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180^{o} PRODUCTION OF p, d, AND t, AND p-p CORRELATION IN p-NUCLEUS COLLISIONS

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180° Production of p, d and t, and p-p Correlation in p-Nucleus Collisions

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ABSTRACT

It is shown that (a) the energy distribution of the 180° emitted protons, deuterons, and tritons from 0.6 GeV to 400 GeV incident energy, (b) the extremely weak angular dependence of single-particle inclusive cross sections in the backward directions, and (c) the existence of forward-backward p-p correlation are due to fragmentation of the effective target (that is, the system of nucleons in the target nucleus along the axis of the incident proton) in proton-nucleus collisions. Correlation effects in violent processes are also briefly discussed.

Baryon-production at $\theta_{lab} = 180°$ has attracted much attention[1-10] in the past few years. The vast interest is caused by the belief that by studying such reactions one can obtain information on the "cumulative effect"[2] or information on "the high-momentum part of nuclear wave functions"[8,9] and/or knowledge about "the most violent collisions."[1,10]

180° proton, deuteron and triton production in proton-nucleus collisions from 0.6 up to 400 GeV have been observed.[1,2,4,6,7] Angular distributions for such particles in the "backward directions" have been measured.[2,3] "Forward-backward pp correlation" experiments have also been reported.[5] Unfortunately, this impressive progress made on the experimental side has not been matched by corresponding theoretical work.

The striking features of backward baryon-production in proton-nucleus collisions can be summarized as follows:

I. Energetic protons have been observed[1] at $\theta_{lab} = 180°$ in p-nucleus collisions at 0.6 and 0.8 GeV using a number of nuclear targets. The inclusive cross section (in lab) per nucleon $A^{-1}(d\sigma/d^3p)$ (A: target mass number) can be fitted well by $B_p \exp[-\alpha_p P_p^2/(2M_p)]$. Here, P_p is the magnitude of the momentum (lab) of the observed proton, M_p is its mass, B_p and α_p are momentum-independent parameters.

II. Copious deutrons and tritons have also been observed in the same experiment.[1] The cross sections $A^{-1}(d\sigma/d^3p)_\lambda$ can be fitted by $B_\lambda \exp[-\alpha_\lambda P_\lambda^2/(2M_\lambda)]$ where λ = d and t indicates deutrons and tritons respectively.

III. (a) The A-dependence of α_λ (λ = p,d,t) at fixed energy ε is weak. (b) This A-dependence is more marked for d than for p, and for t than for d. (c) For given λ and A, the dependence of α_λ on ε is very weak. (d) For given A and ε, the differences between α_p, α_d, and α_t are large. (e) α_d/M_d and α_t/M_t are almost identical.

IV. For given A and ε, the difference between B_p, B_d, and that between B_p and B_t are large, but that between B_d and B_t is small.

V. 180° production of p, d, and t have also been observed in proton collisions with a variety of nuclear targets at $\varepsilon = 7.7$ GeV[2] and at 400 GeV.[4] It is found that the single particle inclusive cross-section also falls exponentially with increasing kinetic energy of the observed particle. The most remarkable feature is: while the corresponding slopes vary very slowly (about 30%) when the incident energy ε is increased from 0.6 GeV[1] to 7.7 GeV,[2] it remains practically constant in the energy range 7.7 GeV to 400 GeV.[4]

VI. Angular distributions for p and d in p + Pb at 7.7 GeV have been measured.[2] It is seen that there is practically no angular dependence for $140° \lesssim \theta_{lab} \leqslant 180°$. This behavior seems to persist down to lower incident energies.[3]

VII. Backward proton emission (50 to 145 MeV) has been measured[5] in coincidence with forward outgoing protons (255 to 350 MeV) in p-nucleus interaction at 640 MeV. A pronounced correlation is observed when the two outgoing protons are in the neighborhood of $\theta_{lab} = 122°$ and 12° respectively. Keeping the backward proton at 122°, a rather broad distribution in angle is seen for the forward proton.

Mechanisms of 180° production of protons at 0.6 and 0.8 GeV (point I) have already been discussed by several authors.[8-11] The related questions (point II to point VII) have, however, been left open.

In fact, it is not obvious whether and how the existing 180° proton-production models[8-11] can be extended or modified to accommodate the above-mentioned experimental facts, e.g., 180° d and t production at the same -- as well as much higher (up to 400 GeV!) -- incident energies.

An attempt is made in this paper to understand these facts (I to VII) in terms of the "two-component picture" for high-energy hadron-nucleus collisions proposed some time ago.[12] We show, in particular, that 180° production of proton, deutron and triton are due to fragmentation of the excited effective target and that *no* large-momentum-transfer is involved in such reactions. This means, in contrast to the popular models,[8,9,10] baryon-production at $\theta_{lab} = 180°$ is *neither* due to high virtual momenta of the nucleons before the collision[8,9] *nor* a consequence of "most violent proton-nucleus collision,"[1,10] where the observed protons are bounced back by "chunks"[1] or by "correlated clusters."[10]

We recall that the proposed picture[12] consists of two assumptions (both of which are based on empirical facts[13]):

(a) The time needed for the formation of multibody final states in hadron-hadron collisions at high energies is so long that in high-energy hadron-nucleus multiparticle production processes the nucleons in the path of the incident hadron inside the target nucleus can be viewed as acting collectively, and in first-order approximation can be considered as a single object -- an effective target (ET). The mass of the ET, M_{ET}, is proportional to ν_{ET}, the number of nucleons along the path of the incident hadron $M_{ET} = \nu_{ET} M$. (M is the nucleon mass).

(b) The hadron-ET process can be described by the same picture as that used to describe the collision between two hadrons. In particular, such a process is either a gentle or a violent collision (energy and momentum transfer is relatively small in gentle but large in violent collision events). We recall, after a gentle collision the projectile and the target in general become excited and fragment (separately).

In spite of the obvious over-simplification, this picture has so far been successful in describing the gross features of hadron-nucleus and nucleus-nucleus collisions at sufficiently high-energies.[12-15] A comparison between the experiments mentioned in I-VII and the present picture can also be considered as a critical test for the latter.

If this picture is correct, the only possible sources for *energetic* deutrons and tritons in high-energy hadron-nucleus collisions are: (1) the compound system formed by the incident hadron and the ET in a violent process (see Fig. 1.b of Ref. 13); (2) the excited ET after a gentle collision with the incident hadron (see Fig. 1.a of Ref. 13). Now, since the energy- and momentum-transfer in violent collisions are much larger than the corresponding quantities in gentle processes, the (lab) velocity of the compound system (in a violent event) is, in general, much higher than that of the excited ET (in a gentle event). Hence, energetic baryons observed in the backward lab angles are predominantly fragments of the excited ET.

The (lab) energy- and momentum-transfer (ΔE and $\Delta\vec{P}$) from the incident hadron to the ET in a gentle collision has the following effects: Firstly, the ET gains internal energy $E'_{ET}(\text{int}) = M^*_{ET} - M_{ET}$, where M^*_{ET} is the energy of the excited ET (in its rest frame) after the collision. Secondly, after the collision the ET moves with the (lab) velocity: $\vec{\beta}_{ET} = \Delta\vec{P}\{|\Delta\vec{P}|^2 + M_{ET}^{*2}\}^{-\frac{1}{2}}$ which is small for $|\Delta\vec{P}| \ll M_{ET} < M_{ET}^{*}$. *In our picture this is the source of the observed energetic protons, deuterons, etc., in the backward angles.*

Having identified the origin of these baryons, we may now go one step further and ask: "How is the total energy and momentum of the excited ET distributed among its ν nucleons?"

In the rest frame of the excited ET, the ν nucleons are assembled with a net momentum $\sum_{i=1}^{\nu} \vec{p}_i^{\,\prime} = 0$. The energy associated with the relative motion of these ν nucleons is $E'_{ET}(\mathrm{int})$ (which is the difference of the energy-transfer to the ET and the kinetic energy of the excited ET that moves as a single object in lab). "If λ of these nucleons, chosen at random, should go off together as a single fragment, what would be the mean square total momentum $|\vec{P}'_\lambda|^2$, where $\vec{P}'_\lambda$ is the sum of the above-mentioned λ $\vec{p}_i^{\,\prime}$s?" A similar question has already been asked, and answered, by Feshbach and Huang[16] and Goldhaber[17] in connection with projectile fragmentation in relativistic heavy-ion collisions.[18]

Suppose that the FH statistical hypothesis[16] can be applied[19] to the excited ET which consists of ν nucleons. In the rest frame of the excited ET the inclusive cross section for a baryon of mass M (M = nucleon mass) can be obtained by the method suggested by Goldhaber:[17]

$$(d\sigma/d^3p)'_\lambda \propto \exp[-|\vec{P}'_\lambda|^2/(2\sigma^2)] \qquad \text{and} \qquad \sigma^2 = \sigma_0^2\lambda(\nu-\lambda)/(\lambda-1) \ , \quad (1)$$

where σ_0^2 is proportional to $\langle p'^2 \rangle$, the mean square momentum of the nucleons in the ET, which is (up to a constant) the average kinetic energy of each nucleon in the ET after collision (in its rest frame). Since the excitation is due to energy- and momentum-transfer from the incident proton as it "goes through"[20] the nucleons in the ET, this kinetic energy is expected to be a slowly increasing function of the incident energy ε, and reaches a limiting value for $\varepsilon \to \infty$.

Comparison between the corresponding lab expressions (note that for $|\vec{\beta}_{ET}| \ll 1$, the lab quantities $(d\sigma/d^3p)_\lambda$ and p^2 are approximately the same as those in the rest frame of the excited ET) of Eq. (1) and the empirical parametrization of Frankel et al[1] (see I and II above) gives

$$\alpha_\lambda^{-1} = \frac{\nu - \lambda}{\nu - 1}\left(\frac{\sigma_0^2}{M}\right) \quad , \qquad \lambda = p, d \text{ and } t \, . \qquad (2)$$

This is obviously in agreement with the properties mentioned in III(a), (b), (c) and (d). (The data[1] requires $\sigma_0 \approx 160$ MeV/c which is to be compared with ~110 MeV/c in normal nuclear matter, indicating the fraction of energy-momentum transferred to the ET in the collision is indeed small.) Note also that III(e) implies $\nu \approx 5$ independent of A -- again[21] indicating that gentle hadron-nucleus collision are more peripheral for heavier target nuclei.

We now discuss the magnitude of the (lab) cross sections $(d\sigma/d^3p)_\lambda$. The geometrical and statistical nature of this model taken together with the conservation laws gives

$$(d\sigma/d^3p)_\lambda = a(\bar{\nu}/\lambda)\, D_\lambda I_\lambda \qquad (3)$$

where a is the mean geometrical cross section, $\bar{\nu}$ is the average number of nucleons in the ET (note both a and $\bar{\nu}$ are independent of λ), $D_\lambda(p)$ is the *normalized* momentum distribution [see Eq. (1)],

$$D_\lambda(p) = \left(\frac{\alpha_\lambda}{2\pi M_\lambda}\right)^{3/2} \exp\left(-\alpha_\lambda \frac{p^2}{2M_\lambda}\right) \qquad (4)$$

and I_λ is determined by the internal degrees of freedom of the fragment which consists of λ nucleons. The ratio I_d/I_p can be determined by taking into account the constraints, with respect to isospin, spin and relative orbital angular momentum, which should be satisfied when two nucleons form a physical dentron. It is 3/64 (we recall that only s and p waves contribute at such low internal energies). Similarly, we obtain $I_t/I_p = 9/448$.

It follows from Eqs. (3) and (4) that

$$\frac{B_d}{B_p} = \frac{1}{2}\,\frac{I_d}{I_p}\left(\frac{\alpha_d M_p}{\alpha_p M_d}\right)^{3/2} \quad ; \quad \frac{B_t}{B_p} = \frac{1}{3}\,\frac{I_t}{I_p}\left(\frac{\alpha_t M_p}{\alpha_p M_t}\right)^{3/2} \qquad (5)$$

which also turns out to be in agreement with the data[1] within experimental error. (For example, at 0.8 GeV using Ta target, the theoretical values of B_d/B_p and B_t/B_p are 0.01 and 0.003 while the corresponding experimental values are 0.01 and 0.006 respectively.)

The limiting behavior of σ_0^2 in Eq. (1) for $\varepsilon \to \infty$, taken together with the fact that the dominating part of the 180° baryons are fragmentation products of the excited ET which moves rather slowly ($|\vec{\beta}_{ET}| \ll 1$), explains the remarkable energy-independence of the slope mentioned in V.[4] Furthermore, it follows from $|\vec{\beta}_{ET}| \ll 1$ and the isotropic emission in the excited ET's rest frame [see Eq. (1)] that the distribution in the neighborhood of $\theta_{lab} = 180°$ should be approximately independent of the (lab) production angle (see VI). At smaller angles ($\theta_{lab} \lesssim 140°$, say) contributions from violent p-ET collisions should be taken into account.[12]

We turn now to the pp correlation data.[5] The agreement between the experimental facts mentioned in VII and the present picture can already be seen without detailed calculations. Firstly, the two observed protons are back-to-back in a slowly moving frame -- the rest frame of the excited ET. Secondly, since such back-to-back correlations are simply consequences of momentum conservation, it is expected only to occur when the number of particles in the excited ET is relatively small. This implies that such events are more peripheral collisions. The observed A-dependence ($A^{1/3}$; see Fig. 4 of Ref. 5) confirms this expectation. Thirdly, in contrast to the predictions of Ref. 8 (see Ref. 5), the forward proton *can* have kinetic energies in the observed range. This is because, also the forward proton is a fragment of the excited ET. Fourthly, in contrast to the predictions of Ref. 10 (see Ref. 5), the rather broad angular distribution of the forward proton (see Fig. 2 of Ref. 5) is expected. Both the $p_\perp$-distribution of the ET[22] and the possible existence of undetected particles which also take part in the momentum-balance, lead to this "broadening effect." All the above-mentioned qualitative arguments have been checked quantitatively. The agreement is good.

In this connection, it is useful to point out the basic difference between this correlation and the p-p correlation observed by Nagamiya et al.[23] Although both of them are of kinematical nature (momentum conservation) which takes place in relatively small systems, the emission system in the latter case is *not* the *excited ET* in a *gentle* collision with the corresponding EP (effective projectile) *but* rather the *conglomerate* formed by the EP and the ET in a *violent* collision. In fact, since the rapidity of the conglomerate is in general a function of the incident energy as well as of the masses of the colliding nuclei (a simple expression for the mean rapidity of this compound system, as well as a more reliable method for the determination of this value from experiments, can be found in Ref. 15), we expect to see pp and πp back-to-back correlations in the rest frame of the conglomerate. Correlation experiments using *unsymmetric* projectile-target combinations will be helpful to differentiate between this and "the quasi-elastic nucleon-nucleon scattering"[24] mechanism.

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References and Footnotes

1. S. Frankel et al, Phys. Rev. Letters 36, 642 (1976).

2. A.M. Baldin, Talk given at the 7th International Conference on High Energy Physics and Nuclear Structure, Zurich, Switzerland, 1977, Dubna report E1-11368 (1978) and the papers cited therein.

3. V.I. Komarov et al, Phys. Letters 69B, 37 (1977).

4. Y.D. Bayukov et al, Univ. Pennsylvania preprint (UPR-0058E, 11/78) (1978).

5. V.I. Komarov et al, Phys. Letters 80B, 30 (1978).

6. G. Fujioka, Talk given at the 5th International Seminar on High-Energy Physics Problems, Dubna USSR 1978, (to be published).

7. J. Geaga et al, private communication (1979).

8. R.D. Amado and R.M. Woloshyn, Phys. Rev. Letters 36, 1435 (1976).

9. S. Frankel, Phys. Rev. Letters 38, 1338 (1977).

10. T. Fujita, Phys. Ref. Letters 39, 174 (1977).

11. Further references can e.g. be found in Refs. 2, 5 and 10.

12. Meng Ta-chung, in Proceedings of the Topical Meeting on Multiparticle Production on Nuclei at Very High Energies, Triest, Italy 1976, edited by Bellini et al (ICTP Triest 1976) p. 435 and Phys. Rev. D15, 197 (1977).

13. For details and further references see Ref. 12. A summary of this picture can be found in: Meng Ta-chung and E. Moeller, Phys. Rev. Letters 41, 1352 (1978).

14. H.B. Mathis and Meng Ta-chung, Phys. Rev. C18, 952 (1978).

15. Meng Ta-chung, Phys. Rev. Letters (in press).

16. H. Feshbach and K. Huang, Phys. Letters 47B, 300 (1973).

17. A.S. Goldhaber, Phys. Letters 53B, 306 (1974).

18. D.E. Greiner et al, Phys. Rev. Letters 35, 152 (1975) and papers cited therein.

19. That is, we assume the validity of this hypothesis not only in the large A limit (see also Ref. 17).

20. Based on the Chou-Yang model for hadrons in high-energy hadron-hadron collisions. See J. Benecke et al, Phys. Rev. 188, 2159 (1969) and the papers cited therein.

21. Compare Ref. 14.

22. We recall, one of the characteristics of the gentle (i.e., low momentum-transfer) hadron-hadron collisions at sufficiently high energies is that the dominating part of the outgoing particles have very small transfer-momenta ($\lesssim$ 0.2 GeV/C).

23. S. Nagamiya et al, Phys. Letters (in press);
I. Tanihata, private communication.

24. R.L.Hatch and S.E.Koonin, Caltech preprint (1978) and the papers cited therein.

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