drastic change of the multiplicity dependence with incoming energy will be explained; presumably the explanation will be connected with the change of the general shape of the p_T distribution³⁵⁾; the flatter (non- e^{-6p_T}) component increases and seems dominant even for $p_T < 2$ GeV/c at $\sqrt{s} = 540$ GeV.

6.2 FLUCTUATIONS OF THE "EVENT TEMPERATURE"

After first obtaining a temperature for the average inelastic event and then comparing temperatures for event samples with different multiplicity, we can now go a step further and define a temperature for each event by calculating the average transverse momentum $\bar{p}_T$ of all particles in the final state. Clearly, such a definition becomes more meaningful the more particles are produced in one event. The "event temperature" will fluctuate for purely statistical reasons since the multiplicity of produced particles is finite. But in addition to these trivial fluctuations there may be physical fluctuations of the event temperature. One can measure the latter by going to the limit of infinitely large multiplicity. The dispersion D_n of the event temperature at fixed particle multiplicity in the central region [$x_F = p_L/(p_L)_{\max} < 0.3$] is defined by

$$D_n^2 = \langle \bar{p}_T^2 \rangle_n - \langle \bar{p}_T \rangle_n^2,$$

where the brackets " $\langle \rangle$ " mean averaging over all events with fixed n .

Figure 8 shows the dependence of $R_n^2 = (D_n/\langle p_T \rangle_n)^2$ on $1/n$. The limit of this quantity for $1/n \rightarrow 0$ is finite, and this limit has to be interpreted as a measure for the physical fluctuations of the event temperature. In fig. 9 the normalized dispersion R_∞ as obtained by extrapolation to $n \rightarrow \infty$ is plotted for αp and $\alpha\alpha$ interactions as a function of the c.m. energy $\sqrt{s_{NN}}$ per nucleon-nucleon collision and compared with pp data³⁶⁾ at the same energy. The values of R are smaller for αp and $\alpha\alpha$ than for pp, whereas the average $\langle p_T \rangle$, as we have seen before, is the same. The decrease of the event temperature fluctuation in αp and $\alpha\alpha$ collisions can perhaps be qualitatively explained by multiple nucleon-nucleon (NN) collisions. In one $p\alpha$ or $\alpha\alpha$ event on the average about 1.2 or 1.7 NN collisions take place, respectively. This implies that the event is a mixture or average over different

Fig. 8 Normalized dispersion squared $R_n^2 = (D_n / \langle \bar{p}_T \rangle_n)^2$ as a function of the reciprocal multiplicity $1/n$ for $\alpha\alpha$ collisions at $\sqrt{s} = 125 \text{ GeV}$.

Fig. 9 Normalized dispersion R_∞ for $\alpha\alpha$ and $p\alpha$ collisions as a function of the c.m. energy per nucleon-nucleon collision $\sqrt{s}_{NN}$ compared with R_∞ for pp collisions. Preliminary results (ref. 36).

NN events (with, for instance, different impact parameters). As a consequence of averaging within an individual event the temperature fluctuations must decrease.

Drawing the conclusions from our studies of the temperature, we found that (i) the "temperature" of produced particles is the same for $\alpha\alpha$, αp , and pp interactions; (ii) it does not depend on the final-state multiplicity in any of these reactions -- as opposed to the significant dependence observed at the $p\bar{p}$ collider; but (iii) there are fluctuations of the event temperature which are (iv) smaller for αp and $\alpha\alpha$ interactions than for pp interactions.

6.3 DETERMINING THE VOLUME OF THE PION SOURCE

In contrast to the temperature which is an "intensive" thermodynamic property, the volume is an "extensive" property. The total interaction volume is expected to increase with the mass of target and projectile, even if a nucleus-nucleus collision were a mere superposition of NN collisions. Can we measure the size or the volume of the "source" which emits particles? Our method is based on the second-order interference between identical bosons produced in the interaction. The existence of Bose-Einstein effects in the correlations between two pions of equal charge has been demonstrated by many experiments³⁷⁾ and was used to determine the radius of the pion source as suggested by several authors³⁸⁾. We have studied the number of pion pairs as a function of their four-momentum difference $t_{12} = -(\vec{p}_1 - \vec{p}_2)^2$ and have adopted the conventional procedure to divide the number of like pion pairs by the number of unlike pion pairs. The normalization was done in such a way as to have an equal number of like and unlike pairs at $\sqrt{-t_{12}} > 0.3$. The ratio of normalized like pairs σ_L to the unlike pairs σ_{UL} as a function of $\sqrt{-t_{12}}$ (GeV/c) is shown in fig. 10 for $\alpha\alpha$ and pp collisions. It can be seen that the width of the enhancement at small $\sqrt{-t_{12}}$, which is due to the interference, decreases from pp to $\alpha\alpha$. A function $A \exp(t_{12}R^2)$ was fitted to the enhancement and the size R of the pion source was found to be $R_{\alpha\alpha} = 1.5 \pm 0.1$ fm, $R_{\alpha p} = 1.5 \pm 0.1$ fm, and $R_{pp} = 1.2 \pm 0.1$ fm. Thus, indeed a significant increase of the interaction volume is observed. In the further analysis we plan to investigate the dependence of R on the angle (or rapidity) of the pion pairs and on the multiplicity, and to extract separately size and decay time of the source following the Kopylov-Podgoretsky approach.

7. Summary and outlook

In the foregoing sections some selected results from the first experiments with α particles at the CERN ISR were presented and discussed. These experiments were pilot experiments in the field of p-nucleus and nucleus-nucleus collisions because they were performed at the highest possible accelerator energies, and nuclear interactions were studied, for the first time, with such complex and sophisticated detectors as those installed at the CERN ISR. What is the future of this field?

The ISR are to be closed soon. This definite shutdown arrives at a time of very high productivity in the field of pp and $p\bar{p}$ physics, so there is only room for at most one more run with light ions, which will hopefully be scheduled for the beginning of next year. During this run we plan to measure again $p\alpha$ and $\alpha\alpha$ interactions, but in addition deuterons will be stored to investigate pd and dd interactions. The hope is that the luminosity for $\alpha\alpha$ collisions will be significantly higher than in the first run and that some of the previous measurements can be extended and improved. The measurements with deuterons are interesting on their own as they allow isolation of the interactions of neutrons in a cleaner way than for α particles; but they also provide us with the ideal comparison with $p\alpha$ and $\alpha\alpha$ interactions.

What is the future after this run? In a meeting which took place this year in Bielefeld, Federal Republic of Germany, on "Quark matter formation and heavy-ion collisions"³⁹⁾ many physicists expressed their interest in studying interactions of nuclei at the highest possible energy. Once ^{16}O ions can be accelerated in the CERN Proton Synchrotron (PS) -- there is a proposal for such a project⁴⁰⁾ -- they

Fig. 10 Normalized ratio of like pairs to unlike pairs of charged particles as a function of the invariant four-momentum difference $\sqrt{-t_{12}}$ for $\alpha\alpha$ and pp collisions.

could also be injected and accelerated in the Super Proton Synchrotron (SPS), thus allowing the study of collisions of ^{16}O with various nuclear targets at c.m. energies which are only a factor of $\sqrt{2}$ lower than ISR energies. Moreover, the acceleration of α 's and deuterons in the SPS is technically feasible already at present. It is only a question of sufficient interest and of availability of PS time for such measurements to become real.

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