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Coherent multiple production in proton-nucleus collisions at 200 and 300 GeV/c

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Two stacks of nuclear emulsion were exposed to 205- and 303-GeV/c proton beams. By following the beam protons, inelastic events induced by proton-nucleus collisions are obtained. Then the mean free path for coherent production and its energy dependence are studied. Finally, a feature of the target–mass-number dependence of the cross section for the inelastic proton-nucleus collision is shown.

I. INTRODUCTION

In this article the coherent production induced by the proton-nucleus collision is studied using nuclear emulsion exposed at the Fermi National Accelerator Laboratory. As found in various papers,[1] coherent production is a reaction in which all of the nucleons inside the target nucleus collide coherently with the incident hadron, that is, it is a reaction in which there is substantial constructive interference between the production amplitudes from the individual nucleons, at least in the forward direction. In most common cases this process leaves the target nucleus in its ground state. However, it is pointed out also that coherence is possible when the nucleus goes to a specific excited state.[1]

This coherent production is induced not only by the nuclear reactions, but also by the Coulomb reaction. Since the coherent nuclear reactions take place over the whole volume of the nucleus and the Coulomb reaction occurs at even larger distances, the coherent production is characterized by a small momentum transfer through the uncertainty principle. In this analysis we are not concerned with differentiation between these two types of reactions. As will be shown in Sec. II, coherent particle production is studied at beam proton momenta of 205 and 303 GeV/c. The selection criteria of the coherent events are given in Sec. III and the mean free paths for the events obtained are tabulated. In Sec. IV the energy dependence of these mean free paths is discussed comparing with the other emulsion data so far obtained. Finally, in Sec. V the target–mass-number dependence of the inelastic cross section for proton-nucleus collisions at 205 and 303 GeV/c is derived from the accepted total number of inelastic events.

II. EXPERIMENTAL PROCEDURE

Two emulsion stacks of Ilford K-5 pellicles were exposed to the proton beams at the Fermi National Accelerator Laboratory. Nominal momentum values are 205 and 303 GeV/c, respectively. The exposed beam density is a few times 10^4 particles per cm^2 at 205 GeV/c, and 3×10^3 particles per cm^2 at 303 GeV/c.

Inelastic-collision events were scanned by following the incident beam tracks. The total track length followed is 1060 m for 205 GeV/c and 526 m for 303 GeV/c. Events detected are classified by N_h, the number of heavily ionizing tracks (grain density larger than 1.4 times that of plateau value, corresponding to velocity smaller than 0.7 of the light velocity) longer than 3 μm, and n_s, the number of thinly ionizing tracks, and the notation N_h+n_s, usually adopted in emulsion work, is used.

The events of the types $0+1$ and $0+2$ in which the scattered angle of the proton is less than 5 mrad are excluded. In the $0+2$ events, the part-

TABLE I. Mean free paths for inelastic and $0+n_s$ events and related quantities.

Proton momentum	205 GeV/c	303 GeV/c
Track length[a]	1060 m	526 m
Number of inelastic events[b]	2976	1577
Mean free path for inelastic events[c]	35.6 ± 0.7 cm	33.4 ± 0.8 cm
Number of $0+n_s$[b]	449	280
Mean free path[c] for $0+n_s$	2.36 ± 0.11 m	1.88 ± 0.11 m
Mean n_s for $0+n_s$[d]	7.8 ± 0.4	7.8 ± 0.5
Mean n_s for[d] clean $0+n_s$	7.0 ± 0.4	7.3 ± 0.6

[a] Track lengths of incident protons followed.

[b] Numbers of inelastic and $0+n_s$ events accepted.

[c] Mean free paths to produce them.

[d] Mean n_s's for $0+n_s$ and clean $0+n_s$ (clean $0+n_s$ means the events without slow electrons and/or recoil nucleus).

icle with smaller scattered angle is assumed to be the surviving proton. By this selection of the scattered angle, the elastic events are reasonably excluded. In the elastic scattering at 200 or 300 GeV/c, the scattering angle of 5 mrad gives a condition of $q^2 \gtrsim 1$ (GeV/c)^2, where q^2 is the squared 4-momentum transfer of the proton. The differential cross section $d\sigma/dq^2$ is proportional to e^{-bq^2}, where the value of b is around 10 (GeV/c)$^{-2}$ at these momenta.[2] Therefore, almost all elastic events are excluded by the 5-mrad cut.

Electromagnetic processes, that is, knock-on and direct electron-pair production, contaminate the $0+2$ and $0+3$ events. The electrons with energies less than several tens of MeV are easily identified. The knock-on events with electrons of higher energies are almost completely excluded by the 5-mrad cut. For direct pair production, when necessary, the scattering measurements are performed to identify tracks due to electrons. Thus, in the case of 303 GeV/c, 50 direct pairs per 465 m and, in the case of 205 GeV/c, 23 direct pairs per 248 m are excluded from apparent $0+3$ events. These are not inconsistent with King's result.[3]

After correcting for these electromagnetic events, the total number of inelastic events, 2976 for 205 GeV/c and 1577 for 303 GeV/c, is obtained. The missing rate for the inelastic $0+1$ and $0+2$ events due to the 5-mrad cut is estimated using the results of bubble-chamber-film analyses for proton-proton interactions[4] under the assumption that the cross section for the proton-neutron interaction is the same as for the proton-proton one. According to this estimation, the missing rates for these two types of events are sufficiently small.

The results on inelastic cross sections and related quantities are tabulated in Table I. The prong-number distributions of $0+n_s$ events for both energies are shown in Figs. 1 and 2. Events accompanied by a slow electron or a visible track shorter than 3 μm (recoil nucleus) are called "dirty events," and they are shown in Figs. 1 and 2 by the hatched area. Such low-energy electrons or recoil tracks show that the target nucleus received appreciable energy from the incident pro-

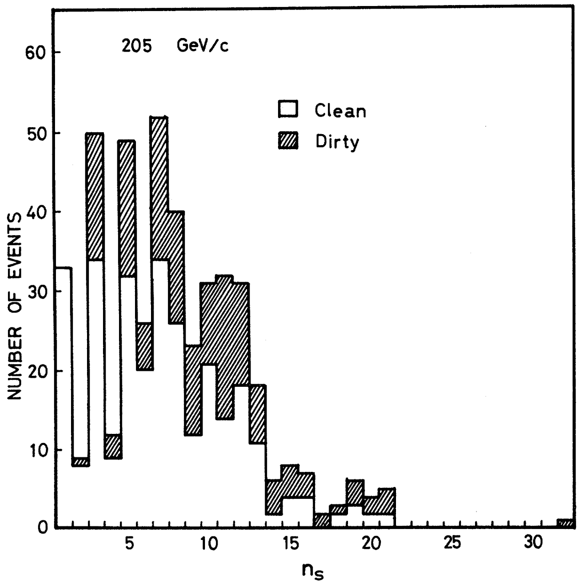

FIG. 1. n_s distribution for $0+n_s$ events at 205 GeV/c.

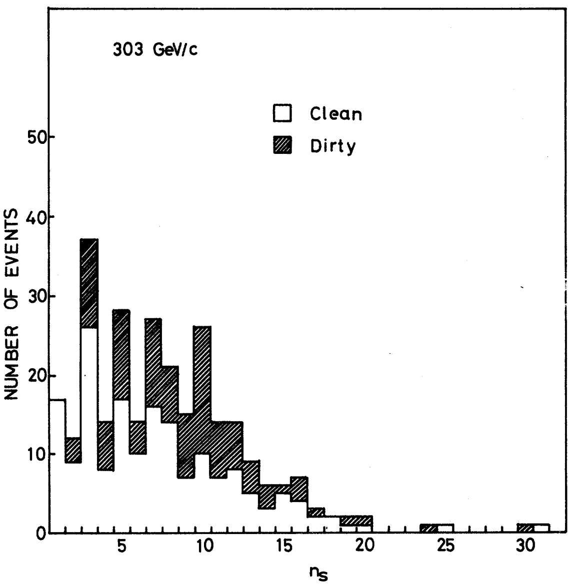

FIG. 2. n_s distribution for $0+n_s$ events at 303 GeV/c.

ton. In this analysis these dirty events were removed from the coherent events, since in most cases it is expected that the nucleus remains in its ground state.[1] As seen in Figs. 1 and 2, the numbers of clean events with multiplicities of 3, 5, and 7 are systematically larger than the neighboring multiplicities. This fact shows that the above-mentioned coherent production contributes to these small and odd-numbered multiplicity events. In connection with this, it is noted that Figs. 1 and 2 also show that the dirty events seem to have the same enhancement at $n_s = 3$, 5, and 7. This enhancement may include the cases in which the nucleus goes to a specific excited state.[1] However, because of low statistics, we are not concerned with this problem.

III. ESTIMATE OF NUMBER OF COHERENT EVENTS

Coherent processes are characterized by the small momentum transfer and this feature can be used as one of the selection criteria of coherent events. In a coherent event the momentum transfer q should lie in the region, $qR \lesssim 1$, where R is the nuclear radius of the target.

As in high-energy collisions $q_{\parallel} \gg q_{\perp}$,

$$q_{\parallel} \lesssim m_{\pi}/A^{1/3},$$

where A is the target mass number.

As shown by Fisher *et al.*,[5] the lower bound of $q_{\parallel}$ can be estimated without knowing the momentum value as

$$q_{\parallel} \gtrsim \sum_i m_i \sin\theta_i ,$$

where m_i is the mass and θ_i is the emission angle of the ith projectile particle.

We define $q_{\min}$ as

$$q_{\min} = \sum_i m_i \sin\theta_i .$$

$q_{\min}$ can be obtained for every observed event and is used for the selection of coherent events. In this calculation we should determine which particle is the projectile proton and it should give a value of the proper mass, because in the case of an incident proton, the projectile charged particles are usually one proton and an even number of pions. We make an assumption that the track with the smallest angle of emission is due to the projectile proton. Even if this assumption does not hold, our purpose is to estimate the lower limit for transferred momentum, and this is evidently fulfilled by this assignment of particles. In the case of neutron emission this procedure gives an incorrect result, but this case occurs less frequently than the proton-emission case, as the neutron case should have one more charged pion than the proton case.

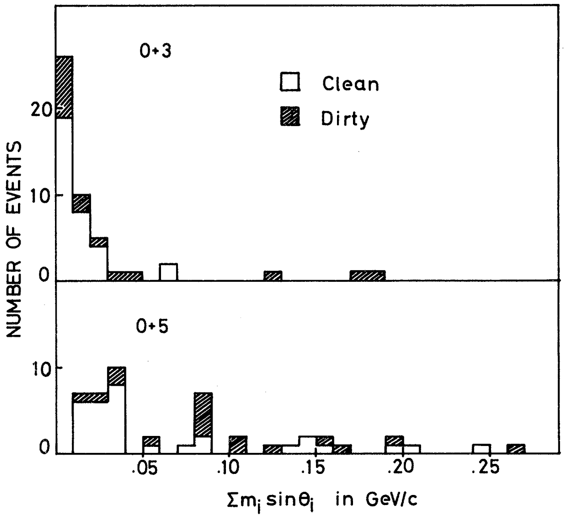

FIG. 3. $q_{\min}$ distribution for 0+3 and 0+5 events at 205 GeV/c.

For light nuclei (C, N, and O) in nuclear emulsion

$$m_{\pi}/A^{1/3} \approx 0.6 \text{ GeV}/c ,$$

and for heavy nuclei (Ag and Br)

$$m_{\pi}/A^{1/3} \approx 0.03 \text{ GeV}/c .$$

Therefore, events with $q_{\min}$ smaller than 0.06 GeV/c are considered as possible coherent events. The distributions of $q_{\min}$ are shown in Figs. 3 and 4. In the region of $q_{\min}$ smaller than 0.06 GeV/c there exist dirty events, and this shows that incoherent events are also included in this $q_{\min}$ region. To estimate the number I of such events, $q_{\min}$ distributions for dirty events and for clean incoherent events are assumed to be similar. Then

$$I = K \times (\text{No. of dirty events at } q_{\min} \leqslant 0.06 \text{ GeV}/c) ,$$

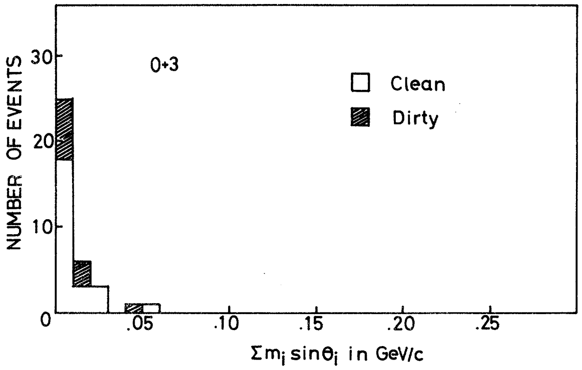

FIG. 4. $q_{\min}$ distribution for 0+3 events at 303 GeV/c.

where

$$K=\frac{(\text{No. of clean events at } q_{\min}>0.06\ \text{GeV}/c)}{(\text{No. of dirty events at } q_{\min}>0.06\ \text{GeV}/c)}\,.$$

For 205 GeV/c this method of correction was used, but in the case of 303 GeV/c the number of events is not large enough to allow us to estimate K. So, instead of K, K' is used, where K' is defined by

$$K'=\frac{(\text{No. of clean events with } n_s \neq 1,3,5,7)}{(\text{No. of dirty events with } n_s \neq 1,3,5,7)}\,.$$

K' is around 1.40 for both 205 and 303 GeV/c.

Another method is to subtract $K' \times$(No. of dirty events at $q_{\min} \leq 0.06$ GeV/c) from (No. of clean events at $q_{\min} \leq 0.06$ GeV/c). As shown in Table II for the case of 205 GeV/c, these two methods give consistent results.

IV. RESULTS AND DISCUSSIONS

Values of the mean free path for proton-nucleus coherent interactions with three and five prongs at 205 GeV/c and with three prongs at 303 GeV/c are given in Table II, where at 205 GeV/c values obtained using both the above-mentioned K and K' corrections are shown. As to other coherent events with other multiplicities not listed in Table II, the statistics are not enough to derive reliable values.

In Fig. 5 the mean free paths for the coherent productions at various proton energies obtained so far by emulsion analyses[6,7] are shown. In other analyses different selection criteria are adopted except for Ref. 7. Therefore, some caution is necessary when we compare our results directly with those of other authors, among which the difference between the selection criteria of $\sum_i m_i \sin\theta_i$ and $\sum_i \sin\theta_i$ would be the main problem. A criterion $\sum_i m_i \sin\theta_i$ is more strict and expected to give systematically lower numbers of coherent events than that of $\sum_i \sin\theta_i$. The difference of the number of coherent events due to these different criteria is considered to be more serious in the lower multiplicty events. If the selection of $\sum_i \sin\theta_i \leq A^{-1/3}$ ($\approx$0.4) is applied to our data, the mean free paths of 0+3 and 0+5 coherent events for 205 GeV/c are $32\pm^{7}_{5}$ m and $76\pm^{30}_{17}$ m, respectively. By comparing these values with those shown in Table II, it is seen that the difference between the two methods is significant in the case of 0+3, but is not so serious for 0+5. In Fig. 5, therefore, one could see the energy dependence of the mean free path for the 0+5 coherent events as continuing to decrease. For 0+3 events, the selection of $\sum_i m_i \sin\theta_i$ gives systematically longer mean free paths than the other, but is better to discuss the absolute value of the mean free path for the coherent events. Figure 5 shows that the mean free path for 0+3 events at 205 GeV/c is somewhat shorter than that at 303 GeV/c. However, the statistics of the data at 303 GeV/c are not sufficient. Therefore, drawing any trend of the energy dependence for the 0+3 coherent events at these energies will be reserved until further studies are finished.

TABLE II. Mean free paths for coherent events.

Proton momentum	Event type	Correction[a] method	Number of events	Mean free path in m
205 GeV/c	0+3	K	23 ± 5	46^{+13}_{-8}
		K'	14 ± 4	76^{+30}_{-17}
	0+5	K	17 ± 4	62^{+20}_{-12}
		K'	14 ± 4	76^{+30}_{-17}
303 GeV/c	0+3	K'	10 ± 3	53^{+22}_{-13}

[a] Defined in the text.

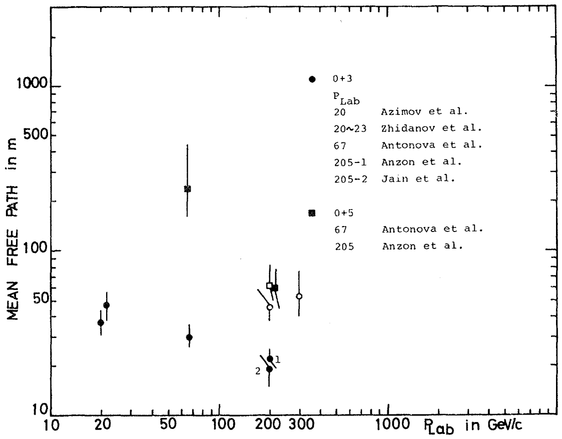

FIG. 5. Energy dependence of the mean free path for coherent productions. ○ and □ are our results. ● and ■ are the results of other authors.

V. MASS-NUMBER DEPENDENCE OF INELASTIC CROSS SECTION

The mass-number dependence of the inelastic cross section for proton-nucleus collisions can be derived using the total number of inelastic events tabulated in Table I.

If the inelastic cross section for proton-nucleus collisions is expressed by $\sigma_0 A^{\alpha}$, where σ_0 is the inelastic cross section for the elementary proton-nucleon collision, which is assumed to be the same as that for the proton-proton collision, and A is the nuclear mass number, then the observed mean free path for the inelastic collision, λ_{ob}, is written as

$$1/\lambda_{ob}=\sigma_0 \sum_i A_i^{\alpha} N_i\,,$$

where N_i is the number of the specific nucleus i in unit volume of emulsion. The summation is carried out over all the nuclei composing the nuclear emulsion. Using this relation, one can derive the α value from the observed λ_{ob}'s to be 0.76 ± 0.01 for 205 GeV/c and 0.77 ± 0.01 for 303 GeV/c. These results show that the A dependence of the inelastic cross section for proton-nucleus collisions at these energies might be somewhat stronger than that shown by $A^{2/3}$.

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[1] M. L. Good and W. D. Walker, Phys. Rev. 120, 1855 (1960); 120, 1857 (1960); J. J. Veillet, CERN Report No. CERN 68-7, 1968 (unpublished); L. Van Hove, CERN Report No. Th. 1746-CERN, 1973 (unpublished); K. Gottfried, in *High Energy Physics and Nuclear Structure, Proceedings of the Fifth International Conference, Uppsala, Sweden, 1973,* edited by G. Tibell (North-Holland, Amsterdam, 1974), p. 79; H. H. Bingham, *ibid.* p. 96.

[2] V. Bartenev, A. Kuznetsov, B. Morozv, V. Nikitin, Y. Pilipenko, V. Popov, L. Zolin, R. A. Carrigan, Jr., E. Malamud, R. L. Cool, K. Goulianos, I-Hung Chiang, A. C. Melissinos, D. Gross, and S. L. Olsen, Phys. Rev. Lett. 31, 1088 (1973).

[3] J. E. Butt and D. T. King, Phys. Rev. Lett. 31, 904 (1973).

[4] G. Charlton, Y. Cho, M. Derrick, R. Engelmann, T. Fields, L. Hyman, K. Jaeger, U. Mehtane, B. Musgrave, Y. Oren, K. Rhiness, P. Schreiner, H. Yuta, L. Voyvodic, R. Walker, J. Whitmore, H. B. Crawley, Z. Ming Ma, and R. G. Glasser, Phys. Rev. Lett. 29, 515 (1972); F. T. Dao, D. Goldon, J. Lach, E. Malamud, T. Meyer, R. Poster, and W. Slater, *ibid.* 29, 1627 (1972).

[5] C. H. Fisher, W. H. Gibson, A. Hason, and W. A. Venus, Nuovo Cimento 27, 761 (1963).

[6] Z. V. Anzon, M. G. Antonova, E. G. Boos, A. A. Goryachikh, I. Ya. Chasnikov, E. K. Kanygina, A. V. Kholmetskaya, G. S. Kolyachkina, P. V. Morozova, G. I. Mukhordova, N. P. Pavlova, Zh. S. Takibaev, C. I. Shakhova, N. P. Bogachev, F. G. Lepekhin, B. B. Simonov, V. G. Bogdanov, N. A. Perfilov, Z. I. Solovjeva, V. G. Khlopin, M. I. Adamovich, M. M. Chernyavsky, N. A. Dobrotin, S. P. Kharlamov, V. G. Larionova, M. I. Tretyakova, K. I. Alekseeva, S. A. Azimov, A. I. Bondarenko, L. P. Chernova, G. M. Chernov, K. G. Gulamov, U. G. Gulyamov, V. V. Lavkov, V. Sh. Navotny, V. I. Petrov, T. T. Riskiev, and T. P. Trofimcva, in *Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, 1973* (Colorado Associated U.P., Boulder, 1973); P. L. Jain, M. Kazuno, Z. Ahmad, B. Girad, G. Thomas, and H. Moses, Lett. Nuovo Cimento 31, 113 (1974); M. G. Antonova, E. G. Boos, P. W. Morozova, N. P. Pavlova, C. I. Shakhova, Zh. S. Takibaev, J. Babecki, Z. Czachowska, B. Furmanska, R. Holynski, K. Karnicka, S. Krzywdzinski, G. Nowar, K. Rybicki, O. E. Badawy, N. P. Bogachev, N. Dalkhazhav, R. Khoshmukhamedov, J. M. Kohli, G. S. Shabratova, K. D. Tolstov, M. M. Chernyavsky, N. B. Maslennikova, G. I. Orlova, M. I. Tretyakova, K. I. Alekseeva, S. A. Azimov, A. I. Bondarenko, L. P. Chernova, G. M. Chernov, K. G. Gulamov, U. G. Gulyamov, V. V. Lavkov, V. Sh. Navotny, T. T. Riskiev, P. G. Lepekhin, N. S. Skripnik, N. S. Svechnikova, T. P. Trofimova, C. Bataar, B. Chadraa, G. Sharkhuu, S. Sugar, and D. Tuvdendorzh, Phys. Lett. 39B, 285 (1972).

[7] S. A. Azimov, U. G. Gulamov, A. P. Chernova, and G. H. Chernov, Dokl. Akad. Nauk. SSSR 192, 1241 (1970); G. B. Zhdanov, M. I. Tretyakova, and M. M. Chernyavsky, Zh. Eksp. Teor. Fiz. 55, 170 (1968) [Sov. Phys.—JETP 28, 91 (1969)].