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MEASUREMENTS OF HIGH p_T LIGHT FRAGMENTS AT C.M. 90° IN 800 A·MeV C + C COLLISIONS

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Abstract

The spectra of high-p_T fragments, p, d, and t, have been measured at c.m. 90° in 800 A·MeV C + C collisions for p_T up to 1.8 GeV/c (proton), 2.5 GeV/c (deuteron) and 2.8 GeV/c (triton), using the Heavy Ion Spectrometer System (HISS) at the Bevalac. Invariant cross sections were measured down to eight orders of magnitude lower than those for production of low momentum protons. The proton spectrum shows a significant deviation from the Boltzmann shape in the high-energy region. The spectra of deuterons and tritons are explained well by, respectively, squaring and cubing the observed proton spectra.

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In high-energy nucleus-nucleus collisions it is important to study particle emission in the high-p_T region for various reasons. If the projectile and target consist of m- and n-nucleons, respectively, the maximum kinetic energy, E_{max}, for protons produced at 90° in the nucleon-nucleon (*NN*) c.m., center of mass, frame is given by

$$E_{max} = (\gamma-1)m_p c^2 + [\frac{2mn}{m+n}-1]\gamma\beta^2 m_p c^2, \qquad (1)$$

where γ and β represent the familiar Lorentz transformation variables that define the *NN* c.m. frame relative to the laboratory frame. At E_{Beam}^{Lab} = 800 A·MeV, E_{max} = 182 MeV for $m = n = 1$ (free *NN* collisions) and E_{max} = 517 MeV for $m = 1$ and $n \to$ large (proton-nucleus collisions), whereas E_{max} reaches 3.9 GeV for C + C collisions ($m = n =$ 12). Therefore, emission of protons at c.m. 90° having kinetic energies above 517 MeV is possible only in nucleus-nucleus collision.

We may think of several mechanisms that induce proton emission in the high-p_T region. The first one is random multiple *NN* collisions. Roughly speaking, if an average momentum transfer per *NN* collision is Δp, then the total momentum transfer after the n-th *NN* collision would reach $\sim\sqrt{n}\,\Delta p$. Therefore, if n is sufficiently large, emission of high-p_T protons is possible. The second mechanism is attributable to cooperative processes of several nucleons. A local hot and dense region might be created in the nucleus-nucleus collision through a macroscopic compression of matter. Then, nucleons might be strongly correlated which may induce high-momentum transfers on the order of $\hbar/\Delta x$, where Δx is a typical correlation length. In the first process, a Boltzmann-type spectrum is expected in the low-p_T region, whereas particle emission would be suppressed relative to that in the high-p_T region because of the limited number of *NN* collisions. On the other hand, in the second process a new exponential component may appear in the high-p_T region.

In the past, the proton energy distribution at c.m. 90° in 800 A·MeV C + C collisions has been measured for proton energies up to 700 MeV.[1] The spectrum shows a "shoulder-arm" shape with the turning point between the shoulder and arm located at $E_p^{c.m.}$ ~ 200 MeV. Above this energy the spectrum shape approaches an exponential,

$$E(d^3\sigma/dp^3) \propto \exp(-E_p^{c.m.}/E_0), \qquad (2)$$

with $E_0 \approx 68$ MeV. In the present experiment we have extended these measurements to higher proton energies, where the cross section is four orders of magnitude lower than that at $E_p^{c.m.} = 700$ MeV, to study if other new features start to appear.

A layout of the experimental setup is shown in Fig.1. A two-arm spectrometer system was constructed upon a base of the Heavy Ion Spectrometer System[2] (HISS) at the Bevalac. A magnetic field of 17.5 kG was applied over a region of 2-meter diam. × 1-meter gap. A carbon target was mounted inside the magnet gap. The magnetic field served two purposes: to eliminate low-energy particles from the event trigger and to analyze momentum of high-energy particles. Here, we report measurements of inclusive spectra by the A-arm shown in Fig.1. Two sets of three-plane multi-wire proportional chambers (WCA1; 20 cm × 20 cm, WCA2; 20 cm × 30 cm), two sets of six-plane drift chambers (DC1, DC2; 1 m × 2 m), and 47 sets of plastic scintillators (TA1, TA2, TA3) were used to measure particle tracks, dE/dx, and time-of-flight. Particle identification was almost perfect up to $p_{Lab} \approx 4$ GeV/c. The momentum resolution was typically 6 % at $p_{Lab} = 3$ GeV/c, and the absolute cross section value is reliable to within ±20 %. Details of the spectrometer performance will be discussed elsewhere.

Fig. 2 shows the observed proton energy distributions at c.m. 90° in 800 A·MeV C + C. Open circles indicate the present results, whereas closed circles show the data reported in Ref.1. The open and closed circles have no kinematical overlaps. We have checked the consistency of the present data for protons, deuterons, and tritons with those reported in Ref. 1 at 45° in the laboratory frame where two data sets overlap.

These data cover invariant cross sections over eight orders of magnitudes. The solid line in Fig.1 shows our previous fit[1] with an exponential shape given by Eq.(2). Clearly, the data show a smooth inward deviation from this exponential shape not only in the low-energy region below about 200 MeV but also in the high-energy region above 700 MeV. It should be noted that the slope of the spectrum at the high energy region is quite similar to that of negative pions.[1] No second slow exponential components have been observed at the level of cross sections down to $\approx 10^{-8}$ of the major cross sections.

Thus far, the c.m. 90° spectra have been studied extensively for the purpose of studying the participant dynamics, since at this angle the influence from the projectile and target fragments would be the smallest. It has been known that any thermal model[3-5] cannot explain the data, because they predict a pure exponential shape over the entire kinematic domain of emitted protons. We, therefore, compared our data with (a) a generalized thermal model called the phase-space model[6,7] and (b) the cascade model using the code of Cugnon[8]. As shown in Fig.2, the phase-space model seems consistent with the data. Although it slightly overestimates the yield in the low-energy region, it explains inward deviations from the exponential shape in both low- and high-energy regions. In regard to the cascade model, calculations were possible only up to $E_p^{c.m.} \approx 850$ MeV because of the limitation of the computation time. In the low-energy region, the model gives a reasonable fit to the data, but it gives a steeper slope than the data in the high-energy region, and at $E_p^{c.m.} \approx 850$ MeV the calculated cross section is by a factor of 6 smaller than the observed one. These comparisons tell us that the observed inward deviation from the exponential in the high-p_T region is likely due to a limited phase space available in this region, but the microscopic mechanisms that limit the available phase space are not totally due to the limited number of the random multiple *NN* collisions. In other words, some coherent mechanism other than random multiple *NN* collisions might be needed to fill up the available phase space.

It may be worthwhile to note that a modified thermal model proposed by Siemens and Rasmussen,[9] that is, the radial explosion model in which an exploding flow is superposed on the thermal spectrum, may also be consistent with the data at least in a qualitative manner. In this model, the apparent temperature is given by $T_{app} = T\gamma_0^{-1}(1-\beta_0/\beta)^{-1}$, where T is the temperature of the system, β_0c is the flow velocity, βc is the velocity of the emitted particles, and $\gamma_0 = (1-\beta_0^2)^{-1/2}$. The value of T_{app}, thus, decreases as β increases and it approaches constant as β approaches 1. This is consistent with the observed smooth variation of the slope for proton cross sections and with the fact that the slope of the spectrum at high-energy region is similar to that for pions. Quantitatively, however, no detailed comparison is currently available.

Shown in Fig.3 are the deuteron and triton spectra at c.m. 90° from the same collision. Deuteron cross sections cover about 7 orders of magnitudes and triton about 5 orders. In both cases we have tried to compare the data with squares and cubes of the observed proton cross sections, respectively, as expected from a coalescence model.[10,11] Amazingly, for over the six orders of magnitudes the cross sections satisfy the coalescence relation of

$$E_A(d^3\sigma/\,dp_A^3) = C_A[E_p(d^3\sigma/\,dp_p^3)]^A \qquad \text{for } \vec{p}_A = A\cdot\vec{p}_p, \tag{3}$$

with $C_A = (3.5\pm0.7)\times10^{-5}$ $[(\mathrm{mb/sr})c^3/(\mathrm{GeV})^2]^{-1}$ for d and $= (1.0\pm0.3)\times10^{-9}$ $[(\mathrm{mb/sr})c^3/(\mathrm{GeV})^2]^{-2}$ for t. These values are consistent with the values reported in Ref.1 to within the quoted errors.

We also note that both the deuteron and triton spectra are not of an exponential type, reflecting the fact that the proton spectrum is not exponential. Therefore, from Fig.3 we conclude that the light composite particles are formed through final state interactions among nucleons over a wide range of kinetic energy.

In summary, we have observed proton cross sections at c.m. 90° in 800 A·MeV C + C collisions over 8 orders of magnitudes in cross section. A substantial inward deviation from the exponential shape is observed not only in the low-energy region below 200 MeV but also in the high-energy region above 700 MeV. The inward deviation at high energy is most likely due to the decreased phase space for the emission of high-energy protons, but the microscopic mechanism to fill up the phase space seems not totally due to the random *NN* collisions. We have also measured deuteron and triton spectra in the same conditions and found that the power law [Eq.(3)] holds extremely well between proton spectrum and the spectra of composite particles, even 7 orders of magnitudes in the cross sections. This result implys that the final state interactions are important in the formation of these composite particles in wide ranges of kinetic energies. Finally, we mention that experimental research to clarify microscopic mechanism of proton emission in the high-p_T region is currently in progress in our group by measuring two-proton correlations using the B-arm spectrometer show in Fig.1.

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References

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1. S. Nagamiya, M.-C. Lemaire, E. Moeller, S. Schnetzer, G. Shapiro, H. Steiner, and I. Tanihata, Phys. Rev. C 24, 971 (1981).
2. D. E. Greiner, Nucl. Phys. *A*400, 325c (1983).
3. G. D. Westfall, J.Gosset, P. J. Johansen, A. M. Poskanzer, W. G. Meyer, H. H. Gutbrod, A. Sandoval, and R. Stock, Phys. Rev. Lett. 37, 1202 (1976).
4. J. Gosset, J. I. Kapusta, and G. D. Westfall, Phys. Rev. C 18, 844 (1978).
5. S. Das Gupta and A. Z. Mekjian, Phys. Rep. *C*72, 131 (1981).
6. J. Knoll, Phys. Rev. C 20, 773 (1979).
7. The calculation by the phase-space model was done by J. Knoll, private communication (1983).
8. J. Cugnon, T. Mizutani, and J. Vandermeulen, Nucl. Phys. *A*352, 505 (1981).
9. P. J. Siemens and J. O. Rasmussen, Phys. Rev. Lett. 42, 880 (1979).
10. H. H. Gutbrod, A. Sandoval, P. J. Johansen, A. M. Poskanzer, J. Gosset, W. G. Meyer, G. D. Westfall, and R. Stock, Phys. Rev. Lett. 37, 667 (1976).
11. M.-C. Lemaire, S. Nagamiya, S. Schnetzer, H. Steiner, and I. Tanihata, Phys. Lett. 85*B*, 38 (1979).

Figure Captions

FIG. 1 Layout of the experimental setup.

FIG. 2 Proton energy distribution measured at c.m. 90° in 800 A·MeV C + C collisions. Data are compared with the phase-space model (dot-dashed curve) and the cascade model (dashed curve).

FIG. 3 Deuteron and triton spectra measured at c.m. 90° in 800 A·MeV C + C collisions, as compared with squares and cubes, respectively, of the observed proton spectrum.

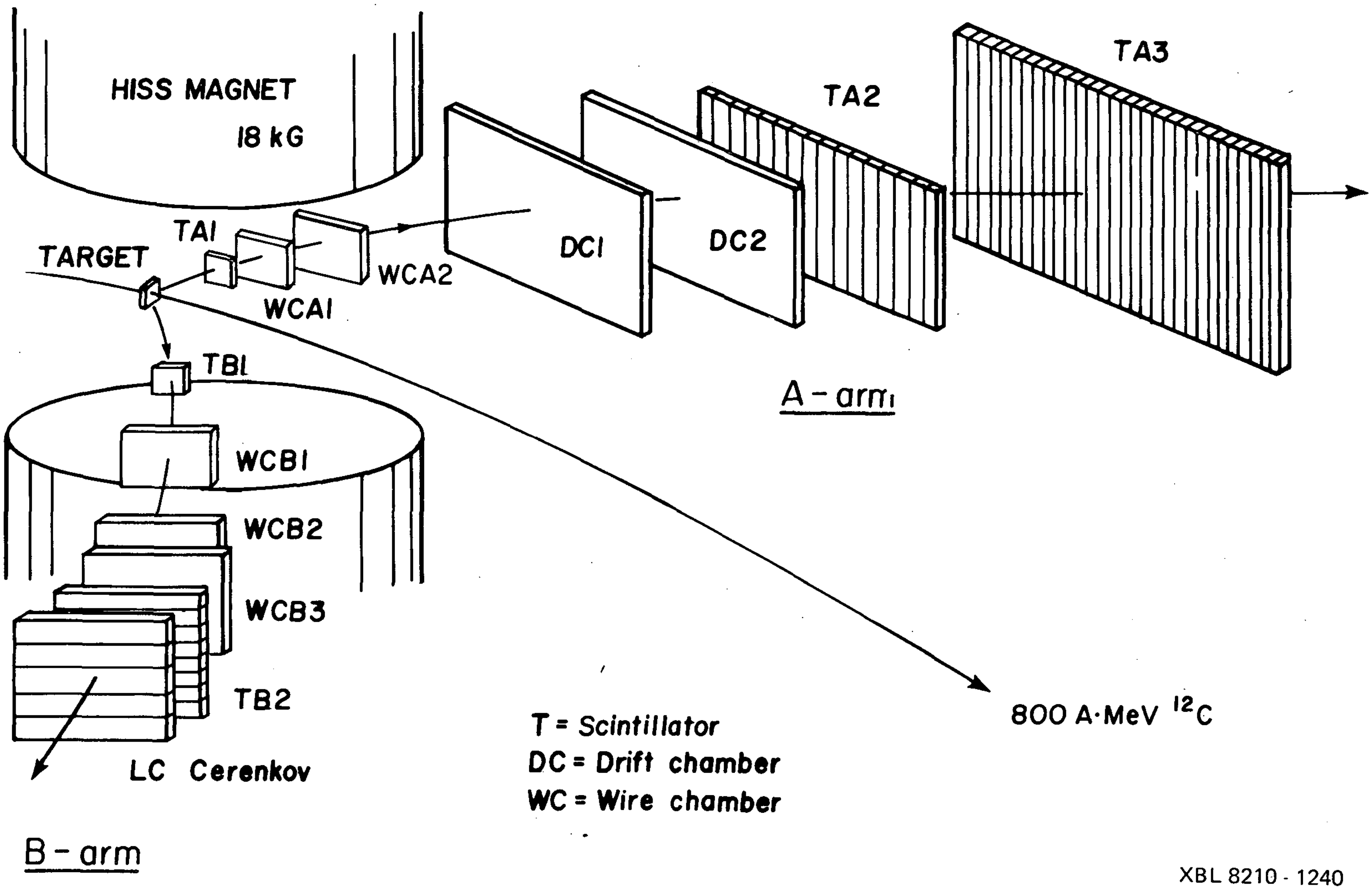
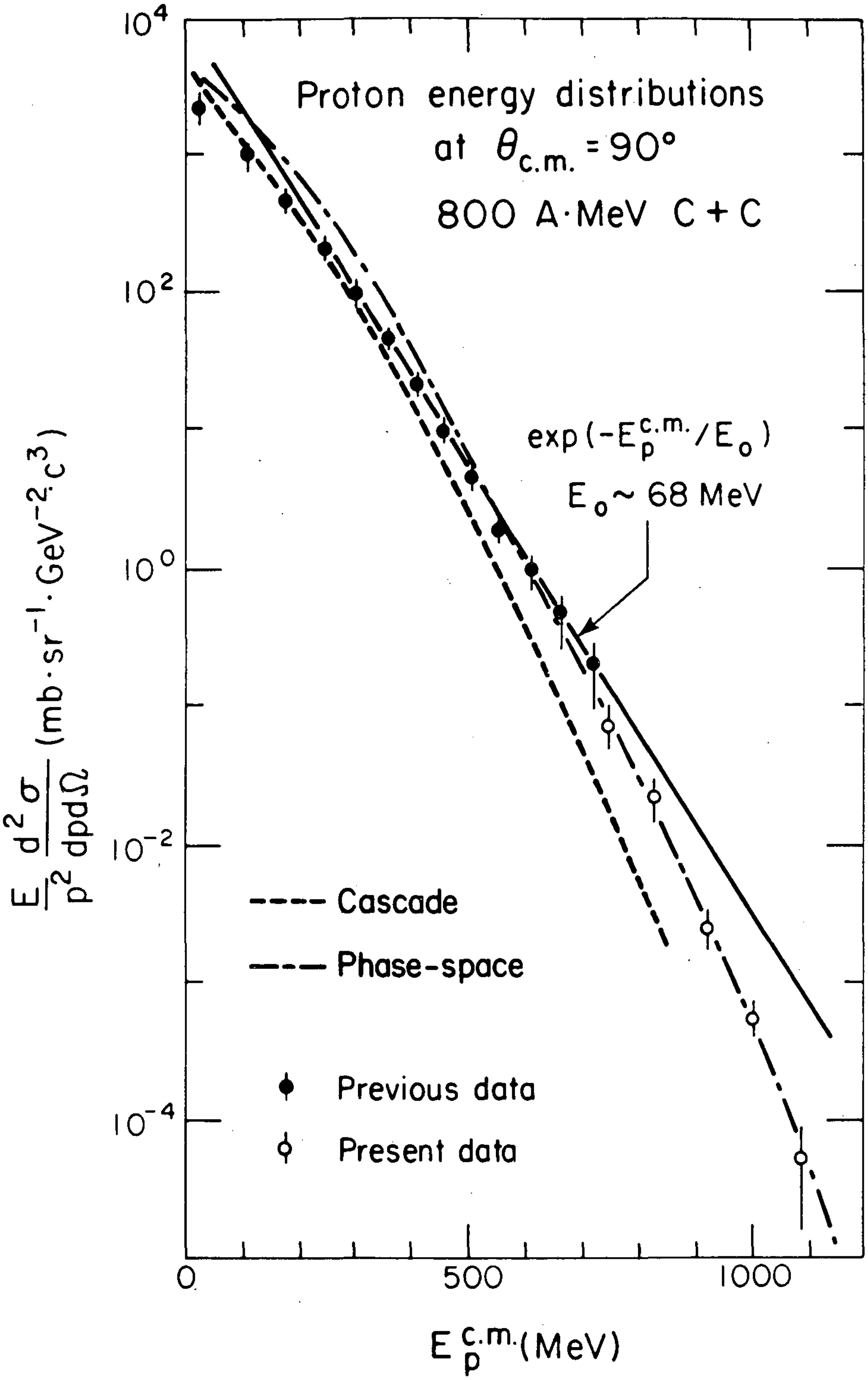

HISS MAGNET
18 kG
TA3
TA2
DC1
DC2
TA1
TARGET
WCA2
WCA1
TB1
A-arm
WCB1
WCB2
WCB3
TB2
800 A·MeV ¹²C
LC Cerenkov
T = Scintillator
DC = Drift chamber
WC = Wire chamber
B-arm
XBL 8210-1240

Fig. 1



XBL 839-872A

Fig. 2

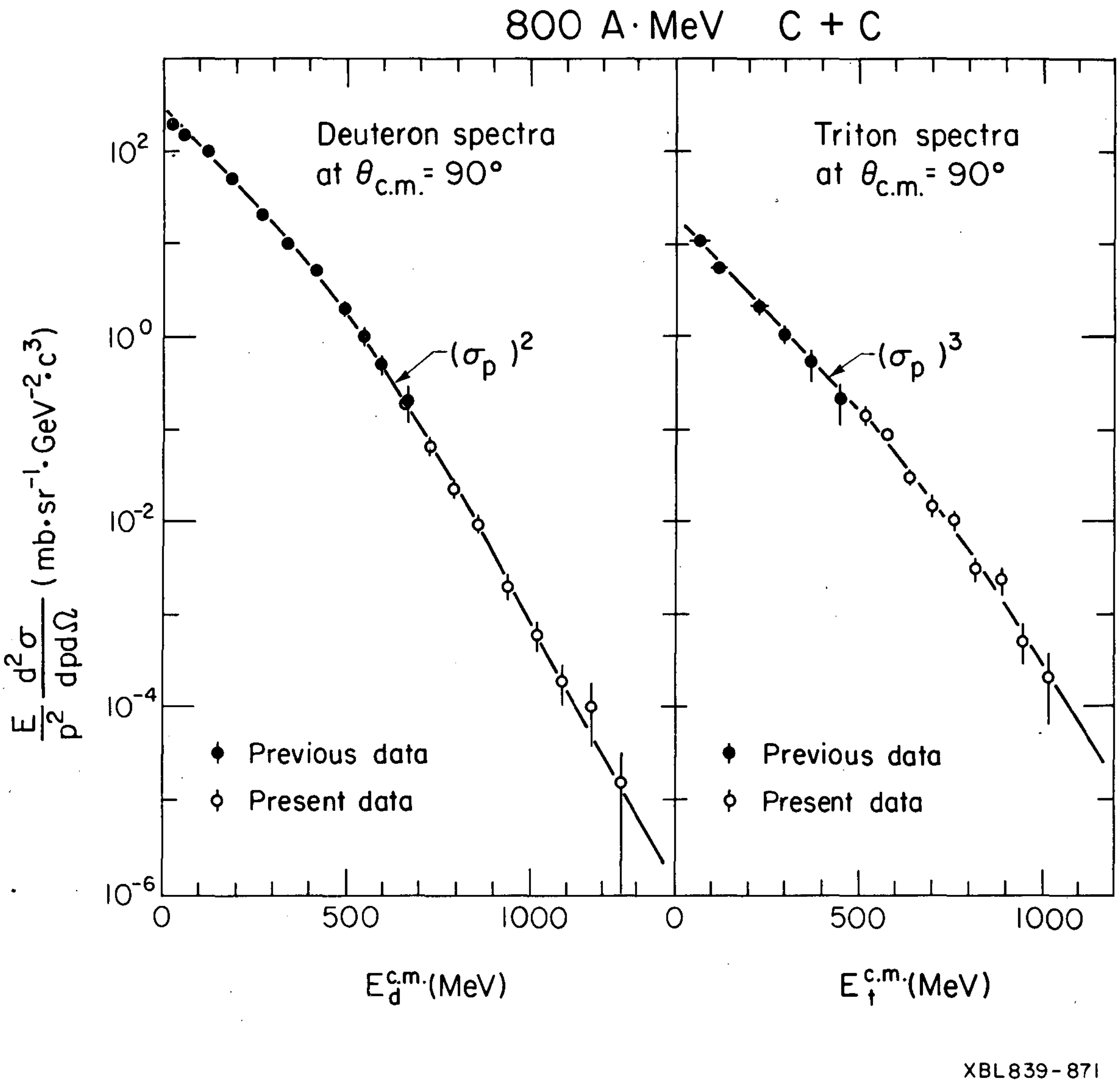

800 A·MeV C + C
Deuteron spectra at θc.m.= 90°
Triton spectra at θc.m.= 90°
(σp)2
(σp)3
Previous data
Present data
Previous data
Present data
E/p2 d2σ/dpdΩ (mb·sr-1·GeV-2·c3)
Ed c.m.(MeV)
Et c.m.(MeV)
XBL839-871

Fig. 3

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