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PARTICLE PRODUCTION IN RELATIVISTIC HEAVY ION COLLISIONS

James P. Vary

AMES LABORATORY, DOE
IOWA STATE UNIVERSITY
AMES, IOWA

Date Transmitted: April 1978

PREPARED FOR THE DEPARTMENT OF ENERGY
UNDER CONTRACT W-7405-eng-82

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ABSTRACT

Within the framework of multiple scattering theory we present and contrast both the conventional limiting case of independent multiple collisions of nucleons and the multiple scattering of collective degrees of freedom. Dramatically different predictions may be obtained for particle production in relativistic nucleon-nucleus and nucleus-nucleus collisions. We first study the pion multiplicity distributions to uncover evidence for a coherent-collective mechanism. Attention is then focused on potentially more conclusive tests - subthreshold (in the nucleon-nucleon kinematics) production of massive particles: $\bar{p}$, K^-, ψ/J and W, as examples. Evidence for a collective mechanism is found by examining subthreshold $\bar{p}$ production data in particle-nucleus collisions and contrasting with results from the IMC model including realistic Fermi motion. As perhaps the leading candidate for a coherent-collective mechanism we specifically adopt the Coherent Tube Model to explain these data since it has been successful in high energy particle-nucleus collisions.

I. INTRODUCTION

Two principal views of the collisions of relativistic heavy ions have emerged.

A. The heavy ions collide, then interpenetrate and form hot and dense baryonic matter which is equilibrated. With this one assumes some particular equation of state and a baryonic mass spectrum in order to predict particles that are produced.

B. The other approach comes from multiple scattering theory and here it is necessary to distinguish two limiting situations.

i. "Single Particle Dynamics" - Conventional multiple scattering approach using hadron-hadron scattering amplitudes plus initial baryon distributions to predict a total scattering amplitude in lowest order.

ii. "Collective Particle Dynamics" - Where the multiple scattering is that of certain coherent or collective degrees of freedom.

The most important emphasis of the above segregation of viewpoints is to underscore the fact that even within multiple scattering theory one has a selection: the scattering variables. In particular it has not been adequately stressed that multiple scattering theory is a microscopic approach which, when selective summations are incorporated into the lowest order terms, is equivalent to expanding about some collective degree of freedom. Thus, for example, if one imagined a particle-nucleus collision as dominated by particle-alpha particle scattering mechanisms then one could rewrite the entire multiple scattering formalism such that the leading term represented the particle-alpha collective scattering terms and the remaining terms included all corrections. While complete theoretical presentations in this vein have not been frequent in the literature it is important to keep in mind what is generally possible. It will be the purpose of this talk to stress primarily the multiple scattering approach to particle production and contrast the results obtained within the two subareas of single particle and collective particle dynamics. In this context we will be concentrating on rapid development of simplified versions in order to detect order of magnitude effects that could be evident in the data. Scattering through the strong interactions from a collective degree of freedom at intermediate and high energies, if provable, would indeed constitute a novel scattering mechanism and is worth considering along with the whole class of efforts predicting and searching for novel phenomena.

The main issues surrounding the single and collective particle limits of multiple scattering theory can easily be sketched.

In the limit of single particle dynamics the primary need is for the <u>total</u> hadron-hadron scattering amplitudes including all inelastic channels and the complete isospin dependence. Next, we must have a complete theory including the explicit treatment of the inelastic channels in order to accurately describe particle production. Finally, one must assess the questions of convergence - in other words, how large are the corrections to a lowest order description.

For the collective particle limit one must first answer the question: "What are the appropriate collective variables?" This usually requires an ansatz. Next, one postulates an "effective" scattering amplitude expressed in these variables. A main issue would then be how to derive such an effective scattering amplitude from the microscopic information available in the single particle limit. Again, one must also assess the question of convergence. How large are the corrections to an amplitude dominated in lowest order by collective scattering mechanisms? For example, how large are the single particle collision effects as corrections.

It may be possible, in view of the evidence presented here, that the single particle limit dominates in one (impact parameter and/or energy) domain and the collective particle limit dominates in another. This raises the important question of how does the transition occur? One then needs a complete unified model and a clear description of the transition region(s) as well.

II. THEORETICAL DEVELOPMENTS

The main philosophy of our approach will be to make as reasonable assumptions as possible but to emphasize the need for simplified versions of the multiple scattering approach in the collective and single particle limits. Thus one puts a primary emphasis on achieving models which are easily utilized and can be rapidly applied to the experimental situations that are feasible. Therefore, we do not encourage undue attention to the detailed numerical results that emerge but rather we concentrate on the trends and on possible order of magnitude effects that could be detected to discern the correct approach in a given situation.

In this spirit we will initially assume two models; the first is called the independent multiple collision (IMC) model[1] and the second is the coherent tube model (CTM).[2] These characterize respectively the single particle and collective limits of multiple scattering theory.

The hallmark of the IMC approach is that it includes realistic nucleon-nucleon data (including an isobar model for pion production), Fermi motion for the nucleons, and realistic density distributions to describe the colliding nuclei. The initial version (used for the results quoted in this presentation) neglects the complications of energy degradation, reabsorbtion and full isospin dependence.[3]

The coherent tube model has been summarized in the literature. However it is important to stress that for the purposes of these calculations we will invoke the "universality" assumption for our effective collision cross section whereby particle-tube and tube-tube collisions have the same cross sections as nucleon-nucleon scattering at the appropriately scaled energy. Thus, our calculations are to be distinguished from those that input detailed quark distributions in the CTM. We are also working to modify our approach in this direction and results will be published in the near future.

We now summarize the main multiple scattering ingredients that are common to both the IMC and the CTM approaches. We first define the conventional particle (p) - nucleus (A) thickness function by

$$T_{pA}(\vec{b}) = \int_{-\infty}^{\infty} \rho_A(\vec{b},z)dz \tag{1}$$

where b represents the particle impact parameter and ρ_A is the target density distribution normalized to A particles. The thickness function contains the information of the possible particle-nucleon collisons that can occur at this particular impact parameter. If we generalize this to the nucleus-nucleus (A-B) collision situation we construct the thickness function given by

$$\begin{aligned} T_{AB}(\vec{b}) &= \int \rho_A(\vec{b}-\vec{b}',z)\rho_B(\vec{b}',z')d^2b'dzdz' \\ &= \int T_{pA}(\vec{b}-\vec{b}')T_{pB}(\vec{b}')d^2b' \end{aligned} \tag{2}$$

where we have expressed the total thickness function in terms of the nucleon-nucleus thickness functions for the projectile and target respectively in the last equation. These functions are normalized to

$$\begin{aligned} &\int T_{pA}(\vec{b})d^2b = A \\ &\int T_{AB}(\vec{b})d^2b = AB \end{aligned} \tag{3}$$

which represents the maximum possible number of nucleon-nucleon (N-N) collisions that can occur in the particle-nucleus and the nucleus-nucleus situations respectively when there is no "reflection".

Now, rather than developing total scattering amplitudes we will use the ingredients above to go directly, by means of probability arguments, to obtain cross sections. We define the quantity $\sigma T_{AB}(b)/AB$ as the total probability that one specific nucleon from nucleus A scatters from one specific nucleon from nucleus B. From this we construct the probability distribution that there will be exactly i N-N collisions when A collides with B at impact parameter b

$$P(i,AB,b) = \binom{AB}{i}\left(\frac{\sigma T_{AB}(b)}{AB}\right)^{i}\left(1 - \frac{\sigma T_{AB}(b)}{AB}\right)^{AB-i} \tag{4}$$

Now it is possible to construct certain average quantities which are properly averaged over impact parameter. For example we can calculate the probability that there are exactly i N-N collisions in an inelastic A-B collision:

$$P(i,AB) = \int d^2b\ P(i,AB,b)/\sigma_{AB}^{R} \tag{5}$$

where we have divided by the total reaction cross section for the collision which is computed within Glauber theory.

In addition we easily compute the average number of N-N collisions per inelastic A-B collision:

$$\langle i\rangle_{AB} = \sum_i \int d^2b\ iP(i,AB,b)/\sigma_{AB}^{R} = AB\,\frac{\sigma}{\sigma_{AB}^{R}} \tag{6}$$

where we see that a simple analytic result emerges: that is, the average number of collisions is just the maximum number possible, AB, modified by a scale factor which is the ratio of the N-N total cross section to the A-B total reaction cross section. This can be very useful for simple estimates as we shall see below.

III. IMC MODEL FOR PION PRODUCTION

With the quantities defined above we are prepared to obtain a simple model for pion production in relativistic heavy ion collisions. Before obtaining the complete distribution of produced pions it is convenient to make a quick estimate of the mean multiplicity. Assuming, as we do throughout this chapter, that σ and $\bar{n}$ (the mean multiplicity of pions produced per N-N collision) are energy independent for a region of interest, then an estimate of $\bar{N}(AB)$, the mean multiplicity of pions produced in inelastic A-B collisions, is

$$\bar{N}(AB) \simeq \bar{n}\langle i\rangle_{AB} \tag{7}$$

Since this single moment of the multiplicity distribution is insufficient, by itself, to compare theory and experiment, we wish to incorporate the distribution of pions produced in each N-N collision and eventually obtain the full pion distributions in an A-B collision. Analysis of the experimental p-p data[4] reveals that $\bar{n}$ is about 0.7 between 1 and 3 GeV/c incident lab momentum p_L and is approximately a constant. Therefore, we concentrate on incident nucleon momentum p_L/A at 3 GeV/c and neglect energy dependence in the N-N pion production distribution as the internuclear cascade proceeds. This simplified IMC model may be expressed in terms of p(n), the probability that n pions ($0 \leq n \leq n_{max}$) are produced in an N-N collision in this energy range. The available data[4] yield

$$\begin{aligned} p(0) &= 0.39 \\ p(1) &= 0.46 \\ p(2) &= 0.14 \\ p(3) &= 0.02 \; . \end{aligned} \tag{8}$$

The probability that N pions are produced in an A-B collision where there were i N-N collisions is

$$R(i,N) = \sum_{j=j_0}^{\min(N,i)} \sum_{\{A\}} \frac{j!}{k!\ell!\ldots r!}[p(n_{max})]^k[p(n_{max} - 1)]^\ell\ldots$$

$$[p(1)]^r[p(0)]^{i-j}\binom{i}{j}, \quad (9)$$

where

$$j_0 = \max(0,(N - 1)/n_{max} + 1) \quad (10)$$

rounded down and j represents the subset of the i collisions producing pions; {A} represents the set of all unique arrangements (i.e., fixed set of values for k, ℓ, ...,r) satisfying the two conditions

$$kn_{max} + \ell(n_{max} - 1) + \ldots + r = N,$$

$$k + \ell + \ldots + r = j. \quad (11)$$

Then the total probability that there are N pions produced in an A-B collision at $P_L/A = 3$ GeV/c is

$$P_N(AB) = \sum_i R(i,N)P(i,AB). \quad (12)$$

We present P_N as the solid curve in Fig. 1(a) for ^{40}Ar incident on Pb_3O_4 at 3 GeV/c per nucleon, which is the weighted sum of results for a ^{208}Pb and a ^{16}O target. All three density distributions were taken from fits to electron-scattering data and scaled to the total mass.

A reasonable way to extract the π^- spectrum would be to define $f(\pi^-,pp)$, $f(\pi^-,pn)$, and $f(\pi^-,nn)$ as the probability that a produced pion is a π^- in a pp, pn, or nn collision, respectively, at this energy. Based on the available data,[4] interpolations, and symmetries, we roughly

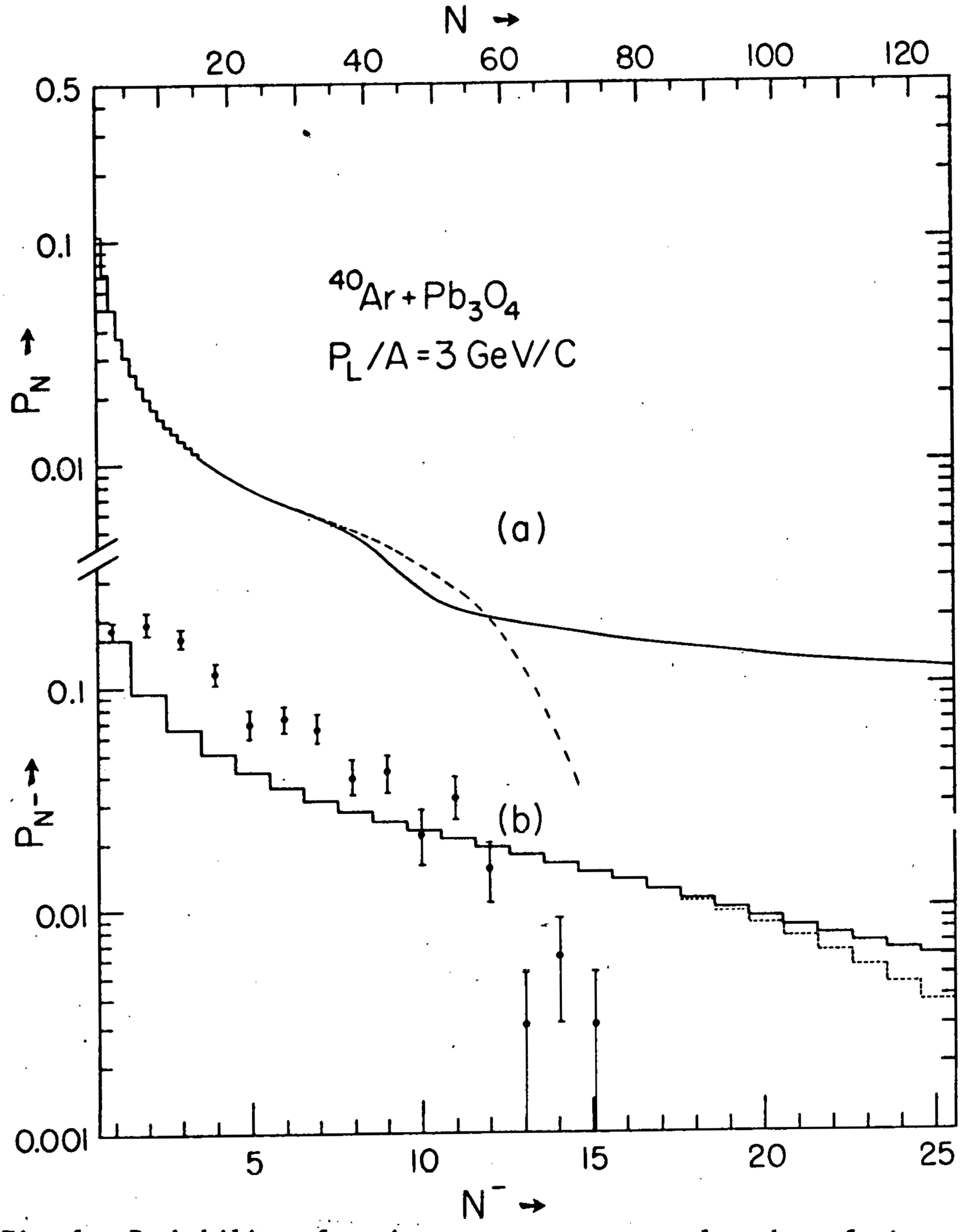

Fig. 1. Probability of a given event versus total number of pions (N) in that event or versus the number of negative pions (N^-) in that event. The probabiliteis P_N and P_{N^-} are given by Eqs. (12) and (13) respectively in the text. The solid curves give the results of the full IMC model while the dashed curves represent the results of an approximate resonance production model as described in the text. The data for the negative pion multiplicity spectra are from Ref. 5.

estimate these values to be 1/9, 1/3, and 2/3, respectively. Then, with the charge and baryon number of projectile and target nuclei, one obtains the distribution of collisions of each type and extracts $\bar{q}_{AB}(\pi^-)$, the probability in an A-B collision that a pion produced in an arbitrary N-N collision is a π^-, which is 0.375 for $^{40}Ar + {}^{16}O$ and 0.405 for $^{40}Ar + {}^{208}Pb$. Then, using the results for $P_N(AB)$, we construct $P_{N^-}(AB)$, the spectrum of produced π^-, from

$$P_{N^-}(AB) = \sum_{N=N^-}^{N_{max}} \binom{N}{N^-} (\bar{q})^{N^-} (1 - \bar{q})^{N-N^-} P_N(AB) \ . \tag{13}$$

The weighted sum of these results, denoted simply as P_{N^-} and renormalized by $1 - P_{N^-=0}$ for ^{40}Ar incident on Pb_3O_4 at 3 GeV/c per nucleon, is given as the solid curve in Fig. 1(b) and is compared with the available data.[5] It was found that the shape of P_{N^-} is very insensitive to changes in $\bar{q}$ by as much as 25%. Significant probability for rather high-multiplicity events appears as a striking result of the IMC model in contrast with the data. For example, the area under the curve for $N^- > 15$ indicates about 20% of the events will have > 15 negative pions whereas there are no events experimentally beyond 15. Approximately 10% are predicted in the range 16 to 25.

By truncating the number of collisions that contribute to the pion distribution one can hope to get a rough estimate of the effect of assuming all pions are produced via an isobar mechanism. These results are indicated as dashed curves in Figure 1. Reductions do occur but they are insufficient to explain the data.

We now wish to consider the effects of collective particle dynamics on the multiplicity spectra. As described in the introduction, the main issues are to propose the appropriate collective variables and the associated effective scattering amplitudes. We specifically adopt the Coherent Tube Model (CTM) which has been applied successfully to particle-nucleus collisions at high energies and the extension to nucleus-nucleus collisions is described in the next section. The qualitative effects of such a mechanism on the pion spectra are visible through the quantitative calculations of $\overline{p}$, ψ/J and W boson production displayed in the following section. There are two dramatic effects. First, the CTM yields a substantial cross section for "subthreshold" production - that is, production when the energy per nucleon alone would be insufficient to produce particles by independent N-N collisions. Second, and of direct relevance to the situation here, at energies per nucleon well above threshold (where the mean multiplicity in an N-N collision is relatively flat) the CTM yields a dramatic reduction in the cross sections for particle production from the IMC result.[6] This indicates that there is ample flexibility to describe the π multiplicity data with an admixture of a coherent production mechanism into the IMC.

In the pion spectra this reduction, through the CTM, of high multiplicity events is quite dramatic and was predicted in Ref. 1. A detailed calculation is now available from Dar and co-workers.[7]

IV. SUBTHRESHOLD PRODUCTION OF HEAVY PARTILCES

Having established the fact that the pion multiplicity spectra admits the possibility of a coherent production mechanism we now must ask the question how can we more directly test this hypothesis? We argue here that the best method of testing the presence of a coherent mechanism is to study the production of heavy particles at energies below the nucleon-nucleon threshold; that is, at energies where the collisions of independent nucleons would be insufficient to produce these particles.

A. Independent Multiple Collisions with Fermi Motion

Here we will augment the IMC model in order to include the effects of Fermi motion which will play a significant role in the subthreshold production regime.

Starting from Equation (9) we introduce the following approximations to the IMC model for inclusive production of particles which have very small cross sections in nucleon-nucleon collisions ($\bar{p}$ for example). This condition is well satisfied in our applications here. Thus, when p_1 is small compared to unity we can approximate Equations (9)-(12) as yielding an inclusive cross section of the following form

$$\sigma_{AB}(\bar{p},P_L) \simeq \sigma_{AB}^{R} \sum_{i=1}^{AB} P(i,AB)\, i p_1 p_0^{i-1}$$

$$\simeq \sigma_{AB}^{R}\, p_1 \sum_{i=1}^{AB} i\, P(i,AB)$$

$$\simeq \sigma_{AB}^{R}\, p_1 \langle i \rangle_{AB}$$

$$= AB\sigma(\bar{p},S_L) \tag{14}$$

where $\sigma(\bar{p},S_L)$ is the inclusive $\bar{p}$ production cross section in an N-N collision and where S_L is the invariant mass squared corresponding to a nucleon at rest in the projectile colliding with a nucleon at rest in the target.

To include Fermi motion, we define the distribution of invariant mass squared in N-N collisions where one nucleon is in the momentum distribution ρ_A and the other is in ρ_B and there is a relative motion P_L/A between the two

$$F(S) = \int d^3k_1 \int d^3k_2 \rho_A(\vec{k}_1+P_L/A)\rho_B(\vec{k}_2)\sigma(S - (k_1+P_L/A+k_2)^2) \tag{15}$$

In the limit of a single Slater determinant approximating the ground state of the colliding nuclei, ρ_A and ρ_B are sums of the momentum space single particle wavefunctions comprising the determinant. We then compute the smeared elementary production cross section

$$\hat{\sigma}(\bar{p},P_L/A) = \int_{4m^2}^{\infty} F(S)\sigma(\bar{p},S)dS \tag{16}$$

where m is the nucleon mass. From this we obtain the Fermi motion corrected IMC result

$$\hat{\sigma}_{AB}(\bar{p},P_L/A) \simeq AB\hat{\sigma}(\bar{p},P_L/A) \tag{17}$$

Before presenting the results of the IMC model it is worthwhile to develop the alternate approach from coherent scattering.

B. Coherent Scattering - Coherent Tube Model

We introduce this model in a form generalized to the A-B collision situation. Here projectile and target nuclei, at relativistic energies in the center of momentum frame, are Lorentz contracted disks. Hence, we assume that a contracted linear array of nucleons in the projectile interacts with a contracted target array when they pass within an N-N cross section, and that the array-array interaction is equivalent to an N-N interaction at the same excess energy (Q value) available for particle creation. This ansatz of a coherent scattering mechanism has been quite successful in explaining high energy particle-nucleus collisions. It is not altogether obvious that the assumptions are completely valid for application to the lower energy pion multiplicities discussed in the previous section. However it has been shown successful there.[7]

From the above we see that the distributuion of the number of target nucleons j struck by an arbitrary projectile nucleon is P(j,1B), which we interpret as the distribution of tube "lengths" j, struck by such a nucleon. Hence, the uncorrelated distribution of array-array collisions is P(i,1A) P(j,1B). We argue this is an adequate approximation to the true distribution for our present purposes. For a collision of an "i" array on a "j" array, the available energy for mass production, M_x (neglecting binding energies) is

$$M_x = m[\left\{i^2 + j^2 + 2ij\left(\frac{P_L^2}{A^2 m^2} + 1\right)^{1/2}\right\}^{1/2} - i - j] \ , \qquad (18)$$

The equivalent Lab momentum of a single nucleon on another, $\overline{P}_L$, that yields the same M_x is

$$\overline{P}_L = m\{[2(M_x/2m+1)^2 - 1]^2 - 1\}^{1/2} . \qquad (19)$$

from which one obtains $\overline{S}_L$. Thus, for the CTM

$$\sigma_{AB}(\overline{p}, P_L/A) = \sum_{ij} P(i,1A)\, P(j,1B)\, \sigma(\overline{p},\overline{S}_L) . \qquad (20)$$

C. Antiproton Results

There is very little data of sufficient quality and quantity to make a detailed comparison of these two limits of the multiple scattering theory. However, the best example seems to be subthreshold antiproton production.[8-10] These data were taken as the ratio of antiprotons to negative pions and were restricted to protons incident on copper targets at energies ranging from 3 GeV to about 6 GeV in the lab. In addition only certain momentum bins were examined and only at a few angles in the laboratory. We plot in Figure 2 the collection of these data. The reason for the spread in data points at a given energy is due to the different momentum bins and laboratory angles measured. Overall there is a spread of about an order of magnitude in these data depending on these variables.

The elementary production cross section in nucleon-nucleon collisions was taken from Gaisser, Halzen and Kajantie.[11] The resulting cross sections in the IMC including Fermi motion and the CTM are displayed in Figure 2. For the IMC the single particle wavefunctions were obtained from the work of Beiner[12] for Ni^{58} and the additional single

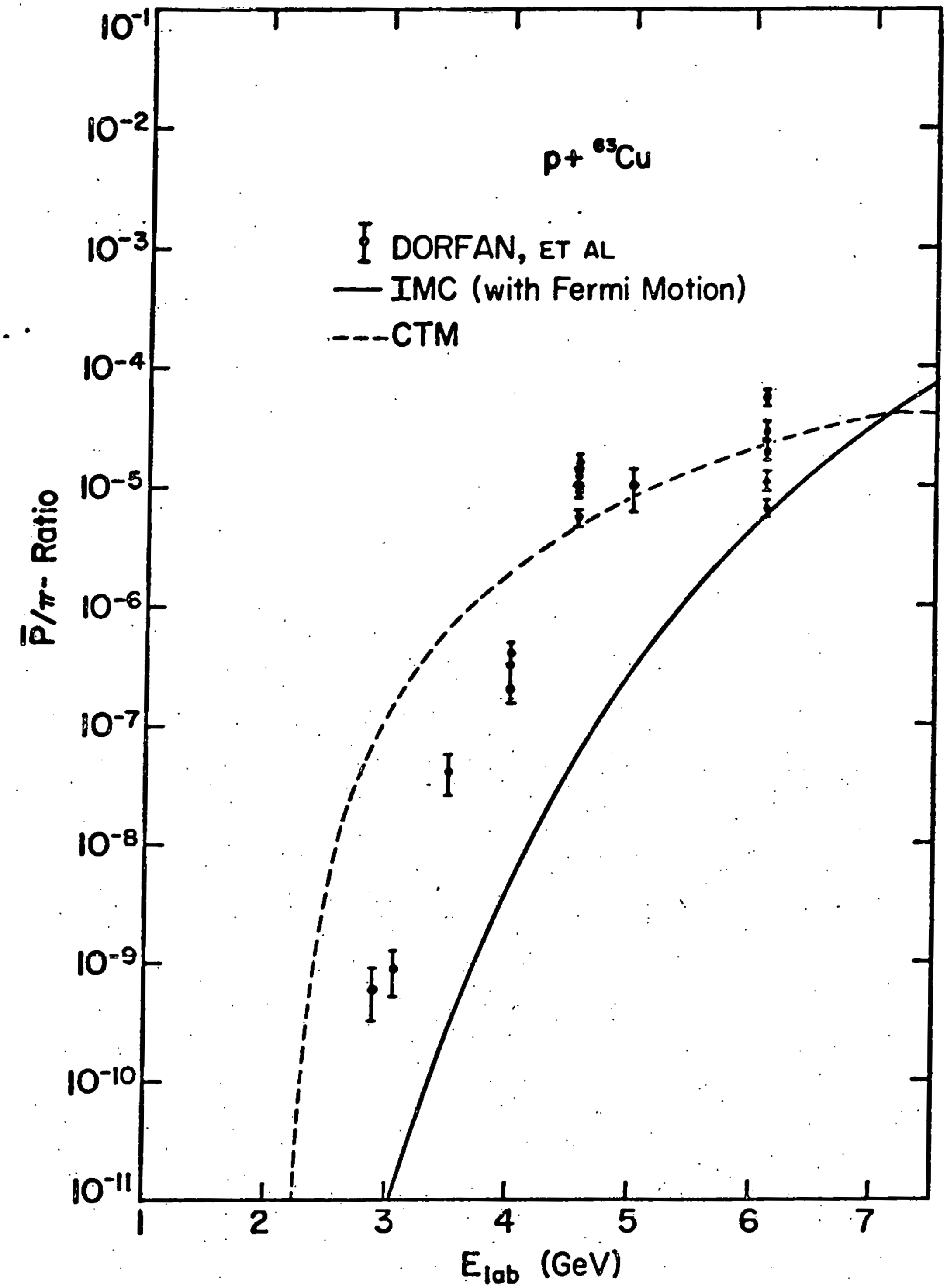

Fig. 2. Ratio of antiproton to negative pion production as a function of incident lab kinetic energy for protons on ^{63}Cu. The data are from Refs. 8-10 for various lab angles and momentum bins. The two curves represent the single particle or IMC limit (solid curve) and the collective particle or CTM limit (dashed curve) respectively of multiple scattering theory.

particle wavefunctions needed were calculated from a Woods-Saxon potential in a standard fashion.

It is clear from these calculations that the IMC underpredicts the cross sections by as much as several orders of magnitude at the lowest laboratory energies. On the other hand the CTM overpredicts the cross sections at the lowest energies. Thus we conclude that a substantial admixture of coherent production in the independent multiple collision approach is motivated by comparison with these data.

We now show how these differences are substantially enhanced in nucleus-nucleus collisions. Figure 3 protrays the results of these models for ^{40}Ca incident on ^{90}Zr. Here we have chosen to display the inclusive antiproton production cross section as a function of incident lab momentum per nucleon. For the Fermi motion in this particular example we have taken single Gaussian distributions with rms momenta appropriate to these nuclei. More realistic Fermi motion distributions would cause curve b to fall off somewhat slower as the lab momentum is decreased. Nevertheless, it is readily seen for lower energies such as available at the BEVALAC, that antiproton production cross section measurements would be highly instructive as to the role that coherent production plays in these collisions.

D. Application to the Production of ψ/J.

This subsection follows primarily the work of Reference 13 which neglects the Fermi motion contribution to the IMC model. For the elementary cross section $\sigma(J/\psi,P_L)$ in μb with P_L in GeV/c we fit two functional forms to the available data[14]

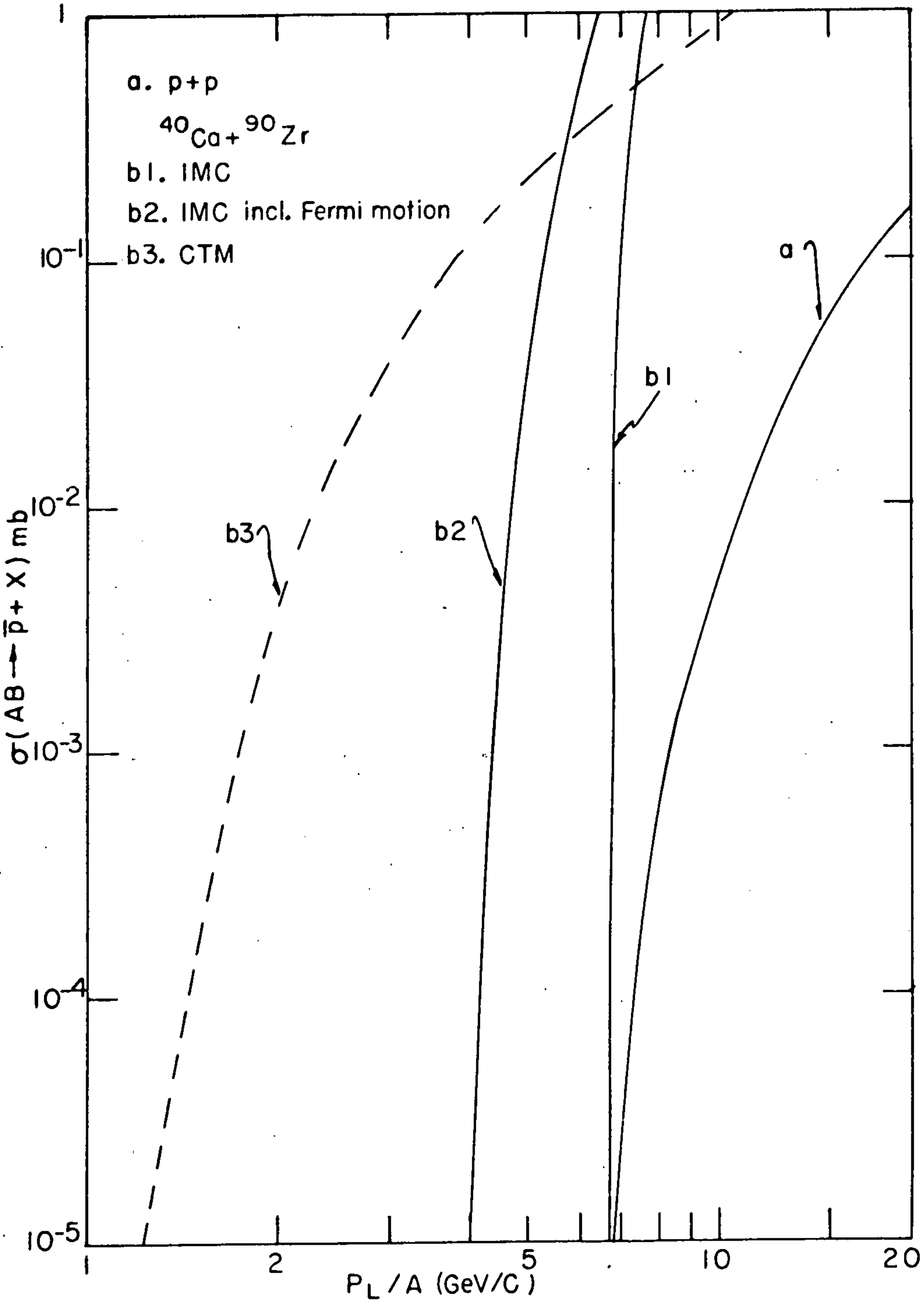

Fig. 3. Predictions of different limits of multiple scattering theory for the inclusive antiproton production cross section in collisions of ^{40}Ca on ^{90}Zr over a range of incident Lab momenta per nucleon.

$$\sigma(J/\psi,P_L) \simeq 2[1 - \exp(-(P_L-13)/500)]^2 \qquad (21)$$

$$\sigma(J/\psi,P_L) \simeq 3 \times 10^{-5}[P_L - 13]^{3/2} \qquad (22)$$

These differ considerably above ISR energies. They are depicted as curves (e) in Figures 4 and 5 respectively along with the subset of N-N data above 0.01 μb.

The CTM results (Equation (20) for the ψ/J example) are depicted as solid curves in Figures 4 and 5 as a function of P_L/A for a few characteristic A-B situations. A central feature when compared with the IMC (dashed lines) is the substantial cross section for "subthreshold" ($P_L/A < 13$ GeV/c) production of J/ψ due to the kinematics of array-array processes. The second major feature noted earlier is that at some value of lab momentum per nucleon the CTM results cross over and are substantially less than the IMC results thereafter. This is the feature of production well above threshold noted earlier that would reduce the pion multiplicity spectra in the high multiplicity regime for the case displayed in Fig. 1. The example in Fig. 5 is somewhat unrealistic since the parameterization for the elementary cross section continues to rise at very high lab momenta.

E. Application to the Production of the W Boson

Again we follow the work of Reference 13 but include results from Reference 20. Clearly, the collective-coherent effect will result in the enhancement of W production and a lowering of the effective threshold for production in nucleus-nucleus collisions. This possibility is of very fundamental interest.

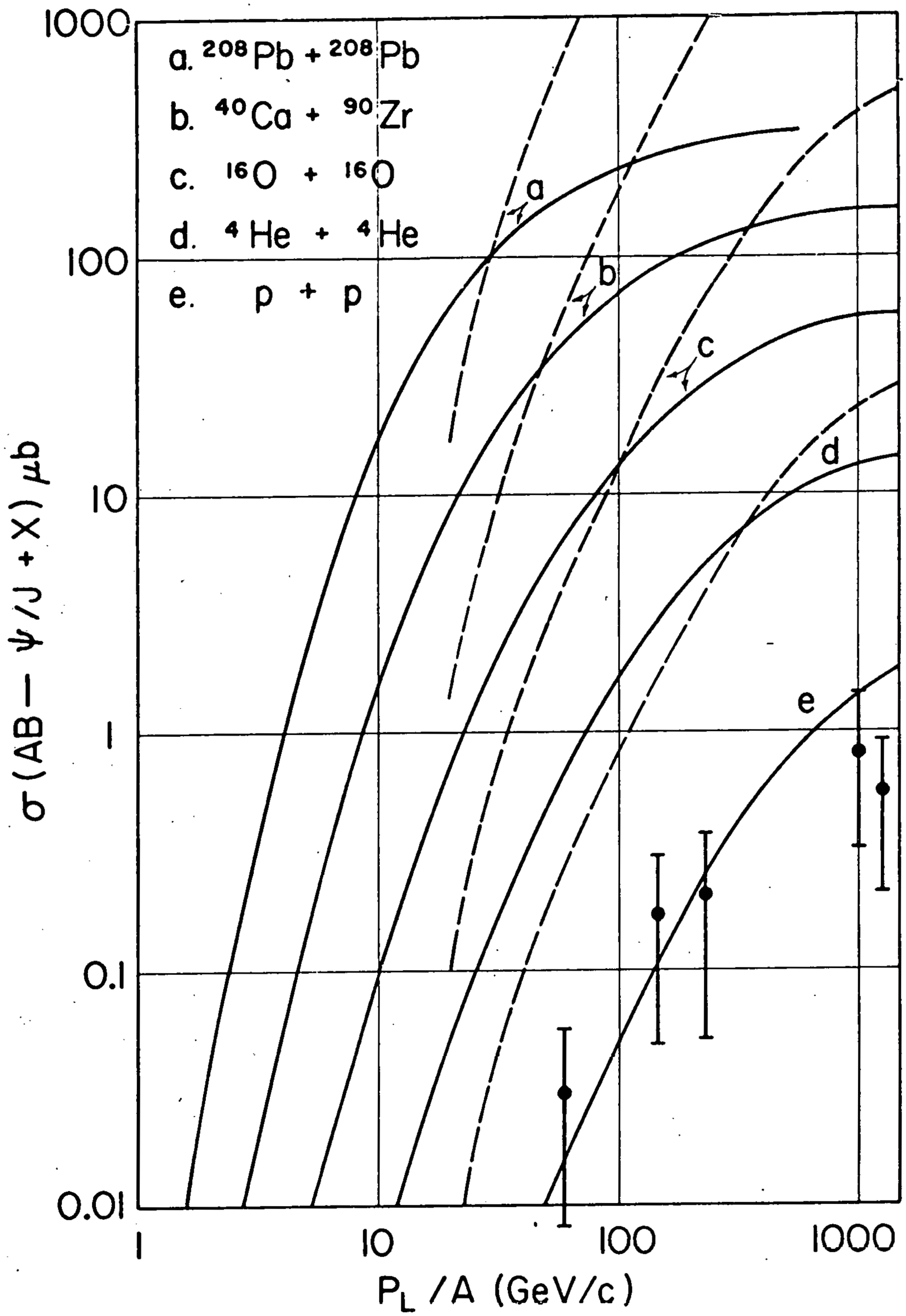

Fig. 4. Absolute cross section for ψ/J production in microbarns for nucleus-nucleus collisions versus lab momentum per nucleon. The momentum dependent nucleon-nucleon cross section used (curve e) corresponds to Eq. 21. Only that subset of the p-p data from Ref. 14 above .01 μb is depicted. The solid curves correspond to the IMC model as described in the text.

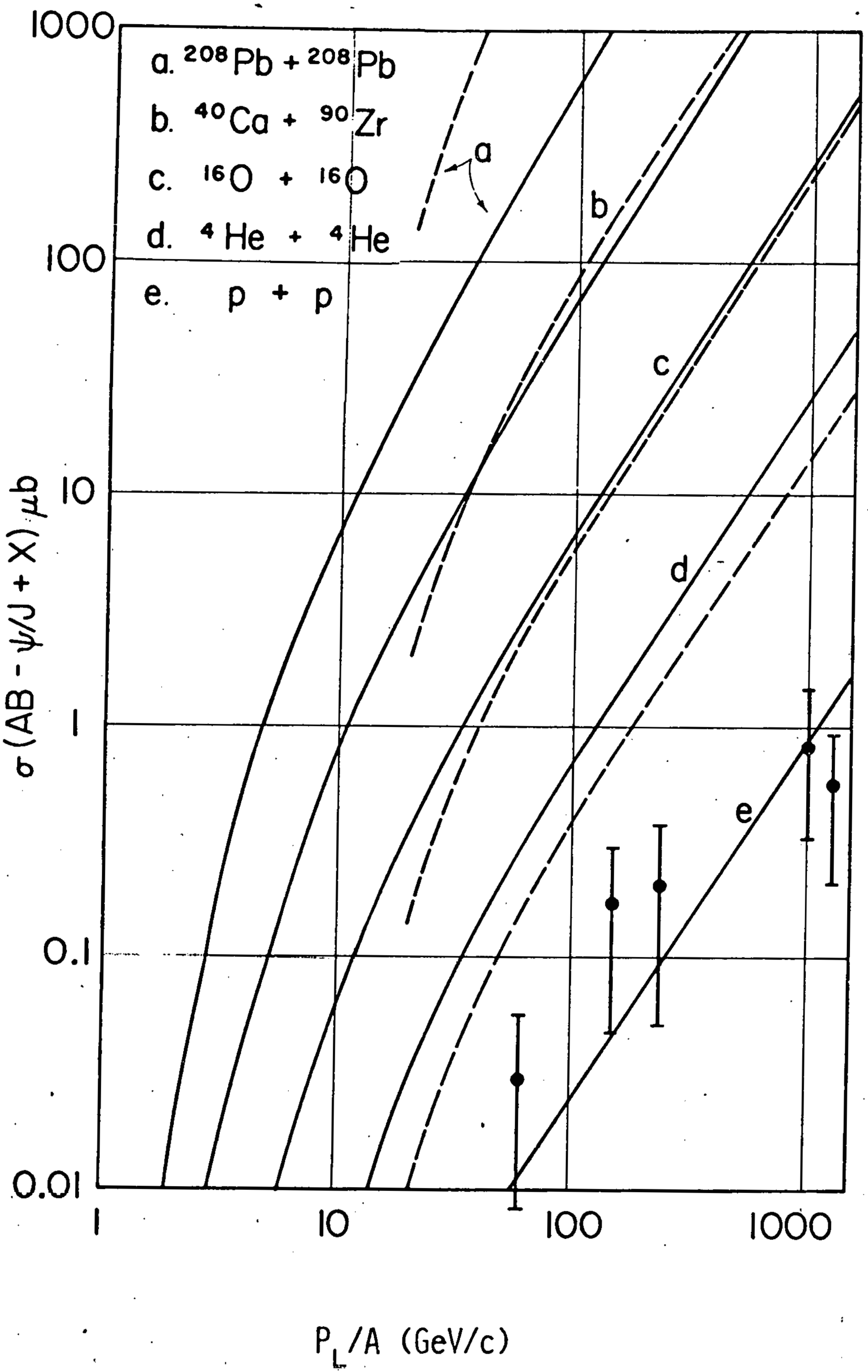

Fig. 5. The momentum dependent nucleon-nucleon cross section (curve e) used for the nucleus-nucleus results corresponds to Eq. 22. See caption to Fig. 4.

Our present-day intuition (for the W production mechanism) would have us write down an interaction Lagrangian with an up and anti-down quark (ignoring terms of order θ_C) undergoing annihilation at some space-time point through a Drell-Yan type process. Since W production has yet to be discovered we know nothing of possible form factors. With the existence of a form factor, one might argue convincingly for the required coherent effect. However, the annihilating quarks within nucleons are well known to be distributed in longitudinal and transverse momenta within the nucleon.[15] This equivalently implies spatial distribution for the annihilating quarks, one a quark from a nucleon in one nucleus and the other an antiquark from the sea associated with a nucleon in the other nucleus. The tube-tube collisions, as discussed above, to produce the W must therefore be interpreted as collisions of two parton tubes. An equivalent justification for such parton tube collisions results even if one does insist on point annihilation as in the initial Lagrangian. The remaining partons in the tube are not idle spectators, but contribute to the tube properties in such a way as to make the Brodsky-Farrar[16] counting rules work. Therefore, the actual physical situation should be analogous to Eqs. (18) through (20) with $\bar{p}$ replaced by W. The input similar to Eqs. (21) and (22) is provided by the work of Quigg[17] and Peierls, Trueman and Wang.[18] For the present we assume a W mass of $\sim$60 GeV as expected in the Weinberg-Salam SU(2) x U(1) theory. The resulting cross section for W boson production for the same nucleus-nucleus collisions as in Figs. 4 and 5 as a function of lab momentum per nucleon are given in Fig. 6. Curve e for pp collisions follows from Refs. 17 and 18.

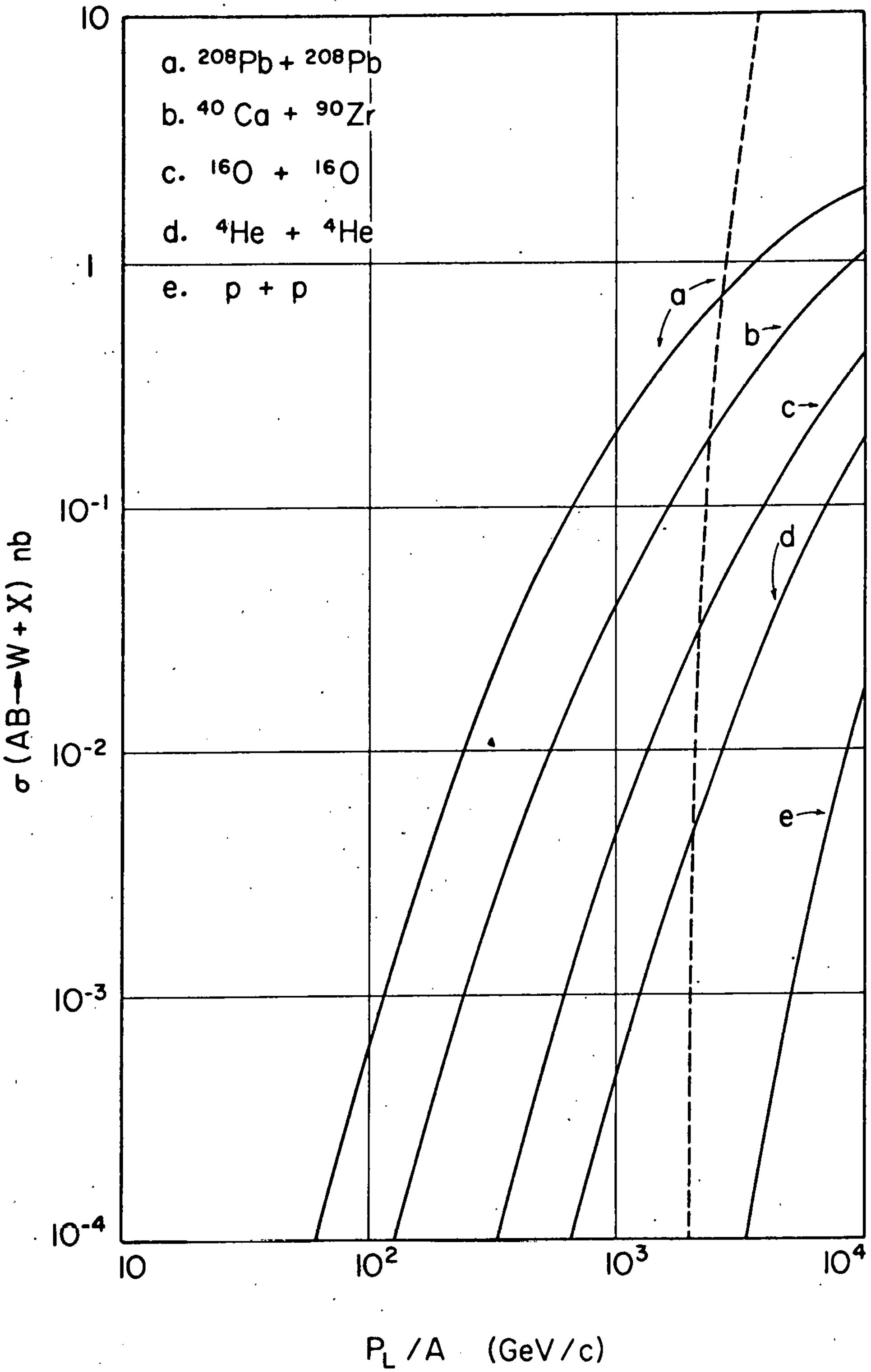

Fig. 6. Cross sections for W production vs lab momentum per nucleon for various nucleus-nucleus collisions. The dashed curve is the independent multiple collision model result for Pb on Pb with no effects of Fermi motion.

The predicted cross sections are substantial even considerably below the 2000 GeV/c laboratory momentum threshold for production in pp collisions (curve e). The dashed curve is the IMC model result for lead on lead. Since the technology of heavy ion beams developed for the BEVALAC program at Berkeley has demonstrated that relativistic beams of ^{208}Pb and ^{238}U are quite feasible,[19] we expect the results in Fig. 6 could provide impetus for the existing Serphukov and Fermilab facilities to examine heavy ion injection systems as well as for GSI to go higher than 10 GeV/A colliding beams. A possible unique detection system could be based on the exceedingly energetic muon coming from the decay $W \to \mu\nu$.

As one final application we discuss the results displayed in Ref. 20 for particle-nucleus collisions at lab momenta ranging from 10 GeV/c to 10^4 GeV/c. The main difference between this application and the ones discussed above is that we include a "realistic" momentum distribution in the IMC model for nucleons within the target nucleus. That is, the ordinary Fermi motion described above is augmented by the effects of short-range correlations. Nucleons colliding with other nucleons in relative s states in the nucleus can experience the hard core replusion of the nucleon-nucleon interaction and this results in very high momentum components in the single particle motion of these nucleons. A reasonable model to incorporate this effect has been included in Ref. 20 and the results of the IMC approach with this momentum distribution are displayed as the cross hatched area in Fig. 7. There is some uncertainty in the exact amount of such short-range correlations and this results in the band of predictions. Even with this

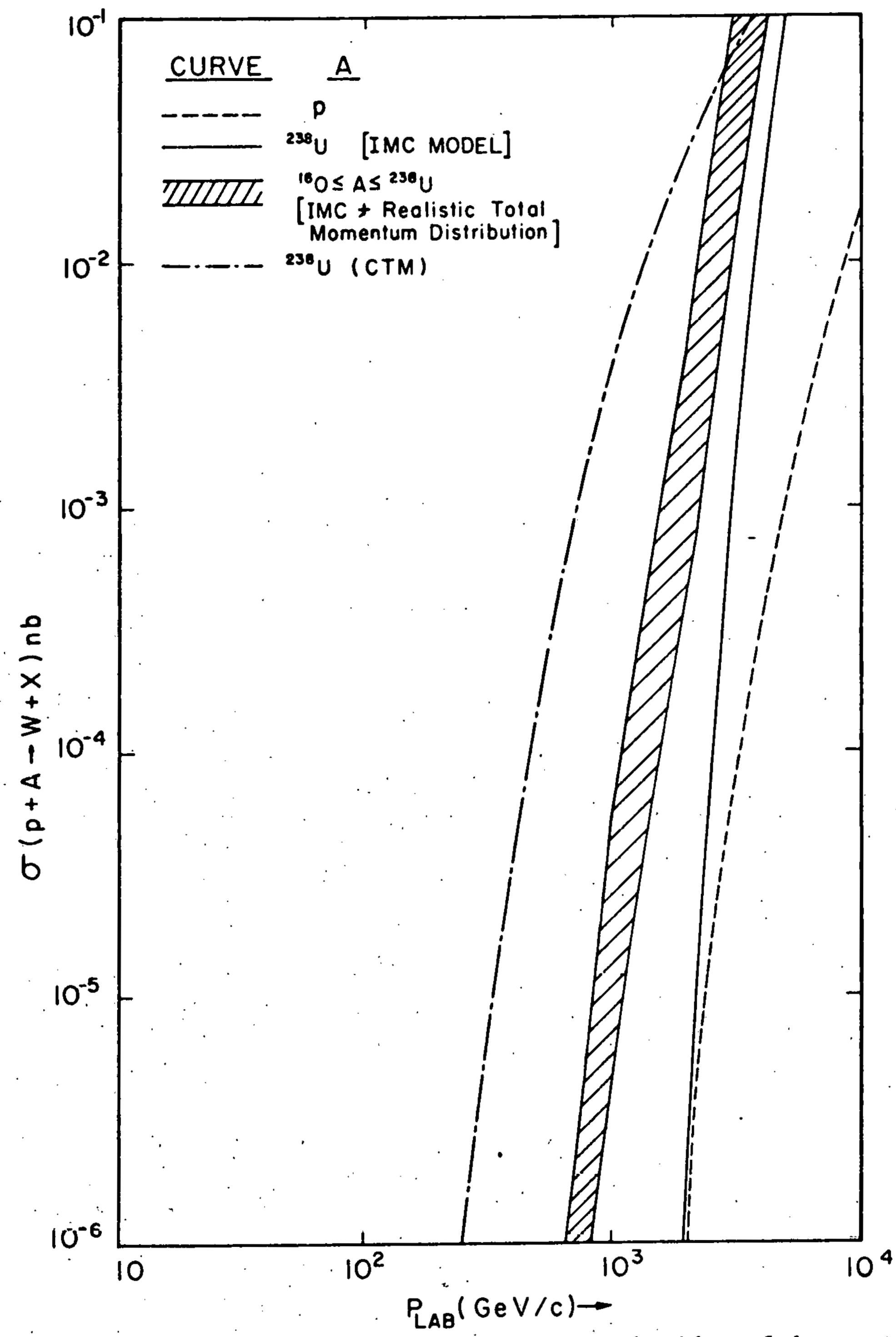

Fig. 7. W boson production cross sections vs. incident lab momentum for protons on various targets. The dashed and solid curves are for p-p and p-U (in the independent multiple collision model) to illustrate cases with no pre-threshold production. The dot-dash curve is the CTM result while the hatched band shows the range of values with ^{16}O and ^{238}U with realistic treatment of the bound nucleon momenta.

increased contribution to the subthreshold production, the IMC falls orders of magnitude below the CTM results at Fermilab energies. The overall production cross sections are indeed quite small. However, it should be noted that cross sectons have been measured in the range of 10^{-3} to 10^{-4} μb at Fermilab.

V. CONCLUSION

The primary purpose of this effort has been to argue that certain experiments would be exceedingly interesting to perform even with existing accelerators. First, it would be very worthwhile to study particle-nucleus collisions in the range of lab energies from 3-6 GeV and to look at the antiproton production cross section as a function of target baryon number. The CTM and IMC models have substantially different target dependence. In addition, all the arguments for antiproton production are easily seen to be valid for kaon production as well. Hence, antiprotons and kaons both should be studied in this energy region.

Second, the production of these particles should be studied in nucleus-nucleus collisions at the Berkeley BEVALAC with the widest range of the product AB.

Another very important conclusion is that if the heavy-ion beam energies could be made substantially larger or if colliding beam arrangements could be devised in the 10-20 GeV per nucleon region then one could study perhaps the production of the W boson. This would indeed be a very exciting possibility.

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