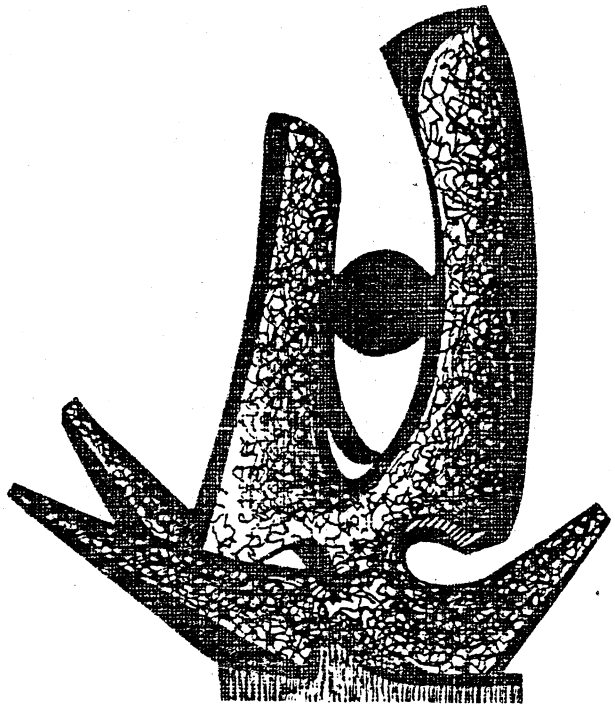
MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

NEW EVIDENCE FOR HOT SPOTS FROM SUBTHRESHOLD PIONS

J. AICHELIN



MARCH 1984

MSUCL-455

MSUCL-455
March 1984

NEW EVIDENCE FOR HOT SPOTS FROM SUBTHRESHOLD PIONS

J. AICHELIN*

National Superconducting Cyclotron Laboratory

Michigan State University, East Lansing, Michigan 48824, U.S.A.

ABSTRACT:

We analyze the excitation function and energy distribution of the reaction $^{12}C + A \rightarrow \pi_0 + X$ for beam energies of several tens of MeV. Employing the statistical decay theory we obtain a good agreement with the data assuming that a hot spot is formed. Its size is determined from the velocity of the emitting source. The cross section for forming a hot spot shows a systematic behavior which fits well with the systematics recently observed in fragmentation reactions.

submitted to Phys. Rev. Lett.

---

* Nato-fellow on leave from University of Heidelberg, F.R.G.

Recently excitation functions of π_o cross section for various asymmetric systems were published [1]. These data supplements earlier ones for the symmetric system C + C [2] and for low projectile energies [3]. The measurements show the systematic behavior of the excitation function, the energy and angular distribution, and the target mass dependence of the cross section.

Two models have been advanced to describe the underlying mechanism for the production of pions in this energy domain for various targets. The first assumes that the necessary energy can be provided by the high momentum component of the Fermi motion. However this model fails to reproduce the excitation function as well as the energy distribution as pointed out by Shyam [4]. The other model describes the pion creation by a process similar to the electromagnetic bremsstrahlung [5]. This model describes the energy distribution properly but fails to reproduce the excitation function. Furthermore there is an ad hoc parameter in this model related to the deceleration of the nuclei during the collision.

We have shown [6] that for the symmetric system C + C the excitation function as well as the pion energy distribution can be remarkably well described making a statistical hypothesis about the reaction mechanism. Here projectile and target nucleons form a highly excited thermalized system whose decay is governed by the available phase space. Because of the time scales involved this picture cannot be extended to heavier targets. Here the time a nucleon needs to travel through the nucleus (~15 fm/c) is larger than the decay time of the system (~5 fm/c). Therefore a complete equilibration of the whole target cannot be expected. Hence for heavy systems we start with the assumption that only a part of the target nucleons together with those of the projectile form a thermalized hot spot which

decays according to the available phase space. The size of the hot spot is determined by the source velocity which can be extracted from the data assuming that the source emits as many particles in the forward hemisphere as in the backward hemisphere. Hints of the existence of such a hot spot in medium energy heavy ion collision were already obtained by analyzing proton correlations [7] as well as the emission of medium mass fragments [8,9]. We shall show in this letter that the excitation function for the π_0 cross section for the measured asymmetric systems can be well reproduced in this model. The same is true for the energy distribution of the medium mass target (Ni). For the reaction C + U we fail to reproduce the high energy tail of the energy distribution.

The basic assumption in our analysis is that the nucleons in the colliding nuclei reach statistical equilibrium in a very short amount of time. From the point of view of the Boltzmann equation, the equilibration is far from instantaneous. Nevertheless to produce an energetic particle by a low-energy collision requires consideration of high-order perturbations on the independent particle wave function. It is plausible that the mathematics of such higher-order perturbations yield results approaching the phase space limit. Also, pre-equilibrium pions are highly suppressed by the limited amount of energy in the nucleon nucleon center of mass system. Measuring pion we cannot say anything about the final fate of the system, because either disassembling or cooling down leads to a very low pion production rate. So pions are a sensitive probe only in a small time window. Given a system in local equilibrium, the time required for a particle emission (5 fm/c) is small compared to the expansion time, or time for other disassembly mechanisms. We thus apply [6]:

$$W_{if}(e)\,de = \frac{\rho(U)}{\rho(E)}\,\frac{(2S+1)m}{\pi^2}\,\sigma_{fi}(e)\,e\,de \qquad (1)$$

where e is the kinetic energy of the evaporated particle, $\rho(E)$ and $\rho(U)$ are the level densities of the hot spot before and after emitting a particle , and σ_{fi} is the inverse cross section for the formation of the compound nucleus. The cross section is obtained from the decay rates by the formula:

$$d\sigma/de = \sigma_0\, W_{if}(e)/\sum_j \int W_{ij}(e_j)\,de_j \qquad (2)$$

where σ_0 is the cross section to form a compound nucleus in the entrance channel.

We determine the level densities by the Fermi gas model. For our applications, considering excitation energies between 9 and 21 MeV/N, i.e. temperatures between 12 and 23 MeV (at normal nuclear matter density), the standard low temperature level density formula is inaccurate and we use instead the general formulas (details of which may be found in ref. 6). The temperature and the chemical potential of the Fermigas are determined by the excitation energy and the nuclear density (0.15 n/fm^3).

At the excitation energies considered pion creation is possible not only at the first evaporation step, but also after one or more nucleons are emitted. However even at the highest energies the first 3 steps lead to more than 95% of the observed pions. We apply therefore a cascade calculation [6]. This does not mean that after each evaporation step the residue needs a long time to restore thermodynamical equilibrium. It can also be viewed as a consequence of the maximum entropy principle: knowing

only that a particle is emitted which carries a certain energy , an equilibrium distribution of the residue has the highest entropy.

Equation (1) requires the inverse cross section, which we take as geometric for the nucleon absorption $\sigma(A+n\rightarrow(A+1))=\pi R_A^2$, where R_A is the hot spot radius. The pion cross section is far from being geometric. Although the pion absorption cross section of a excited nucleus is required, for lack of information we take the measured absorption cross section of a cold nucleus. Optical model calculations [11] show that for low energies the nucleus gets increasingly transparent whereas at higher energies there is an enhancement due to the delta resonance. We extract the π_0 absorption cross section from the available π_+ and π_- measurement taking the geometrical mean. For heavier targets, two data sets exist [12,13]. Unfortunately both disagree in the absolute magnitude as well as in the shape. Because of its agreement with optical model calculations at lower energies we fix our parametrization at low energies at the data of ref. [13] whereas at higher energies we follow the average of both data sets. A convenient parametrization of the π_0 absorption cross section in the range between 20-200 MeV is:

$$\sigma_{\pi_0}(E) = \sigma_m - \alpha\,(E-E_0)^{**}2. \qquad (3)$$

with σ_m = 390,550 mb, α = 0.017,0.026 mb/MeV**2. ; E_0 = 145,115 MeV for Al and Ti respectively. For nuclei in between we make a linear interpolation. The only undetermined parameter in the calculation is σ_0 , the formation cross section for the hot spot. This parameter is fit to the measured excitation function. The calculation shows that the form of the excitation

function is not very sensitive to the particular parametrization of the pion absorption cross section. However, σ_0 and the pion energy distribution are strongly dependent on $\sigma_{\pi_0}(E)$.

Table 1 shows the input values of our calculation as well as total pion creation probability and the pion cross section. The data points at 35 MeV were obtained by applying our analysis to the reaction 35 MeV/N $^{14}N + {}^{27}Al \rightarrow \pi_0 + X$ and $^{14}N + {}^{58}Ni \rightarrow \pi_0 + X$ and transforming it to the $^{12}C + A$ system. This is done in the following way: we calculate the probability P for pion emission of the compound nuclei created in both reactions 35 MeV C+A and 35 MeV N+B , where A is C and Ni and B Al and Ni respectively, and scale the compound formation cross sections as Braun-Munzinger did [3]. Then the theoretical pion cross section is given by:

$$\sigma_{C+A}(\pi_0) = \sigma_{N+B}(\pi_0) \frac{P(C+A)}{P(N+B)} \cdot \left(\frac{12 \cdot A}{14 \cdot B}\right)^{0.68} \quad (4)$$

Figure 1 shows the predicted excitation function compared with the available data [1,3]. The overall magnitude of the cross section is fit with a parameter σ_0, corresponding to the equilibrated system formation cross section. The agreement in the shape of the excitation function is excellent. In the case of Uranium we calculated the cross section for two sets of parameters corresponding to two assumptions about the size of the hot spot.

Figure 2 shows the calculated π_0 energy distribution compared with the data of Ref [1]. The three lower curves show the energy distribution for

60, 74, 84 MeV/N C+C, the two upper curves 84 MeV/N C+Ni and C+U, respectively.

The energy distribution is well described in the C+C system but fails at higher energies in the asymmetric systems. An inspection of the rapidity plot shows that the high energy π_0's of the Ni and U target originate from a system of higher rapidity. This means less participants and therefore higher excitation energy/nucleon. It is an open question whether this is a consequence of different impact parameters resulting in different numbers of participants or whether it originates from the early stage of the hot spot where less nucleons participate and therefore the temperature is higher. Furthermore it may reflect the lack of information about the inverse cross section.

The total compound formation cross section σ_0 shows a simple systematic behavior. If we express the cross section in the form $\sigma_0 = \pi\, b^2_{max}$, then the maximum impact parameter is roughly given by $b_{max} = R_T - R_p + 1.5$, showing that target and projectile must overlap almost completely. This systematics is also valid for the data 44 MeV/N Ar+Ca and Ar+Sn [13]. Larger impact parameter results in fragmentation of the projectile as observed by [14]. Whereas the C+U data are almost isotropic, the C+C data show a small angular anisotropy which cannot be explained in this simple model because of the neglect of the spin of the compound nucleus.

I acknowledge helpful discussions with G. Bertsch and communications with P. Braun-Munzinger.

References:

[1] H. Noll, E. Grosse, P. Braun-Munzinger, H. Dabrowski, H. Heckwolf, O. Klepper, C. Michel, W.F.J. Mueller, H. Stelzer, C. Brendel and W. Roesch, preprint

[2] E. Grosse, preprint GSI-83-27

[3] P. Braun-Munzinger, P. Paul, L. Ricken, J. Stachel, P.H. Zhang, G.R. Young, F.E. Obenshain and E. Grosse, Phys. Rev. Lett. 52 (1984) 255

[4] R. Shyam and J. Knoll, preprint GSI-83-22

[5] D. Vasak, H. Stöcker, B. Mueller and W. Greiner, Phys. Lett. 93B (1980) 243

[6] J. Aichelin and G. Bertsch, Phys. Lett. B, in press

[7] M.B. Tsang et al., preprint MSU

[8] J. Aichelin, J. Hüfner and R. Ibarra, Phys. Rev. C, in press

[9] W.A. Friedman and W.G. Lynch, Phys Rev. C28 (1983) 16

[10] R. Kaps, private communication

[11] D. Ashery, Phys. Rev. C23 (1980) 2173
I. Navon et al., Phys. Rev. C28 (1983) 2548

[12] K. Nakai et al., Phys. Rev. Lett 44 (1980) 1446

[13] H. Heckwolf, E. Grosse, H. Dabrowski, O. Klepper, C. Michel, W.F.J. Mueller, H. Noll, C. Brendel, W. Roesch, J. Julien, G.S. Pappalardo, G. Bizard, J.L. Laville, A.C. Mueller, and J. Peter, Z. Phys. A315 (1984) 243

[14] J. Mougey, Nucl. Phys A387 (1982) 109c

Table 1. Experimental and theoretical values for the three systems. (a) is the observed experimental rapidity of the source, (b) is the number of entrained nucleons extracted from the experimental rapidity, (c) is the number of entrained nucleons we took as a input in our calculation, (d) is the summed pion emission probability over all steps, (e) is the hot spot formation cross section, and (f) and (g) are the theoretical and experimental π_0 cross sections. The star marked values are obtained from N + A reactions at 35 MeV/N as explained in the text.

		E/A	(a)	(b)	(c)	(d)	(e)	(f)	(g)
A_1	A_2	[MeV/u]	y_{cm}	N	N	prob	σ_0[mb]	σ_π^{th}[μb]	σ_π^{ex}[μb]
C	C	84	0.20(1)	24	24	1.86 E-4	102	18.9	18.9
C	C	74	0.21(1)	24	24	8.3 E-5	102	8.5	8.5
C	C	60	0.18(1)	24	24	1.8 E-5	102	1.8	1.7
C	C*	35	-	-	24	3. E-8	102	3.E-3	2.6E-3
C	Ni	84	0.16(1)	32(2)	34	1.97 E-4	321	72	72
C	Ni	74	0.14(1)	34(3)	34	8.85 E-5	321	32.5	31
C	Ni	60	0.12(1)	36(3)	34	1.8 E-5	321	6.6	7
C	Ni*	35	-		34	4.0 E-8	321	1.3E-2	3.4E-3
C	U	84	0.11(1)	46(4)	43	1.85 E-4	940	174	174
C	U	74	0.10(1)	48(5)	43	7.74 E-5	940	76	63
C	U	60	0.09(1)	48(5)	43	1.22 E-5	940	11.5	13

Figure captions:

Fig 1: Calculated total π_0 cross section and the data of ref's. [1,3]. The points at 35 MeV/N are extracted from the reactions $^{14}N + A \rightarrow \pi_0 + X$ as explained in the text. N is the number of entrained nucleons and σ_0 is the hot spot formation cross section. In the case of Uranium we calculated the excitation for two different number of entrained nucleons (dotted line N=43, full line N=47)

Fig 2: Angle integrated π_0 spectra for the reactions $C + A \rightarrow \pi_0 + X$. The drawn lines are the result of our calculation. The data are taken from ref. [1]. The upper 3 data sets show 84 MeV/N A=U, Ni and C respectively, the lower two data sets 74 MeV A=C and 60 MeV A=C. For Uranium we calculated the energy distribution for 47 entrained nucleons (full line) and 43 entrained nucleons (dotted line), respectively.

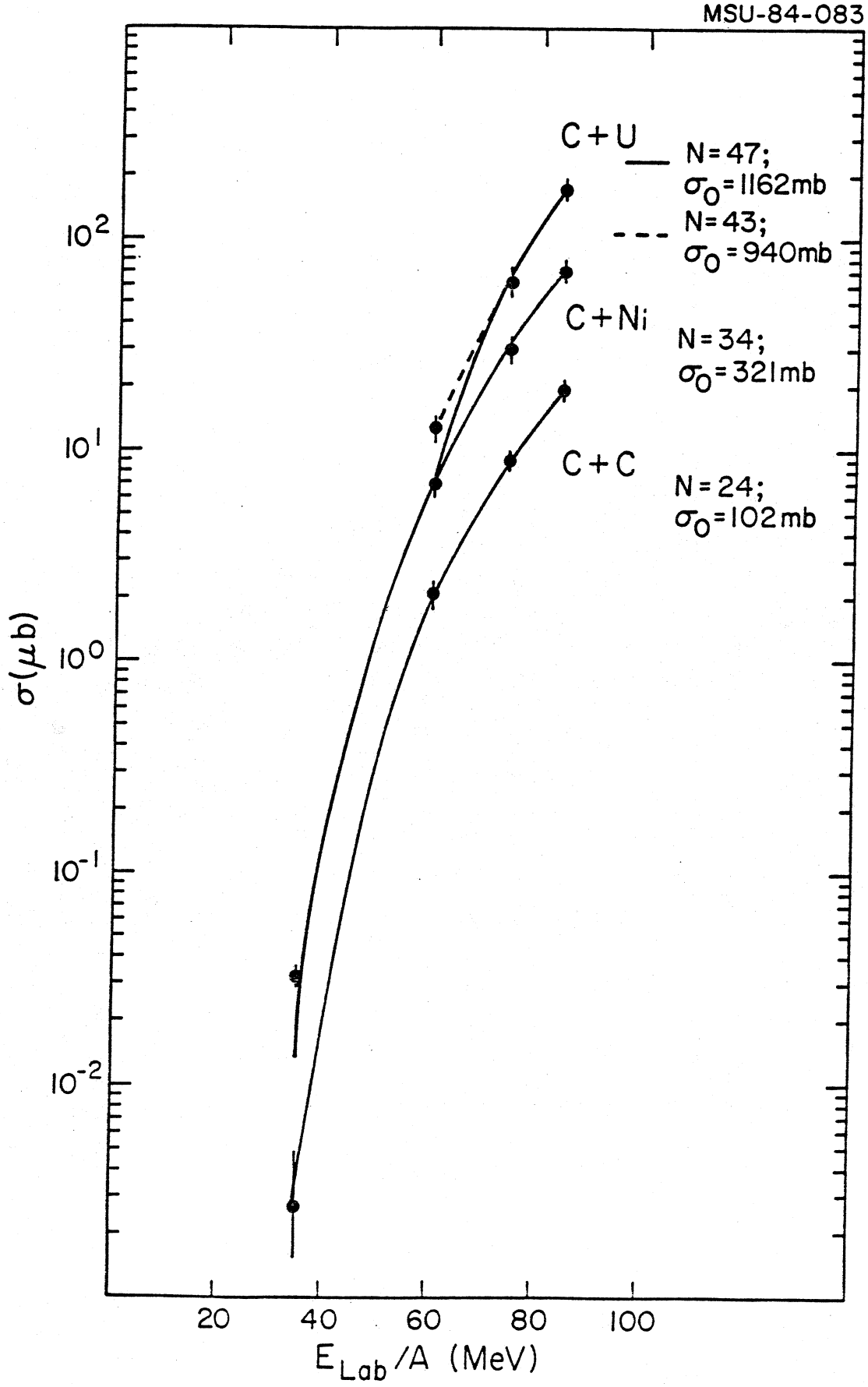

MSU-84-083
C+U
N=47;
σ0=1162mb
N=43;
σ0=940mb
C+Ni
N=34;
σ0=321mb
C+C
N=24;
σ0=102mb
σ(μb)
10^2
10^1
10^0
10^-1
10^-2
20
40
60
80
100
E_Lab/A (MeV)

Figure 1

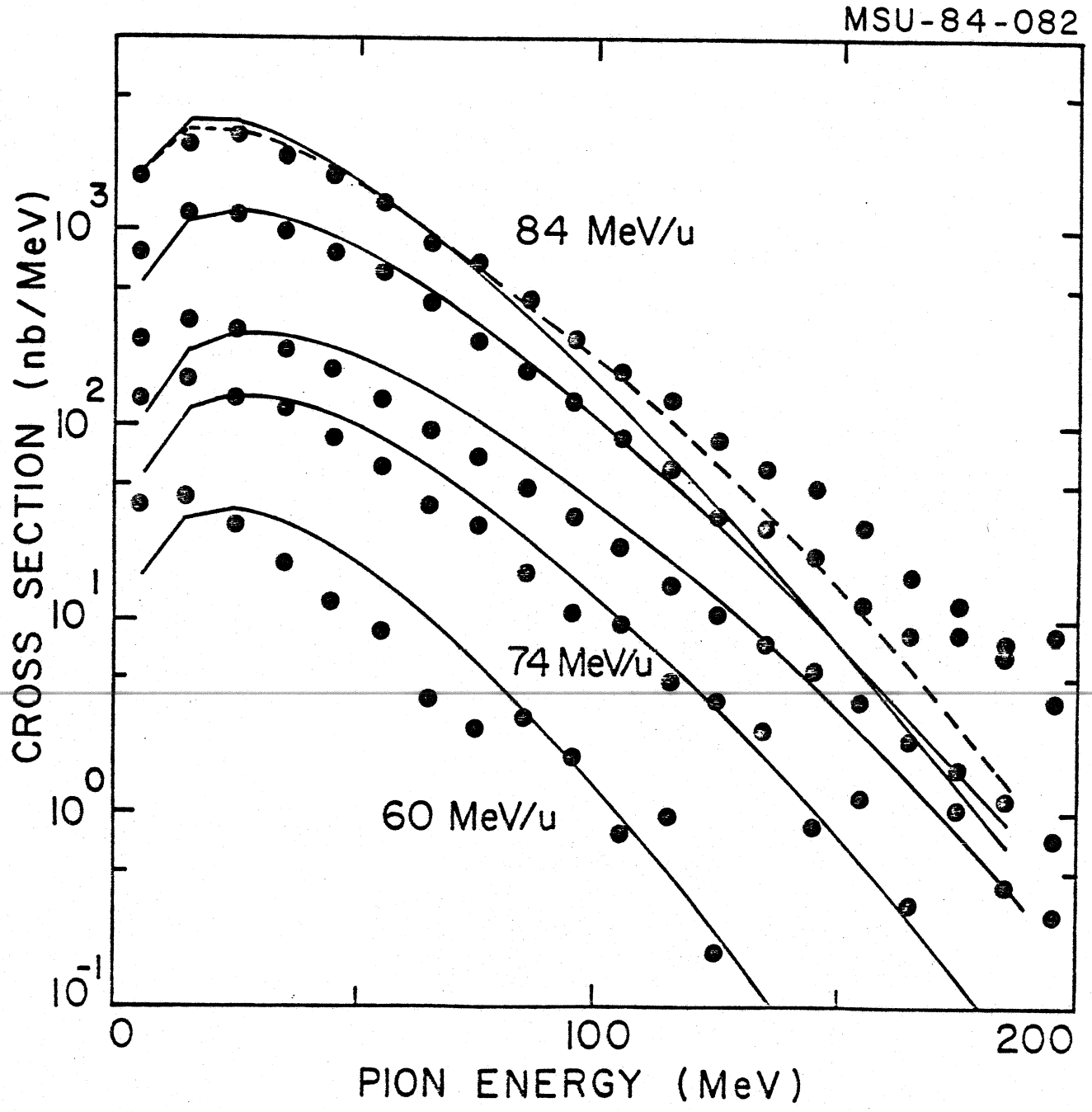

MSU-84-082
CROSS SECTION (nb/MeV)
10^3
10^2
10^1
10^0
10^{-1}
84 MeV/u
74 MeV/u
60 MeV/u
0
100
200
PION ENERGY (MeV)

Figure 2