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ENERGY DEPENDENCE OF LIGHT PARTICLE EMISSION FROM INTERMEDIATE ENERGY HEAVY ION COLLISIONS

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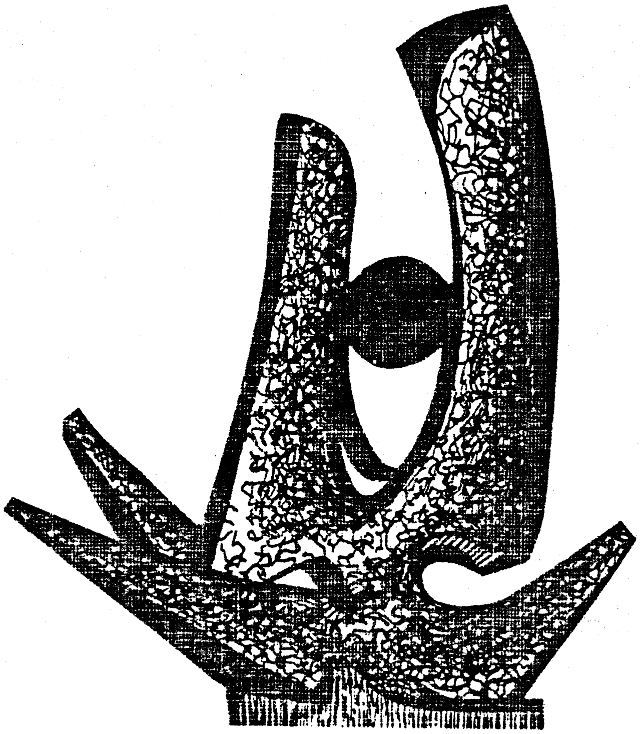
Contribution to Nordic Meeting on Nuclear Physics
Füglsø, Denmark
Aug. 16-20 1982



AUGUST 1982

MSUCL-387

MSUCL-387
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Energy Dependence of Light Particle Emission from Intermediate Energy Heavy Ion Collisions

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Abstract

High energy nucleus-nucleus collisions can provide a unique method of studying nuclear matter at densities and excitations far from the normal ground state. In these collisions a source can be identified with a velocity intermediate between the projectile and target velocities as well as sources that can be associated with decay of excited projectile and target nuclei. The study of light particle spectra (p,d,t and alpha) associated with this intermediate source can provide information on the equation of state of nuclear matter. Results are presented for O and Ne induced reactions on heavy targets ranging in energy from 9 to 800 MeV/nucleon. Analysis of these light particle data in terms of a single moving source model leads to a consistent description of a system in thermodynamic and chemical equilibrium. Extracted d/p and t/p ratios are almost independent of incident energy while the alpha/proton ratio increases dramatically at low bombarding energies.

An important concept in high energy nucleus-nucleus collisons is the formation of a highly excited, localized region of participant nucleons moving with a velocity intermediate between the projectile and target velocities.. The study of this zone as a function of incident projectile energy can provide information about the behavior of nuclear matter at densities and excitations far from the normal ground state. Specifically one can study the equation of state of nuclear matter and perhaps observe phenomena such as phase transitions and flash temperatures.

In Fig. 1 two different visualizations are shown for the interaction of two high energy nuclei. In the fireball model [1] it is assumed that the interaction of the two nuclei occurs on a sufficiently short time scale that the reaction is localized to the overlapping volume of the nuclei. One further assumes that the two overlapping regions undergo a completely inelastic collision in which the kinetic energy of the projectile volume is completely tranformed into internal excitation forming a highly excited and compressed system of nuclear matter. In the hydrodynamic model [2], as the projectile approaches the target nucleus, pressure is built up in the interaction region until the projectile bounces off at an angle leaving behind an intermediate, excited region and an excited target remnant. In both cases there is an identifiable intermediate velocity source. This intermediate source is the subject of this paper.

An obvious property of this intermediate region, which can be systematically studied, is its disassembly into pions, nucleons, and light nuclei. In a thermodynamic description assuming both thermal and chemical equilibrium [3] in the intermdiate system, the temperatures and relative abundances of the emitted fragments are predicted to vary smoothly with incident energy. If one introduces an equation of state incorporating compression, a discontinuity in the temperature and a sudden increase in the production of nucleons relative to light nuclei can be predicted to occur near a critical temperature termed the flash temperature [4]. Thus by studying a wide range of incident energies and resulting temperatures one can possibly observe properties of the nuclear matter equation of state.

The range of interesting incident projectile energies reaches from 9 MeV/nucleon up to 800 MeV/nucleon. This range spans energies from just above the coulomb barrier up to energies where pion production becomes significant. Velocities range from far below the fermi velocity up to relativistic velocities many times the speed of sound in nuclear matter. Until recently, a gap has existed in the available data above the energies of current cyclotrons (approx. 30 MeV/nucleon) and below the lowest easily available energies at the Bevalac (approx. 200 MeV/nucleon). Presently this region is being studied at the CERN Synchrocyclotron (SC), at SARA, and at the Bevalac Low Energy Beam Line. In the near future, heavy ion induced masurements in this energy range will be available from GANIL, the MSU K500 Cyclotron, and Saturne II. The data considered here are double differential cross sections for p, d, t, and alphas emitted in the the reactions of O + Au at 9, 13, and 20 MeV/nucleon [5], Ne + Ta at 43 MeV/nucleon [6], Ne + Au at 100 amd 156 MeV/nucleon [7], Ne + U at 241 and 393 MeV/nucleon [8], and Ne + Pb at 800 MeV/nucleon [9].

The first question that must be answered in the study of this intermediate zone is its isolation from contributions resulting from the excited projectile and target nuclei. In order to illustrate the kinematical regions of the measured inclusive spectra associated with an intermediate source, one can calculate the contributions from the three sources at one impact parameter using the fireball model with the results being shown in Fig. 2. Sources of protons from the residual projectile and target nuclei are shown in Fig. 2a while Fig. 2b depicts the contribution from the intermediate source. In Fig. 2c the sum of the three sources is given. At angles larger that 50 degrees and energies above 30 MeV, the sum is dominated by the intermediate source. Certainly there could be a wide spectrum of thermal emitting sources for these particles as well as other origins such as nucleon-nucleon scattering broadened by fermi motion. However, this simple parameterization can be useful in reducing large amounts of data to a few parameters that can be studied as a function of incident energy. This intermediate source can be described by a single source taking the form of a relativistic Boltzmann distribution [10] characterized by the cross section σ_0 and the temperature τ. This distribution is assumed to be isotropic in a frame moving with velocity β in the laboratory frame. The laboratory spectra are obtained by transforming relativistically from the source rest frame to the laboratory frame. A coulomb correction was applied by shifting the calculated spectra by 10 MeV for Z=1 fragments and by 18 MeV for Z=2 fragments [5]. The parameters β , τ , and σ_0 are determined using a least squares fitting technique to that portion of the spectra identified with the moving source.

In Fig. 3, a representive set of data is shown for Ne + Au at 100 and 156 MeV/nucleon. The solid lines correspond to the coulomb corrected moving source fits to the data as described above. The nearly isotropic, low energy component of the spectra is not described and can be identified with a target-like source. For comparison the firestreak model [10] predictions are shown as dashed lines.

The parameters extracted by fitting all available data for O- and Ne- induced reactions on heavy targets are shown in Fig. 4 where the velocities, temperatures, and cross sections are plotted as a function of laboratory energy per nucleon above the coulomb barrier. In all cases an identical moving source formalism was applied to ensure consistency. The coulomb corrections were significant in the extraction of the cross sections at incident energies below 250 MeV/nucleon. The depicted error bars include known statistical and systematic errors. The solid lines are drawn to guide the eye in the case of the extracted cross sections.

In Fig. 4a, the trend of the cross sections with increasing incident energy for p, d, and t appear to be similar while the alpha cross sections seem to be qualitatively different in that they display a peak around 100 MeV/nucleon. The dashed curve in Fig. 4a is the fireball model prediction for the proton cross section. These calculations agree with the extracted proton cross sections for incident energies above 100 MeV/nucleon but overpredict by a factor of 10 at the lowest incident energy. This discrepancy perhaps suggests the breakdown of the clean-cut geometry assumed in the fireball model and the formation of a hot spot at low incident energies rather than a completely separate fireball.

The fact that the observed temperatures for each of the emitted particles agree at a given incident energy lends credence to the assumption that they are emitted from a common, thermal source. Extracted temperatures are compared with the fireball prediction in Fig. 4b shown as a dashed line. At incident energies above 20 MeV/nucleon, the fireball prediction agrees well with the observed temperatures, reproducing the turn-over at high energies as pion production begins to become important. However, the predicted temperature disagrees at energies below 20 MeV/nucleon. In contrast, a fermi gas description [5], shown by the solid line, reproduces the temperatures up to the point where pion production commences.

Source velocities are shown in Fig. 4c with the fireball velocity shown as a dashed line. The solid line corresponds to the velocity of the source if there were equal participation from the projectile and target or if the source were moving at the velocity of the nucleon-nucleon center-of-mass frame. At low incident energies the velocities tend to agree with the equal participation prediction while at the highest energies the velocities tend to agree with the fireball prediction. Again this observation, as in the case of the temperatures, lends weight to the idea that at low energies a hot spot is formed that is bound to the target while at high energies a fireball is formed. Also, the source velocities for incident energies below 100 MeV/nucleon are comparable to the fermi velocity of the target nucleus.

In Fig. 5 the cross sections for p, d, t and alphas are given in terms of ratios of composite nuclei (d,t, and alpha) to protons. The d/p and t/p ratios are almost constant with respect to incident energy while the alpha/p ratio increases dramatically at low energies. The solid lines correspond to a fireball calculation incorporating thermal and chemical equilibrium treating pions, baryonic resonances, nucleons, light nuclei, and nuclear resonances. After a freeze-out density is reached, the nuclear and baryonic resonaces are assumed to decay into pions, nucleons, and light nuclei. Thus the final predicted proton spectra, for example, will contain contributions from the thermal protons as well as protons from the decay of deltas and nuclear resonances. The constancy of the calculated d/p ratio is due to

this effect. The predicted t/p ratios are too high. When decays from nuclear resonances are excluded from the triton cross section, better agreement between the calculated and observed t/p ratio is obtained as shown by the dashed line. The alpha/p ratio is reproduced by the calculation.

In Fig. 6, two different calculations of the composite to proton ratios are given. One model uses a Hauser-Feshbach approach [11] to predict emission of particles from an equilibrated system at a given temperature and is shown as dashed lines. The agreement of this calculation reinforces the assumption that these composite nuclei are the result of statistical processes. The solid lines represent a quantum statistical approach [12] incorporating an equation of state that has a critical temperature of around 20 MeV resulting in a dip in the predicted d/p and t/p ratios just in the region where no data exist. These predictions will certainly be checked in the near future as new data become available.

Another way to present the extracted cross sections is shown in Fig. 7 where the cross sections are plotted versus mass number [13]. The various incident energies have solid lines drawn through them to guide the eye. The range of temperatures extracted for each beam energy is shown to the right of each set of data. The cross sections associated with low temperatures have maxima at mass number 1 and 4 while the high temperature data are peaked at mass number 1 and decrease monotonically with mass number. This behavior suggests that a qualitative transition is taking place in the production mechanism between high and low temperatures. An attempt has been made to explain this transition in terms of a transition of the emitting nuclear system from a gas phase to a liquid phase [13]. The signature of this phase transition would be a sudden increase in the number of composites, identified with the liquid phase, as compared to the number of nucleons, identified with the gas phase. However, calculations incorporating the gas phase only can account for these cross sections [3,10,14], requiring that heavier composite nuclei be measured and compared with calculation to establish the existence of this phase transition. Measurements of cross sections for fragments with $4 < A < 12$ from an intermediate source are now underway at various accelerators and the required data will be available in the near future.

In conclusion, the global analysis of inclusive measurements can provide an insight into the reaction mechanisms of high energy nucleus-nucleus collisions. The study of light nuclear fragments emitted from an intermediate source may enable one to study the equation of state of nuclear matter and observe collective and critical phenomena in nuclear matter. The most promising incident energy region is near 100 MeV/nucleon where temperatures near predicted critical temperatures of around 20 MeV are produced and a qualitative change seems to occur in the extracted moving source parameters.

The author wishes to acknowledge B.V. Jacak and D.K. Scott who have contributed greatly to the work presented here as well as N. Anantaraman, M.W. Curtin, G.M. Crawley, C.K. Gelbke, B. Hasselquist, W.G. Lynch, M.B. Tsang, M.J. Murphy, T.J.M. Symons, R. Legrain, and T.J. Majors.

This material is based upon work supported by the National Science Foundation under Grant No. PHY 80-17605.

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Figure Captions

Figure 1. Two different models for high energy nucleus-nucleus reactions. The fireball model is depicted in a) [1] and the hydrodynamical model is depicted in b) [2].

Figure 2. Contribution of various sources to inclusive proton spectra. In a) the contributions from the residual target and projectile nuclei are shown. In b) the contribution from the intermediate source is given while in c) the sum of the three sources is given.

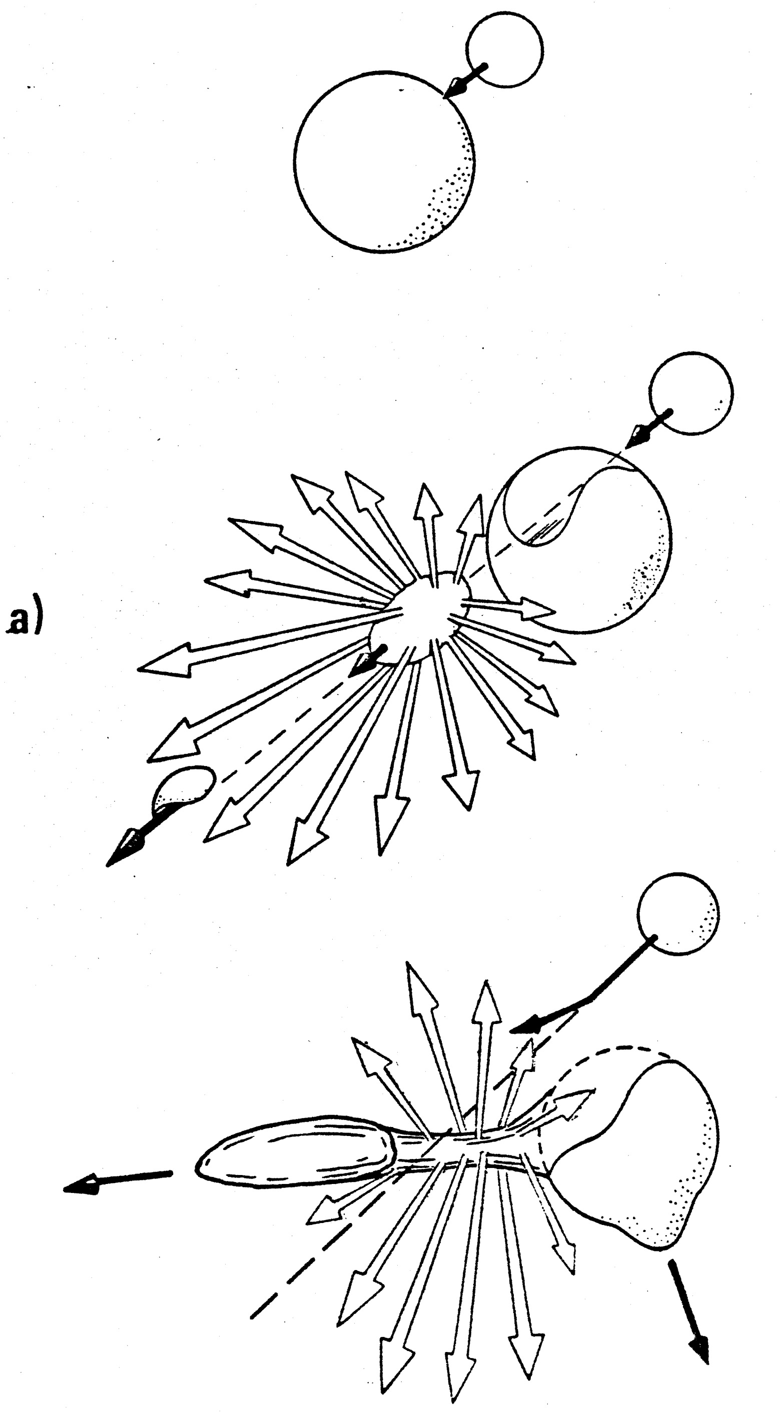
Figure 3. Energy spectra for Ne+Au at 100 [a) and b)] and 156 [c) and d)] MeV/nucleon. Solid lines correspond to moving source fits as in the text. Dashed lines represent firestreak calculations.

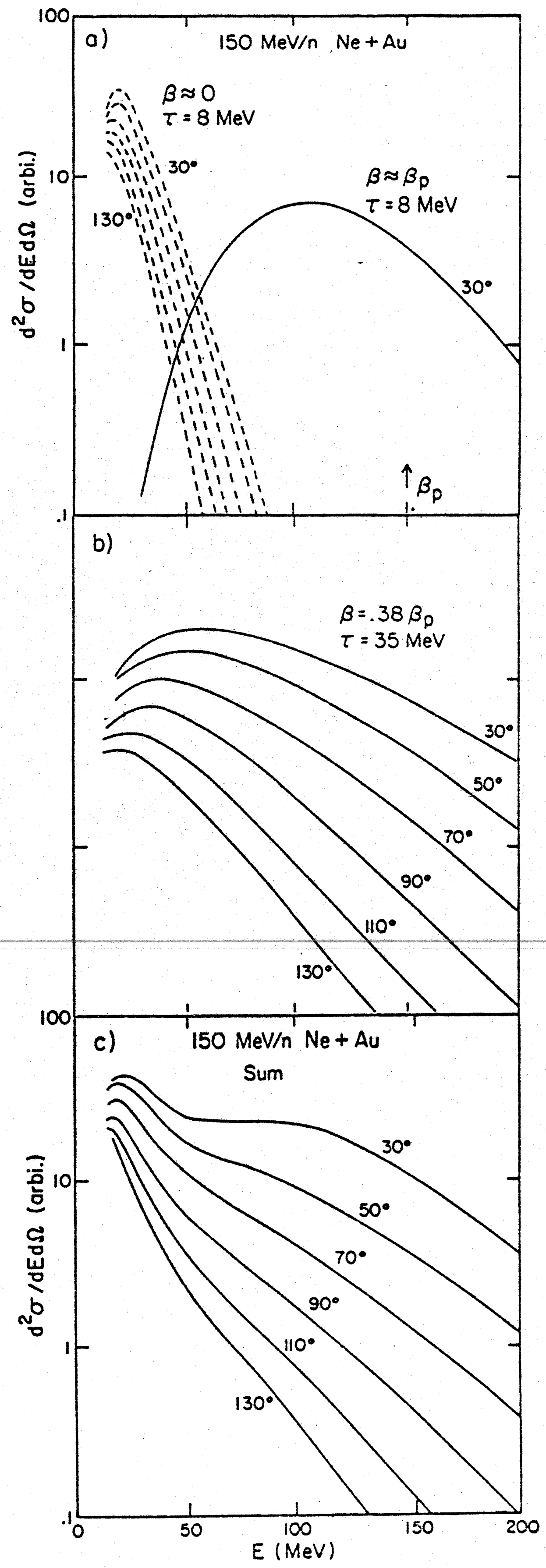
Figure 4. Extracted moving source parameters as a function of incident energy per nucleon above the barrier. The dashed lines correspond to the fireball model prediction. The solid lines in a) are drawn to guide the eye and the fireball calculation is for protons only. In b) the solid line is a fermi gas model prediction and in c) the solid line corresponds to the velocity of the nucleon-nucleon center-of-mass frame.

Figure 5. Ratios of extracted composite to proton production cross sections using the moving source model described in the text. The solid lines correspond to predictions using the fireball model with thermal and chemical equilibrium. The dashed line for the t/p ratio show predictions for tritons without contributions from nuclear resonance decay.

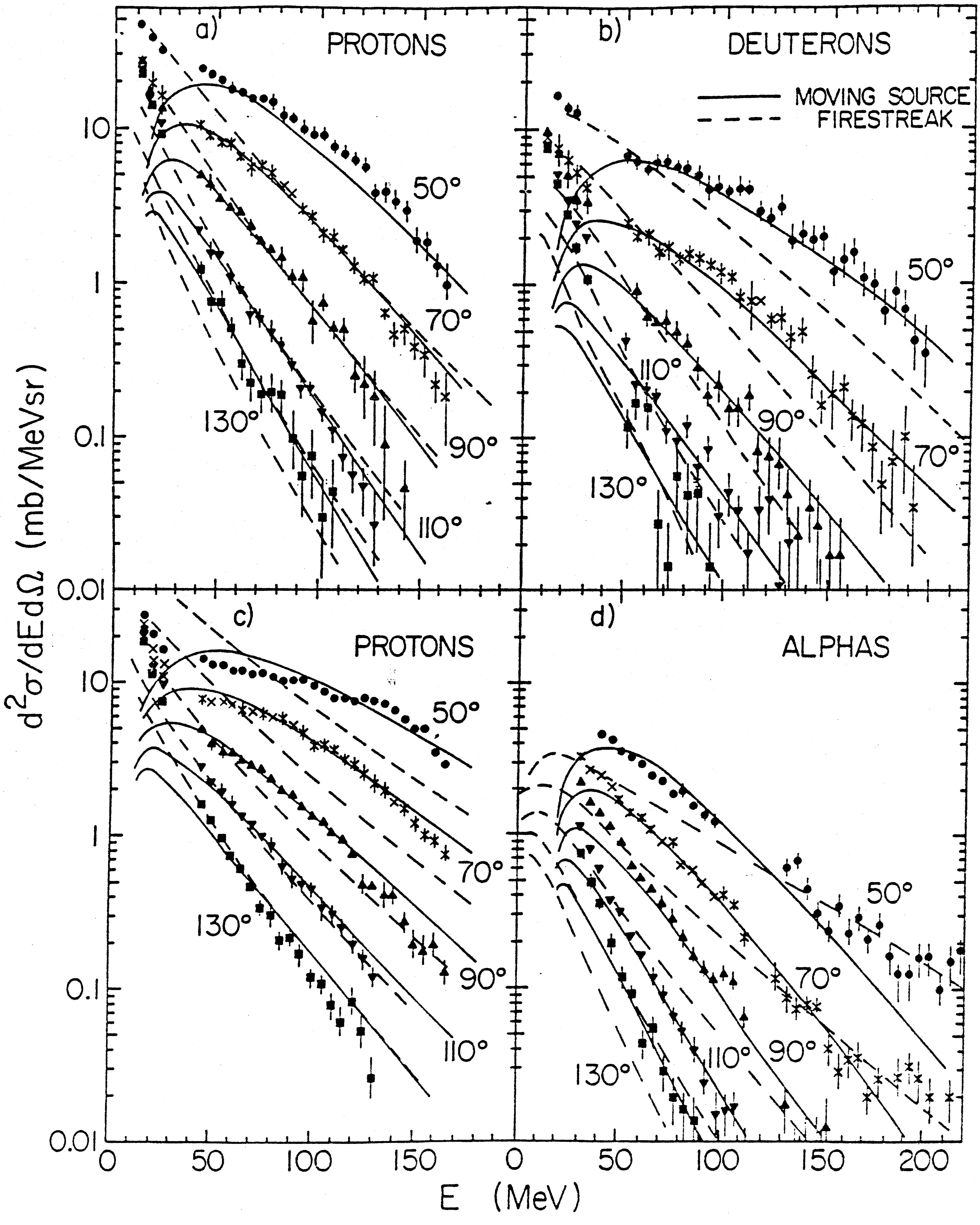
Figure 6. Comparison of calculated composite to protons ratios. The dashed line corresponds to the results of a Hauser-Feshbach calculation [11] while the solid line corresponds to a quantum statistical model calculation [12] (see text).

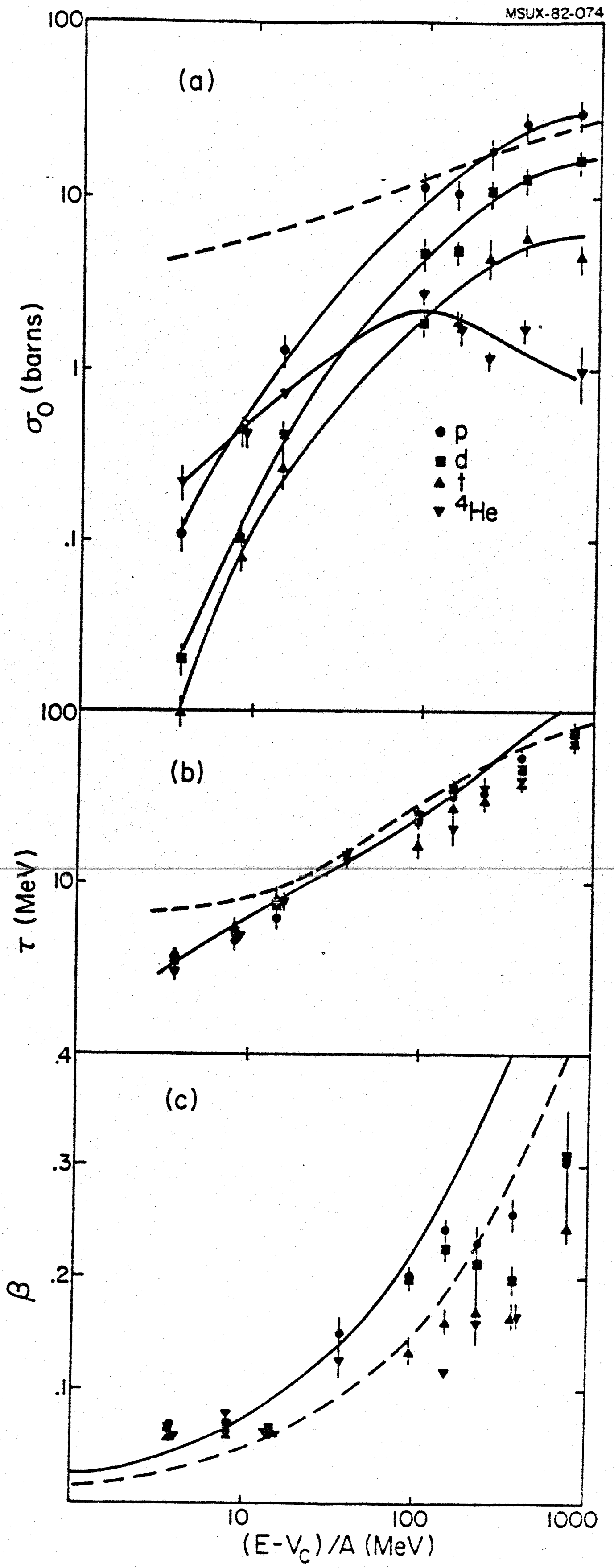
Figure 7. Extracted cross sections plotted versus mass number. The solid lines are drawn to guide the eye at a given incident energy. The extracted temperatures at a given incident energy are given to the right of each set of data.


a)
b)

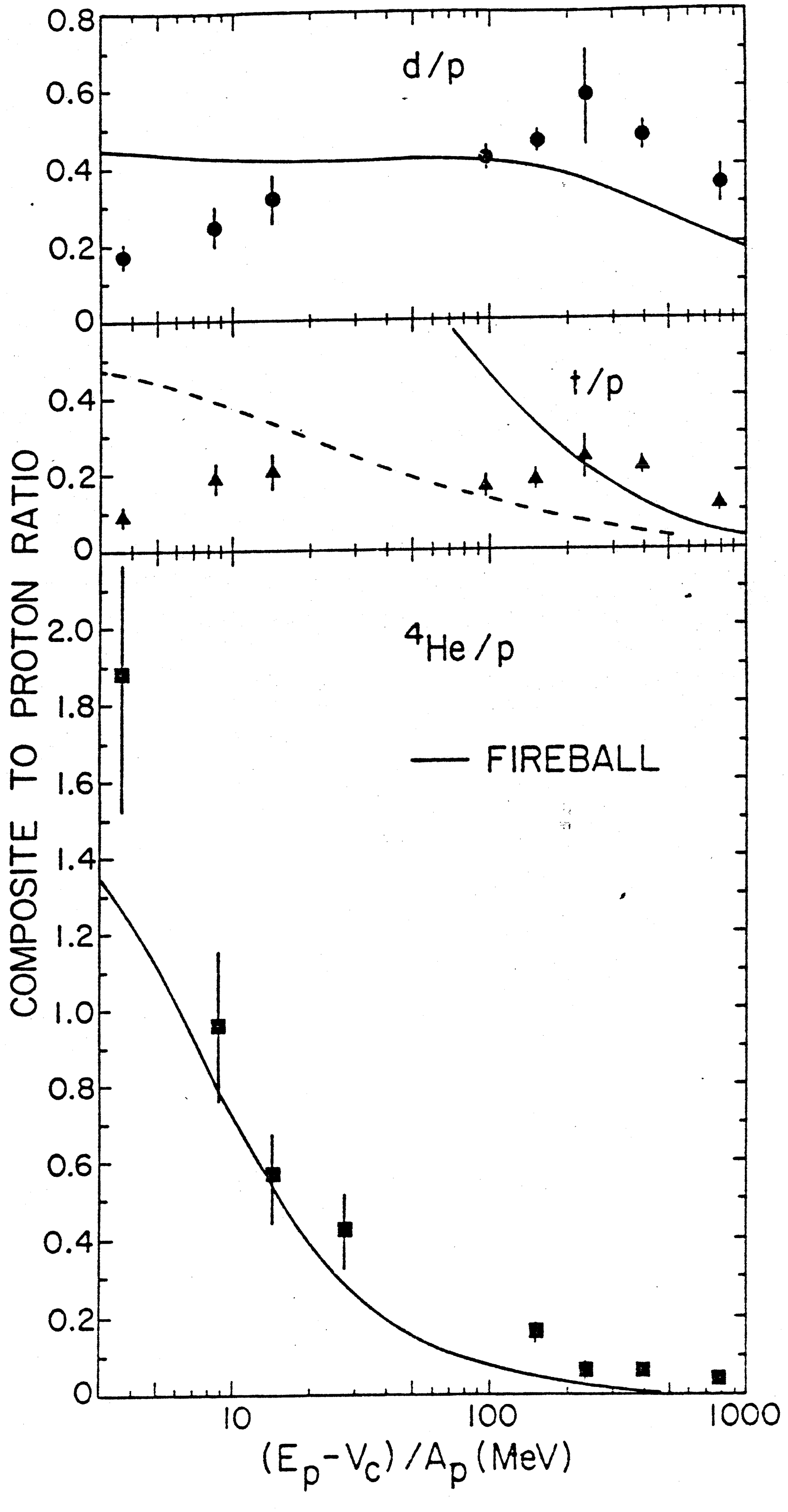

a)
150 MeV/n Ne + Au
$\beta \approx 0$
τ = 8 MeV
30°
130°
$\beta \approx \beta_p$
τ = 8 MeV
30°
$\uparrow \beta_p$
b)
β = .38 β_p
τ = 35 MeV
30°
50°
70°
90°
110°
130°
c)
150 MeV/n Ne + Au
Sum
30°
50°
70°
90°
110°
130°
$d^2\sigma/dEd\Omega$ (arbi.)
$d^2\sigma/dEd\Omega$ (arbi.)
100
10
1
.1
100
10
1
.1
0
50
100
150
200
E (MeV)

MSUX-82-015


a)
PROTONS
b)
DEUTERONS
MOVING SOURCE
FIRESTREAK
c)
PROTONS
d)
ALPHAS
50°
70°
90°
110°
130°
d²σ/dEdΩ (mb/MeVsr)
10
1
0.1
0.01
0
50
100
150
200
E (MeV)

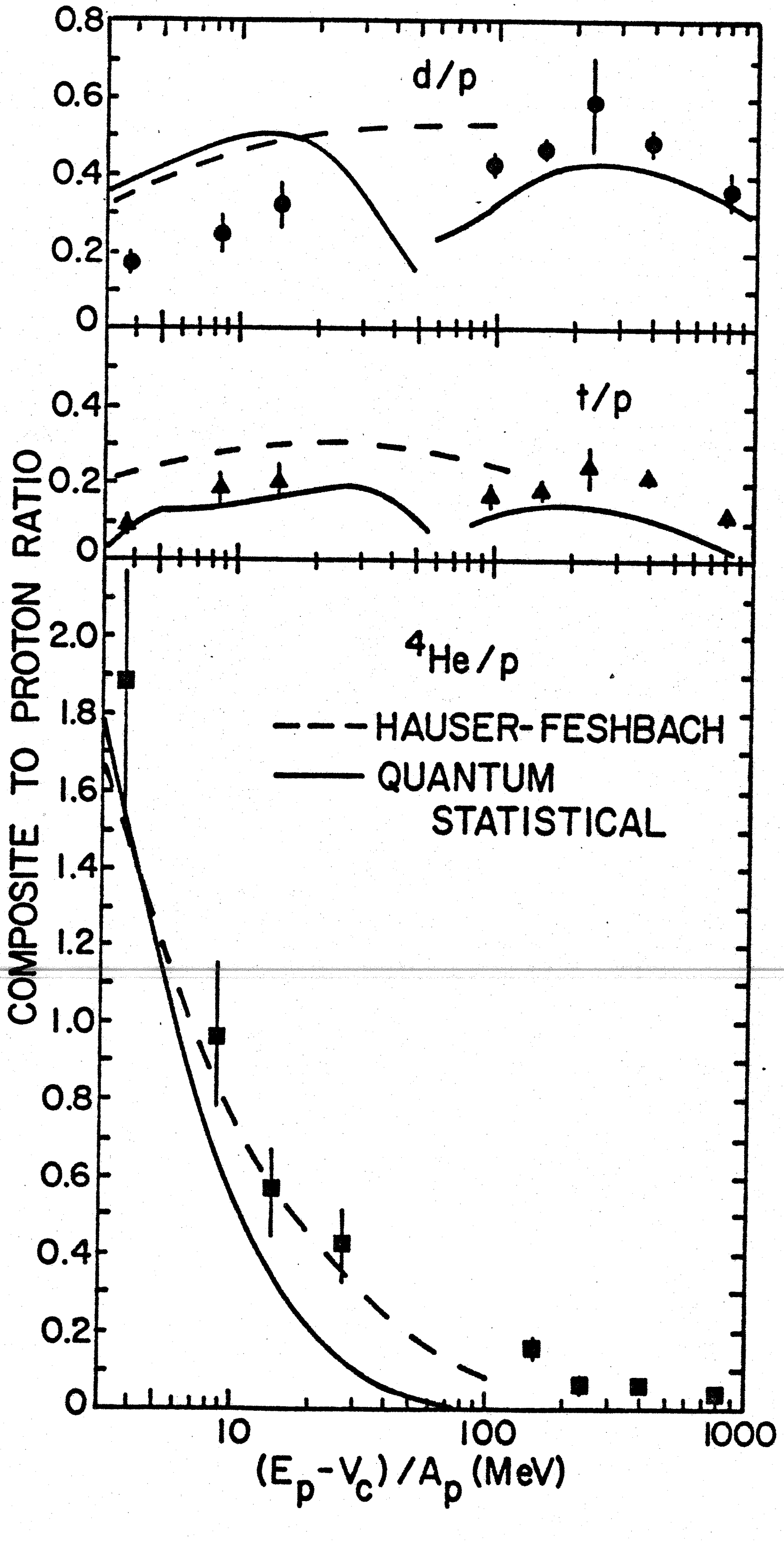

MSUX-82-074
(a)
(b)
(c)
σ₀ (barns)
τ (MeV)
β
(E-V_c)/A (MeV)
100
10
1
.1
100
10
.4
.3
.2
.1
10
100
1000
p
d
t
4He

MSUX-81-478

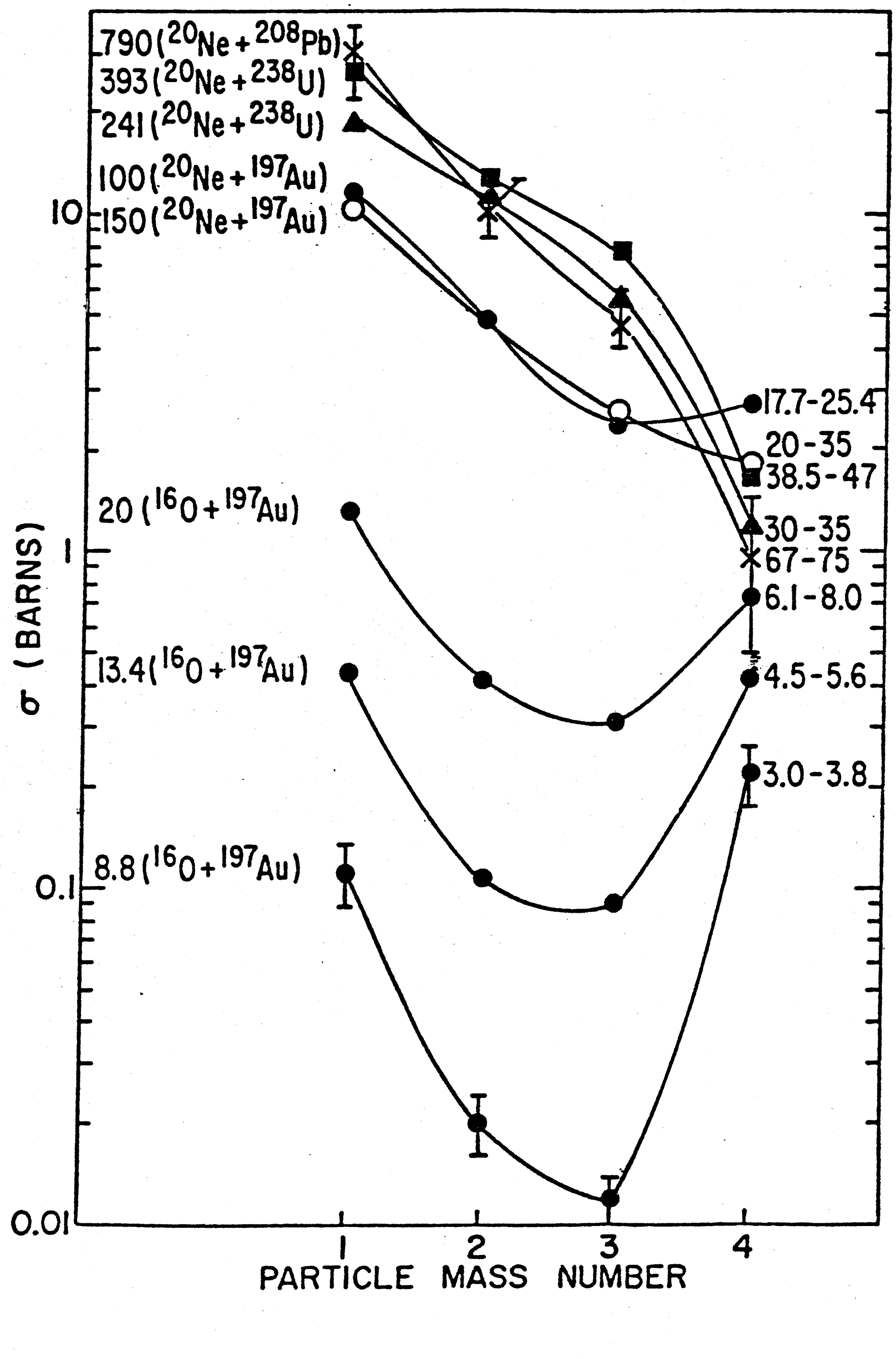


d/p
t/p
^{4}He/p
— FIREBALL
COMPOSITE TO PROTON RATIO
0.8
0.6
0.4
0.2
0
0.4
0.2
0
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
10
100
1000
$(E_p - V_c)/A_p$ (MeV)

MSUX-82-281


d/p
t/p
^{4}He/p
HAUSER-FESHBACH
QUANTUM STATISTICAL
COMPOSITE TO PROTON RATIO
0.8
0.6
0.4
0.2
0
0.4
0.2
0
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
10
100
1000
$(E_p - V_c)/A_p$ (MeV)

MSUX-82-103


790(^{20}Ne + ^{208}Pb)
393(^{20}Ne + ^{238}U)
241(^{20}Ne + ^{238}U)
100(^{20}Ne + ^{197}Au)
150(^{20}Ne + ^{197}Au)
20 (^{16}O + ^{197}Au)
13.4(^{16}O + ^{197}Au)
8.8(^{16}O + ^{197}Au)
17.7-25.4
20-35
38.5-47
30-35
67-75
6.1-8.0
4.5-5.6
3.0-3.8
10
1
0.1
0.01
σ (BARNS)
1
2
3
4
PARTICLE MASS NUMBER