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ALPHA-ALPHA AND ALPHA-PROTON INTERACTIONS IN
THE CERN INTERSECTING STORAGE RINGS

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Abstract: Alpha-alpha and alpha-proton collisions have been studied for c.m. energies of 125 and 88 GeV, respectively, in different experiments at the CERN ISR. Some results obtained so far for elastic scattering, inelastic interactions, and production of particles with large transverse momenta will be reported.

1. Introduction

With the arrival of alpha particles in the CERN Intersecting Storage Rings (ISR) a year ago, nuclei have conquered an energy domain which will hold the world record for particle collisions at accelerators for a few more months to come. A brief historical review may be in order.

Figure 1 shows the CERN particle acceleration network with the 28 GeV Proton Synchrotron (PS), the ISR, and a section of the Super Proton Synchrotron (SPS).

Fig. 1 The CERN particle accelerator network with the Proton Synchrotron (PS), the Intersecting Storage Rings (ISR), and a section of the Super-Proton Synchrotron (SPS).

The PS, the heart of this network, provides the ISR, the SPS, and of course experimental halls at the PS, with protons (and, soon, with antiprotons). A less well known fact is that with relatively minor modifications, light ions can be injected into the PS, and, once they are accelerated there, they have access to the whole network. This possibility was discussed some years ago¹⁾, and deuterons were injected into the ISR for a few short runs. But nobody wanted alpha particles until two years ago, when an experiment was proposed using alphas in the ISR²⁾. So last year, after one (successful) test, alpha particles were stored in the ISR for one week³⁾. For half of the week, alphas circulated in both rings; for the other half, protons were in one ring and alphas in the other.

The beams were accelerated to the highest possible momentum, 31.5 GeV/c per charge, yielding a c.m. energy $\sqrt{s} = 125$ GeV for $\alpha\alpha$ collisions and 88 GeV for $p\alpha$ collisions (or, if one prefers the energy per nucleon-nucleon collisions: $\sqrt{s_{NN}} = 31$ GeV for $\alpha\alpha$ and $\sqrt{s_{NN}} = 44$ GeV for $p\alpha$). The luminosities obtained were $3 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ for $\alpha\alpha$ and $8 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ for $p\alpha$ collisions in a standard intersection, sufficiently high to carry through a rich physics program. As a comparison, for pp collisions, luminosities of $2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ are standard today.

During the α -week, five experimental groups took data at different intersection regions:

- i) Experiment R110 measured production of π^0 with large transverse momenta (large p_T) using an apparatus which consists of a superconducting solenoid magnet, cylindrical drift chambers, and lead-glass and lead/scintillator sandwich shower counters covering the central region.
- ii) Experiment R210/211, whilst setting up for a measurement of small-angle elastic pp scattering, measured elastic scattering with a non-magnetic detection system consisting of plastic-scintillator and drift-tube hodoscopes.
- iii) Experiment R418 measured elastic and inelastic interactions, and production of charged particles with large p_T using the Split-Field Magnet (SFM) detector, a magnet equipped with multiwire proportional chambers (MWPCs) covering a solid angle close to 4π .
- iv) Experiment R806 measured production of π^0 with large p_T using liquid-argon/lead-plate calorimeters.
- v) Experiment R807 measured the production of charged hadrons with large p_T and normal inelastic interactions, using the Axial-Field-Magnet (AFM), a conventional C-type magnet with cylindrical drift chambers covering the central region, Čerenkov counters, and two forward calorimeters.

In the following, some of the results obtained so far are presented and, in parallel, the physics goals are outlined. But a detailed and critical confrontation of results and goals is not intended since many of the results are still preliminary⁴⁾. The talk is divided into three subjects: elastic scattering, inelastic interactions, and large p_T particle production. The use of nuclei introduces a new theme in all three subjects. It has only one name: "multiple interactions"; but the physical content is every time different -- and non-trivial. The three parts may be considered as three variations on this single theme.

2. Elastic scattering

The differential cross-sections $d\sigma/dt$ obtained by R210/211 and R418 are shown in Fig. 2⁴⁻⁶⁾. Experiment R210/211 measured $d\sigma/dt$ (Figs. 2a, c) down to t -values of $0.05 (\text{GeV}/c)^2$. At the SFM detector the lower cut in t is $0.2 (\text{GeV}/c)^2$ -- corresponding to 7 mrad -- at the highest energy (125 GeV for $\alpha\alpha$) but the measurement extends to higher t values (Figs. 2b, d). Experiment R210/211 sees the first diffraction minimum in αp and $\alpha\alpha$ collisions at about $t = 0.2 (\text{GeV}/c)^2$ and at $t = 0.1 (\text{GeV}/c)^2$, respectively, and determines the slopes of the diffraction peak to $41 \pm 2 \text{ GeV}^{-2}$ and $100 \pm 10 \text{ GeV}^{-2}$, respectively. Experiment R418 sees the maximum above the first dip for αp and a second minimum at $0.4 (\text{GeV}/c)^2$ for $\alpha\alpha$ scattering.

According to Glauber's multiple scattering theory⁷⁾, events in the forward peak below the first minimum are predominantly due to single scattering; the first minimum results mainly from the destructive interference between single and

Fig. 2 Differential elastic cross-sections $d\sigma/dt$ versus $|t|$ ($|t| \approx s \cdot \sin^2 \theta / \text{cm}^2$). Preliminary data:

- a) αp ; experiments R210/211 ($\sqrt{s} = 88$ GeV) (Ref. 4)
- b) αp ; experiments R418 ($\sqrt{s} = 88$ GeV) compared with Ref. 5 ($\sqrt{s} = 54$ GeV)
- c) $\alpha\alpha$; experiments R210/211 ($\sqrt{s} = 125$ GeV)
- d) $\alpha\alpha$; experiment R418 ($\sqrt{s} = 125$ GeV) compared with Ref. 6 ($\sqrt{s} = 8.8$ GeV)

double scattering. Between the first and second minimum, double scattering dominates, and the second dip is mainly a result of the interference between double and triple scattering, and so on.

Why is it interesting to study elastic scattering of nuclei at very high energy? It is generally accepted that Glauber's theory provides a successful description of elastic nuclear scattering at high energy if both the nuclear structure and the elementary nucleon-nucleon amplitude are known as input to the theory. Alternatively, by a measurement of elastic scattering, one may probe the nuclear structure or the elastic nucleon-nucleon amplitude if the other input is well known. However, recent experiments which measured elastic $p\alpha$ scattering at FNAL⁵⁾ and pd and dd scattering at the ISR⁸⁾ claimed to see a deviation from the Glauber description, which had to be attributed to "inelastic shadowing"⁹⁾. Figure 3c

Fig. 3 a) Single scattering and b) double scattering; c) double scattering with an intermediate inelastic state in elastic pd scattering.

shows what is meant by inelastic shadowing: after the first scattering the incoming hadron turns into an intermediate inelastic (excited) state, which scatters a second time, thereby returning to its ground state.

This mechanism can introduce an energy dependence to the elastic nuclear cross-section, on top of the one due to the energy dependence of the nucleon-nucleon (N-N) amplitude. (Perhaps it provides an intuitive explanation of the energy dependence of the elastic N-N amplitude, in the framework of multiple scattering approaches to elastic N-N scattering?) Measurements over a wide energy range for collisions of light nuclei are therefore desirable in order to further investigate the relevance of the inelastic intermediate states.

An analysis of such effects requires much (more) work and perhaps the precision of the α -data obtained in the short survey run is not sufficient yet.

3. Soft inelastic interactions

The inelastic cross-section can be divided into fragmentation of nuclei without particle production (σ_{frag}) and multiparticle production (σ_{prod}). The latter constitutes the dominant part at high energies¹⁰⁾. As a good approximation to the production cross-section (σ_{prod}), the cross-section for events with at least one negative particle (σ_{neg}) can be used.

Multiparticle production was measured by R418 and R807. Total multiplicity distributions, inclusive single-particle distributions as a function of rapidity y (or Feynman x_F), and p_T , and two-particle correlations have been analysed by R418. Experiment R807 has studied the multiplicity distribution of particles produced in the central rapidity region and the amount of energy deposited in two forward calorimeters, and correlations between multiplicity and energy deposit.

The average multiplicity and the width of the multiplicity distribution increases for $\alpha\alpha$ and αp collisions as compared to pp collisions at the same $\sqrt{s_{NN}}$ (Fig. 4). Naturally this increase is thought to be due to multiple inelastic interactions. To understand the increase in a quantitative manner, two inputs are needed (analogous to elastic scattering). The "nuclear structure" (or "geometry") input containing the information on the probability of multiple interactions, and the input pertaining to the result of inelastic multiple interactions (the dynamics). Both inputs are far from being trivial and cannot be easily disentangled.

Fig. 4 Multiplicity distributions:

- Charged multiplicity in the central region $|y| \leq 0.8$, measured by R807, for pp ($\sqrt{s} = 31, 44$, and 63 GeV), αp ($\sqrt{s_{NN}} = 44$ GeV), and $\alpha\alpha$ ($\sqrt{s_{NN}} = 31$ GeV).
- Total multiplicity of negative particles for αp ($\sqrt{s_{NN}} = 44$ GeV) compared with pp ($\sqrt{s} = 44$ GeV).
- Total negative multiplicity for $\alpha\alpha$ ($\sqrt{s_{NN}} = 31$ GeV) compared with pp ($\sqrt{s} = 31$ GeV) measured by R418 (uncorrected for acceptance).

The probability distribution for multiple collisions can be calculated at high energies in a geometrical approximation using the profile functions [the thickness of nuclei as function of the impact parameter⁷⁾]. In principle, we do not know the cross-section of the hadron(s) (an excited incoming hadron or an energy flux of hadronic matter) emerging from the first collision. In practice, the number of inelastic collisions in a hadron-nucleus interaction is most often calculated as if only the incoming hadron would collide inelastically several times with the same cross-section.

The second input, the one concerning the outcome of multiple inelastic interactions, is the great challenge for the theorists; and the experimentalist's hope is to determine it by combining a measurement of inelastic hadron-nucleus interactions with an appropriate "nuclear input". The challenge is to predict from a single collision what the number and spectrum of outgoing particles is, after a hadron has collided with nucleons twice or more, inelastically, within a very short time (Fig. 5a) of the order of $\lambda/c \approx 2 \text{ fm}/c$ (λ is the mean free path of a

Fig. 5 Basic cases of multiple interactions:
a) the "hadron-nucleus" type;
b) a non-trivial nucleus-nucleus type;
c) a trivial nucleus-nucleus type.

high-energy proton in nuclear matter). Alternatively, a measurement of the particle spectrum after an inelastic hadron-nucleus interaction should indeed represent a very good test of theoretical models, judging from the variety of different predictions¹¹⁻¹⁵⁾. A major problem in the confrontation of data¹⁶⁾ with theoretical predictions, however, seemed to be that the latter are often made for asymptotically high energies (which one might define as being such that target and projectile fragmentation regions are well separated and a central pionization region has developed). Needless to say that most experiments are not made at asymptotically high energies.

In nucleus-nucleus collisions, another non-trivial case of multiple scattering should occur (Fig. 5b) in addition to the one (Fig. 5a) which can be better studied in hadron-nucleus interactions: Two nucleon pairs collide (here, in their c.m. system) at the same space point and nearly the same time. This should result in local energy densities higher than in a pp collision. A study of this sort of multiple collision is relevant because the hope of observing new phases of nuclear matter in collisions of heavy ions at very high energy is based upon them¹⁷⁾. Figure 5c shows also a (trivial) kind of parallel interaction of nucleon-pairs, separated in space, which can occur in nucleus-nucleus collisions. These interactions will yield twice the same spectrum of particles as a single N-N collision but no higher energy densities in space.

The inclusive spectra $(1/\sigma_{\text{neg}})(d\sigma^{\pm}/dy)$ of positive and negative particles in αp and $\alpha\alpha$ collisions, normalized to the ones in pp collisions, are shown as a function of the rapidity y_{cm} in Figs. 6a-6d. The ratio $R_y^{\pm}(\alpha p/pp)$, for instance, is defined as

$$R_y^{\pm}(\frac{\alpha p}{pp}) = \frac{\left[1/\sigma(\alpha p)_{\text{neg}}\right] \left[d\sigma^{\pm}(\alpha p)/dy\right]}{\left[1/\sigma(pp)_{\text{neg}}\right] \left[d\sigma^{\pm}(pp)/dy\right]}. \quad (1)$$

Fig. 6 Ratios [see Eq. (1)] of particle densities as a function of the rapidity $y_{cm} = \frac{1}{2} \ln(E+p_L)/(E-p_L)$. a) $R_y^+(\alpha p/pp)$, b) $R_y^-(\alpha p/pp)$, c) $R_y^+(\alpha\alpha/pp)$, d) $R_y^-(\alpha\alpha/pp)$.

For αp interactions, $R_Y^\pm$ is above 1, for $y_{cm} \approx 0$:

$$R_0^\pm\left(\frac{\alpha p}{pp}\right) = 1.18 \pm 0.07 \quad (2)$$

and it rises towards high positive rapidities -- the α -fragmentation region. The positive and negative ratio show a different increase: R_Y^- starts to increase at lower y than R_Y^+ . Part of the increase and of the difference between R_Y^+ and R_Y^- can be explained qualitatively as follows: On one hand, most of the "leading" particles in pp interactions are protons, but out of an α particle 50% of the leading baryons are neutrons. Therefore R_Y^+ is expected to be lowered in the region of leading baryons (at the α -side), but should increase in the region of "spectator" protons, at the highest positive y since the latter can only come from nuclei. On the other hand, for pp interactions the ratio of negative to positive pions is known to decrease (down to a value 0.2) towards high rapidities¹⁸, but for $p\alpha$ or $\alpha\alpha$ collisions one expects this ratio to be 1 at the α side. Since negative particles are mostly π^- , one expects therefore R_Y^- to increase towards high positive y_{cm} .

Thus part of the behaviour of $R_Y^\pm$ can be attributed to the different quark composition of a proton and an α , but the increase of $R_Y^\pm$ at high y may also indicate some cascading in the α particle. To determine the amount of cascading, the effect of the different quark content would have to be calculated quantitatively.

A similar behaviour can be observed for $R_Y^\pm(\alpha\alpha/pp)$ at high rapidities, now of course symmetrical at both sides, but the central ratios $R_0^\pm$ are considerably higher:

$$R_0^\pm\left(\frac{\alpha\alpha}{pp}\right) = 1.74 \pm 0.09 \quad (3)$$

For a comparison with theoretical predictions, the central ratio $R_0^\pm$ is best suited, since there the experimental and theoretical uncertainties are smallest. Good agreement is found with the prediction of the parton model of Brodsky et al.¹²) [$R_0^\pm(\alpha\alpha/pp) = 1.8 \pm 0.13$, $R_0^\pm(\alpha p/pp) = 1.16 \pm 0.07$] and with the additive quark model^{9,13,15}) [$R_0(\alpha\alpha/pp) = 1.77$ and $R_0(\alpha p/pp) = 1.16$]. Some other models, such as the energy flux cascade model of Gottfried and the multiperipheral model of Kancheli and Bertocchi¹⁴), which predict $R_0(\alpha p/pp) = 1$, apparently do not agree with the αp data.

4. Hard inelastic interactions

Production of particles with large transverse momenta (p_T), although quite rare, was particularly well covered by four experiments, two (R110 and R806) measuring the production of π^0 and two (R418 and R807) measuring charged-particle production.

Large p_T particle production is known to probe the substructure of nucleons. Therefore, some years ago, people believed that the cross-sections to produce particles with large p_T in hadron-nucleus interactions would increase linearly with the target mass A . This was based on the hypothesis that the underlying process is the rare elastic large-angle scattering of constituents and consequently no shadowing occurs. A systematic measurement done at FNAL (at incoming momenta of 200-400 GeV/c) of the A -dependence of the inclusive cross-section as a function of p_T showed, however, that the particle production increases more quickly than linearly with A ¹⁹). If the invariant cross-section was parametrized as

$$\frac{d^2\sigma(A)}{\pi dy_{cm} d(p_T^2)} \propto A^{\alpha(p_T)} \quad (4)$$

$\alpha(p_T)$ was found to exceed 1 for $p_T > 2$ GeV/c and to reach values as high as 1.3 (at $y_{cm} \approx 0$). This observation of an "anomalous nuclear enhancement" was later confirmed by other experiments and stimulated quite a theoretical activity. Many

Fig. 7 Double hard scattering of parton a out of hadron A with partons b_1, b_2 out of two different nucleons B_1, B_2 leading to a trigger track C.

different and interesting mechanisms were invoked to explain the behaviour of $\alpha(p_T)$, but the most widely accepted explanation was multiple scattering²⁰⁾ on the parton level (Fig. 7): the active parton(s) which cause(s) the large p_T trigger or trigger jet, scatter(s) more than once.

One of the motivations for the α -experiment at the ISR was to search for the mechanism responsible for the anomalous enhancement. It was hoped that a study of the distributions and properties of the secondaries associated with a large p_T trigger track could provide a key. The SFM detector as well as the other detectors is well suited for such a study.

As a first step in the analysis one obtains the inclusive distribution of the large p_T trigger particles. Figures 8a-c show the invariant cross-sections as a function of p_T in αp collisions, obtained by experiment R806²¹⁾, and the cross-sections for positive and negative hadrons measured by R418, together with pp data²²⁾ (multiplied by a factor of 4) at the same $\sqrt{s_{NN}} = 44$ GeV. An enhancement of about 20% is expected at p_T from 3 to 4 GeV/c, based on the A-dependence measured by Cronin et al.¹⁹⁾, if $\alpha(p_T)$ is assumed to be energy independent. The data do not give proof of such an enhancement in αp collisions but are compatible with it. Experiment R418 measured the cross-sections at two different c.m. rapidities and observed a rapidity dependence.

Let us now turn to $\alpha\alpha$ collisions.

Not knowing that there is an anomalous nuclear enhancement in p-nucleus collisions, one would have expected that the inclusive cross-sections in $\alpha\alpha$ collisions would be 16 ($= A^2$) times higher than in pp collisions at the same $\sqrt{s_{NN}}$. Figure 9 shows the invariant cross-sections in $\alpha\alpha$ collisions, compared to pp data²²⁾ (multiplied by 16), and demonstrates that the former become significantly higher than 16 times the cross-sections in pp collisions. At a p_T range above the one studied by R806 and R418 experiment R110 observes as well an enhancement of the π^0 production cross-section by a factor of 24 (at $p_T = 4$ GeV/c) to 40 (at $p_T = 6$ GeV/c)²³⁾. The origin of this enhancement could, of course, be different from the one in hadron-nucleus collisions, but as a first guess one would certainly assume the same.

Three experiments (R110, R418, and R807) have started to study the structure of the associated event. Differences were seen between the distributions of secondaries in αp , $\alpha\alpha$, and pp events but so far no differences which would support one or other of the proposed mechanisms. One example: If, in $\alpha\alpha$ or αp collisions, multiple scattering plays a significant role, one would expect to see this in the momentum distribution of particles recoiling against the large p_T trigger track. There should be more particles but with lower average momentum compared to pp interactions. Yet the momentum distribution of particles opposite to the trigger particle did not show any statistically significant difference. In Fig. 10 the momentum distributions are shown as a function of the scaling variable $x_E \approx p_T/p_T(\text{trigger})$, where $p_T(\text{trigger})$ is the p_T of the trigger track.

It is tempting to speculate what one would conclude if no differences were to be found in a more sensitive, precise comparison. A search for mechanisms other than multiple parton scattering should be done first, of course (it has already started), but then one should consider a second possibility -- which is more in the nature of a question: What is the role of multiple parton scattering in pp

Fig. 8 Inclusive production cross-section $d^2\sigma/\pi dy d(p_T^2)$ as a function of p_T in ap interactions ($\sqrt{s}_{NN} = 44 \text{ GeV}$) compared with pp interactions ($\sqrt{s} = 44 \text{ GeV}$) for
a) π^0 (Ref. 21) (R806);
b) positive hadrons (R418), with pp data from Ref. 22;
c) negative hadrons (R418), with pp data from Ref. 22.

Fig. 9 Inclusive production cross-section in $\alpha\alpha$ collisions ($\sqrt{s_{NN}} = 31 \text{ GeV}$) compared with pp collisions ($\sqrt{s} = 31 \text{ GeV}$):
a) π^0 (Ref. 21) (R806);
b) positive hadrons (R418), with pp data from Ref. 22;
c) negative hadrons (R418), with pp data from Ref. 22.

Fig. 10 The distribution dN/dx_E of particles opposite to a positive large p_T trigger track ($150^\circ < \Delta\phi < 210^\circ$ and $|y_{CM}| < 1.5$) for
a) αp collisions (p_T of trigger > 3 GeV/c)
b) $\alpha\alpha$ collisions with a positive trigger (p_T of trigger > 3 GeV/c)
compared with the one for pp collisions (p_T of trigger > 4 GeV/c).

interactions for particle production in the p_T range 2 to 5 GeV/c? If it were already important in pp interactions, one would expect no change of the x_E distributions, but nevertheless an enhancement of the cross-section for nuclei. There is another reason for considering this possibility. The dependence of inclusive production cross-sections on p_T in this p_T range is not as one expects for single scattering of point-like partons. Only for higher p_T (say > 10 GeV/c) is one (almost) sure that single parton-parton scattering will dominate²⁴). At low p_T (below 1 GeV/c) thermodynamic approaches are successful, the p_T dependence being consistent with a local temperature^{17,25}; this in turn implies that many elementary interactions occur. Between the two extremes -- high p_T and low p_T -- there must be a transition region where a finite number of elementary interactions, which decreases with increasing p_T , are most likely to take place.

A comparison of hard interactions of nuclei (where multiple scattering should be enhanced) with hard pp interactions may tell us how important the multiple scattering of partons is in the latter case.

5. Summary

In a short run of one week with α particles in the ISR, a variety of $\alpha\alpha$ and αp interactions could be studied. Even though the data are still preliminary, several new and interesting features have been found.

- The differential elastic cross-sections have been measured in the diffraction region from $t = 0.05$ to $t = 0.8$ (GeV/c)², and these show the expected minima and maxima. An analysis of the precise position and the height of these structures has yet to be done.
- For inelastic interactions, an increase of the multiplicity is observed as compared with the multiplicity in pp interactions at the same $\sqrt{s_{NN}}$. In particular, the increase of particles in the pionization region (around $y_{cm} \approx 0$) may be noteworthy. If confirmed, it may provide the long-sought crucial test for models of the inelastic hadron-nucleus interaction.
- Particles with large p_T were found to be produced more abundantly in $\alpha\alpha$ interactions than one would expect from four by four independently interacting nucleon-pairs. A mechanism for this enhancement has still to be found.

The sum of these observations supports the hope that the study of very high energy interactions of light ions is a useful approach to a better understanding of various properties of the strong interaction.

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References

- 1) L. Bertocchi et al., Workshop on Future ISR Physics 4-15 Oct. 1976, Study Group Report ISR Workshop/76-F-1 (1976).
- 2) M.A. Faessler, Letter of Intent, CERN/ISRC/79-3 (1979).
K. Braune et al., Proposal to the ISRC, CERN/ISRC/79-10, ISRC/P101 (1979).
- 3) L. Bernard et al., CERN/PS/OP/Note 80-27 (1980).
H. Boutheon et al., CERN/PS/LR 81-14 (1981).
- 4) M.G. Albrow and M. Jacob, Physics with α particles, Discussion Meetings between Experimentalists and Theorists on ISR and Collider Physics (CERN, Geneva), Series 2, Nos. 2 and 3 (Jan. and Feb. 1981).
- 5) A. Bujak et al., Phys. Rev. D 23 (1981) 1895.
- 6) J. Berger et al., Proc. 7th Int. Conf. on High-Energy Physics and Nuclear Structure, Zürich, 1977, Abstract Vol. p. 160.

- 7) R.J. Glauber, *in* Lectures in Theoretical Physics, ed. W.E. Brittin, Vol. 1 (Interscience Publishers, Inc., New York, 1959), p. 315.
- 8) G. Goggi et al., Nucl. Phys. B149 (1979) 381.
- 9) E.S. Abers et al., Nuovo Cimento 42A (1966) 363.
V.N. Gribov, Zh. Eksper. Teor. Fiz 56 (1969) 892 [English transl.: Sov. Phys. JETP 29 (1969) 483].
- 10) J. Jaros et al., Phys. Rev. C 18 (1976) 2273.
- 11) A. Gurtu et al., Pramana 3 (1974) 311.
- 12) S.J. Brodsky et al., Phys. Rev. Lett. 39 (1977) 1120.
- 13) A. Biaľas, Cracow Report INP-1114/PH and TPJU-12/80, to be published in Proc. Workshop on Future Experiments with High-Energy Heavy Ions, GSI, Darmstadt, 1980.
A. Biaľas et al., Acta Phys. Polon. B8 (1977) 585.
A. Biaľas et al., Cracow Report INP-1141/PH and TPJU-10/81 (1981).
- 14) K. Gottfried, Phys. Rev. Lett. 32 (1974) 957.
K. Gottfried, *in* Proc. 5th Int. Conf. on High-Energy Physics and Nuclear Structure, Uppsala, 1973, ed. G. Tibell (North-Holland Publ. Co., Amsterdam, 1974), p. 79.
L. Bertocchi, *in* Proc. 6th Int. Conf. on High-Energy Physics and Nuclear Structure, Santa Fe, 1975, eds. D.E. Nagle et al. (AIP, New York, 1975), p. 238.
- 15) N.N. Nikolaev et al., preprint CERN TH.2541 (1978).
- 16) J.E. Elias et al., Phys. Rev. D 22 (1980) 13.
M.A. Faessler, preprint CERN-EP/81-42 (1981), to be published in Annals of Physics (USA).
- 17) R. Anishetty et al., Phys. Rev. D 22 (1980) 2793.
R. Hagedorn and J. Rafelski, preprints CERN TH.2947 (Sept. 1980) and CERN TH.2969 (Oct. 1980).
R. Hagedorn, preprint CERN TH.3014 (1981).
- 18) See references *in* W. Ochs, Nucl. Phys. B118 (1977) 397.
- 19) J.W. Cronin et al., Phys. Rev. D 11 (1975) 3105.
- 20) P.V. Landshoff et al., Phys. Rev. D 12 (1975) 3738.
J.H. Kühn, Phys. Rev. D 13 (1976) 2948.
P.M. Fishbane et al., Phys. Rev. D 16 (1977) 122.
- 21) A. Karabarbounis et al., preprint CERN-EP/81-46 (1981), submitted to Physics Letters.
- 22) B. Alper et al., Nucl. Phys. B100 (1975) 237.
- 23) R. Rusack, private communication.
- 24) For a recent review on large p_T phenomena, see
M. Jacob and P.V. Landshoff, Phys. Reports 48 (1978) 285.
- 25) R. Hagedorn and J. Ranft, Suppl. Nuovo Cimento 6 (1968) 169.
R. Hagedorn, Nuovo Cimento 56A (1968) 1027.