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ENERGY DEPENDENCE OF NUCLEAR MATTER DISASSEMBLY IN HEAVY ION COLLISIONS

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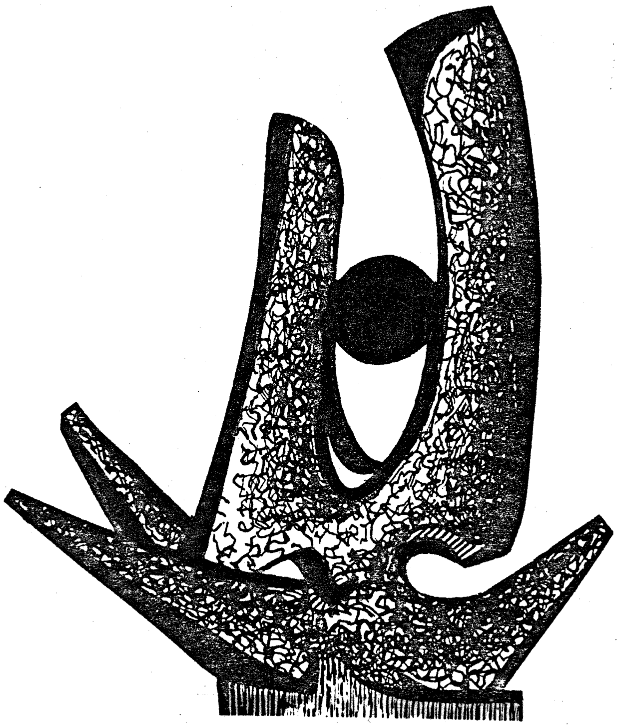

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ABSTRACT

Measurements of light charged particle spectra from ^{20}Ne+Au at 100 and 156 MeV/nucleon are compared with results for similar systems at 9,13,20,42,241,393, and 800 MeV/nucleon. Spectra at each energy are fitted with a single moving source model to extract the temperatures and cross sections for protons and light nuclei in the intermediate rapidity region. The ^{4}He/p production ratio decreases drastically with incident energy, whereas the d/p and t/p ratios are almost constant.

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An important concept in relativistic nuclear collisions concerns the formation of an excited, localized region of participant nucleons moving with a velocity intermediate between those of the projectile and target.[1,2] In this letter we present a new approach to the study of this region over a wide range of incident energies through its dissassembly into nucleons and light composite nuclei. The relative abundance of these emitted fragments as a function of temperature in the zone is characteristic of the detailed mechanism of its disassembly.[3,4,5] Within a thermodynamic model temperature and relative numbers of nucleons and light nuclei are predicted to vary smoothly with incident energy, whereas a hydrodynamical model,[6] incorporating compression, could lead to a discontinuity in the temperature and a sudden decrease in the production of light composite nuclei as a function of incident energy. We report new measurements of p,d,t, and ^{4}He energy spectra and angular distributions from ^{20}Ne-induced reactions on a Au target at incident energies of 100 and 156 MeV/nucleon. Our results for production cross sections and temperatures, when combined with those extracted from previous measurements for ^{16}O or ^{20}Ne-induced reactions on heavy targets, give a consistent picture of an intermediate velocity source with a temperature that varies smoothly with incident energy. We also observe that the deuteron to proton ratio (d/p) is almost independent of energy whereas the ^{4}He to proton ratio (^{4}He/p) varies from 1.9 at 9 MeV/nucleon to 0.05 to 800 MeV/nucleon. These observations lend support to models that describe these reactions in terms of a localized, thermalized, expanding interaction zone.[3,4,5]

The present measurements were carried out at the Lawrence Berkeley Laboratory Bevalac using ^{20}Ne beams of 100 and 156 MeV/nucleon with an intensity of about 5×10^6 particles/sec. A gold target of 100 mg/cm^2 thickness was used and was mounted at 50° to the beam direction. Light particles (p,d,...) were detected using six particle telescopes each made up of a thin ΔE silicon detector (.4 to .8 mm thickness), a thick ΔE silicon detector (5 mm thickness), and a thick E detector comprised of either plastic scintillator, NaI, or CaF$_2$. The energy range of detected protons covered approximately 10 to 150 MeV. The energy calibrations of the telescopes were established using direct beams of 50, 100, and 150 MeV protons. An angular range of 50 to 130° in the laboratory was covered in 20° steps. The energy spectra were corrected for reaction losses using the method outlined in Ref. 3. During the run the telescope angles were changed to allow overlapping spectra to be measured with a typical agreement better than 10%. The relative normalization between different angles is accurate to within 5% (the error is mainly due to uncertainties in the solid angle of each telescope). The absolute normalization, obtained by calibrating an ionization chamber against a scintillator which directly counted beam particles, is accurate to within 25%.

As typical examples of the present data, the spectra obtained for 100 MeV/nucleon ^{20}Ne+Au leading to protons and deuterons, and 156 MeV/nucleon ^{20}Ne+Au producing protons and alphas are shown in Fig. 1. The error bars include statistical errors and any differences in the overlap measurements between different

telescopes. The shape of the proton spectra below 75 MeV emitted energy differs qualitatively from the measurements of 86 Mev/nucleon ^{12}C-induced reactions[7] on Au where the proton spectra exhibit a broad maximum at approximately the beam velocity for $\theta \leq 54^{\circ}$. These data are not included because of these differences and because reactions induced by C and Ne projectiles may behave differently.

In order to isolate the component of the particle spectra originating from an intermediate velocity source, a selection criterion was established. Target fragmentation leads to low energy particles distributed almost isotropically in the laboratory frame. Indeed, in Fig. 1 there is a clear indication for a nearly isotropic component below 30 MeV for protons at both incident energies. Projectile fragments populate forward angles near the projectile velocity. We therefore associate fragments emitted at large angles $\geq 50^{\circ}$ and at energies well above evaporation energies with an intermediate source. This source will contain a superposition of many different sources with velocity and temperature gradients that are treated explicitly in models such as the firestreak model.[3] However, in order to describe a large body of experimental data with a minimum number of parameters, we can approximate these multiple sources with one source described by a relativistic Boltzmann distribution of the form[3]

$$\frac{d^2\sigma}{p^2 dp\, d\Omega} = \frac{\sigma_0}{4\pi m^3} \frac{e^{-E/\tau}}{2(\frac{\tau}{m})^2 K_1 (\frac{m}{\tau}) + (\frac{\tau}{m}) K_0 (\frac{m}{\tau})} \qquad (1)$$

where σ_0 is the cross section, m is the particle mass, τ is the temperature, E is the particle total energy, and K_0 and K_1 are MacDonald functions. 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 using

$$\frac{d^2\sigma}{dEd\Omega} = pE' \frac{d^2\sigma}{p'^2dp'd\Omega'} \tag{2}$$

$$E' = \gamma(E-\beta p \cos \theta_{lab})$$

where the primed (unprimed) quantities refer to the center of mass (laboratory) frame, θ_{lab} is the laboratory angle, and $\gamma=(1-\beta^2)^{-1}$. A coulomb correction was applied by shifting the calculated spectra by 10 MeV for Z=1, and by 18 MeV for Z=2 fragments.[2] The paramters β, τ, and σ_0 are determined by using a least squares method to fit that part of the spectra identified with the intermediate source.

The solid lines in Fig. 1 correspond to fits of a moving source to the data with the parameters given in Table I. The low energy components of the spectra are expected to be due to target evaporation and therefore are not described by the moving source. The fit of the single moving source model to the data is good, especially for the case of 100 MeV/nucleon. For comparison, we include the results of firestreak calculations as dashed lines in Fig. 1. These calculations reproduce the proton spectra at 156 MeV/nucleon satisfactorily but underpredict the other three cases shown in Fig. 1. This effect could be caused

by the breakdown of the straight-line geometry of this model at such low energies.

The ratios of production cross sections (σ_0) and temperatures (τ) for p,d,t, and ^{4}He extracted using moving source fits are shown in Figs. 2 and 3 where the same assumptions and equations were used in all cases. These cross sections correspond to particles produced in the intermediate velocity source and are model dependent. For the present measurements, the total integrated cross sections were obtained by extrapolating the measured spectra to include all angles and energies and the results were typically equal to or slightly larger (at most a factor of 2) than the intermediate source result. Included in the analysis are light charged particle spectra from 9, 13, and 20 MeV/nucleon ^{16}O+Au,[2] 42 MeV/nucleon ^{20}Ne+Ta,[8] 100 and 156 MeV/nucleon ^{20}Ne+Au (present work), 241 and 393 MeV/nucleon ^{20}Ne+U,[9] and 800 MeV/nucleon ^{20}Ne+Pb.[10] The ^{4}He cross section at 800 MeV/nucleon was extracted from the reaction ^{40}Ar+Pb.[10] In Fig. 2 the cross sections for particles obtained from the fits to the intermediate source are shown as ratios of composites (d,t,^{4}He) to protons. These ratios exhibit a striking behavior in that the d/p and t/p ratios are nearly constant with energy, whereas the ^{4}He/p ratio drops drastically with increasing projectile energy. The solid lines correspond to calculations for a free, strongly-interacting gas in thermal and chemical equilibrium at an excitation determined by assuming the moving source is described by a fireball at the most probable impact parameter and using a freeze-out density of

.12 fm^{-3}.[3] The predicted cross sections for p,t, and ^{4}He include the decay of nuclear resonances produced in the thermal system whereas it is assumed that no resonances decay to deuterons. The decay of nuclear resonances is an essential ingredient in the calculation and accounts for the observed constancy of the d/p ratio. The calculation reproduces the trend of the d/p and ^{4}He/p ratios but fails to describe the t/p ratio. A better agreement with the t/p ratio can be obtained by excluding the contributions from resonances that decay to tritons and this result is shown in Fig. 2 as a dashed line. The success of the thermal model in reproducing the constant d/p ratio casts doubt on the interpretations of Ref. 11 where the d/p ratio was related directly to the entropy produced in heavy ion reactions.

The extracted temperatures for p,d,t, and ^{4}He as a function of incident energy are shown in Fig. 3. The approximate agreement of the temperatures for four different particles lends support to the idea that they are produced in a common, intermediate source rather than, for example, from a direct knock-out reaction.[12] The solid line, corresponding to the thermal calculations described above, follows the trend of the extracted values, but is always higher, presumably reflecting the expansion and cooling that takes place from the initial state as the particles are emitted. The flattening of the predicted temperature at low energies is due to the formation of composites.

The success of the thermodynamic description in predicting the overall trends of the cross sections for nucleons and light nuclei as well as the apparent temperatures lends strong support to the formation of a hot, localized source over a large range

of incident energies and extends a challenge to other models to describe these same phenomena. It will be important to establish the extent to which direct knock-out[12] and coalescence[13] models can account for the observed composite to protons ratios and energy spectra. The decrease of the ^{4}He production compared to protons is a striking observation consistent with thermal, explosion models. Our results emphasize the importance of measuring light composite fragments as well as nucleons to study the properties of hot, nuclear matter.

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FIGURE CAPTIONS

Figure 1.--Energy spectra for ^{20}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 2.--Ratios of extracted production cross sections (σ_0) using the moving source model described in 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 with contributions from nuclear resonance decay. Data are from present work and Refs. 2,8,9, and 10.

Figure 3.--Extracted temperatures using the moving source model as described in the text. The solid line corresponds to the fireball prediction. Data are from present work and Refs. 2,8,9, and 10.

TABLE I.--Moving source parameters for data shown in Fig. 1 using equations 1 and 2 incorporating coulomb correction.

Energy (MeV/n)	Particle	Temperature (MeV)	Velocity Fraction	Cross Section (barns)
156	p	32±3	0.47±.02	10.5±2.1
	^{4}He	20±2	0.21±.02	1.7±.4
100	p	22±2	0.49±.04	11.4±2.3
	d	25±3	0.47±.05	4.8±1.0

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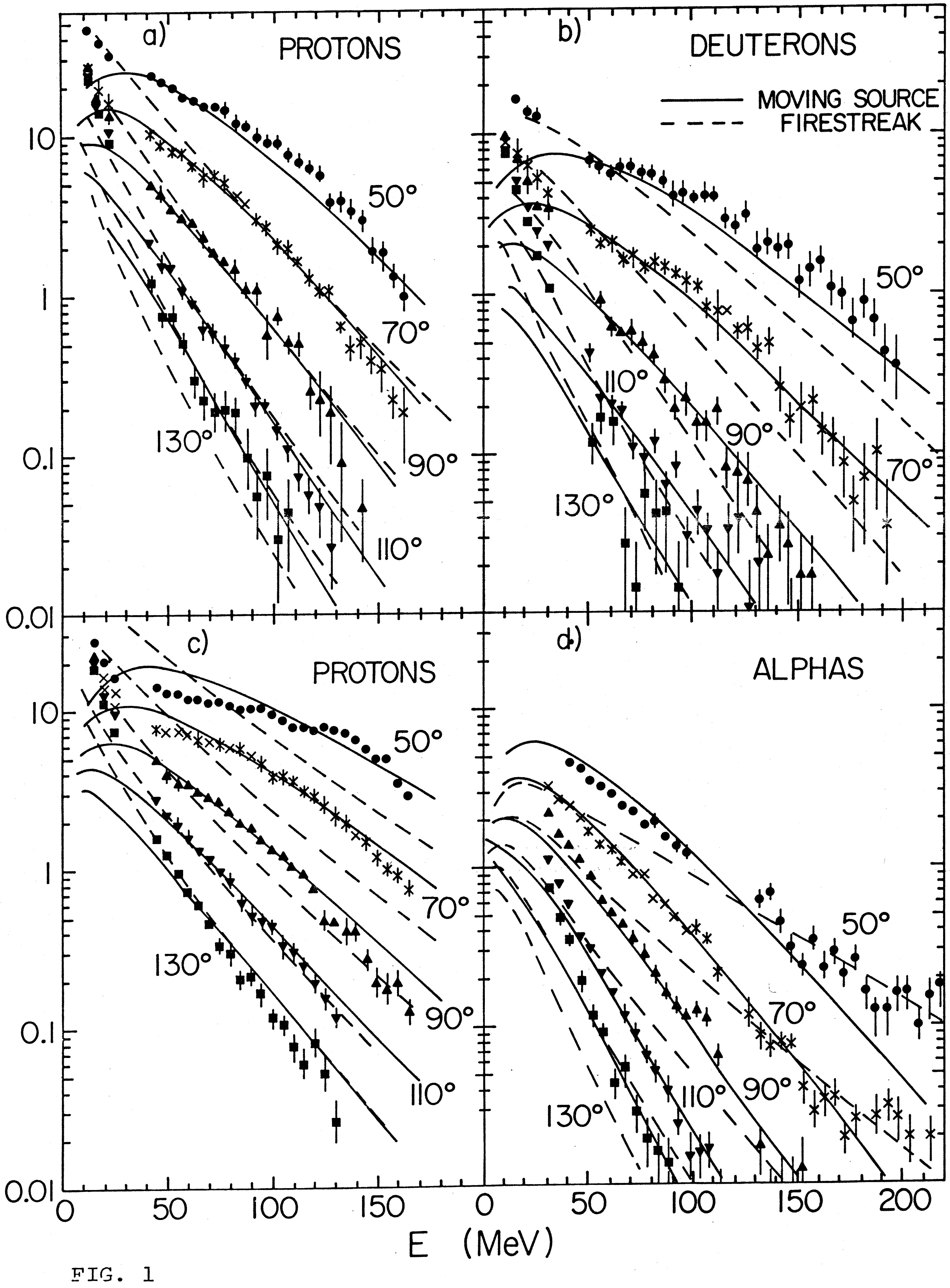

FIG. 1

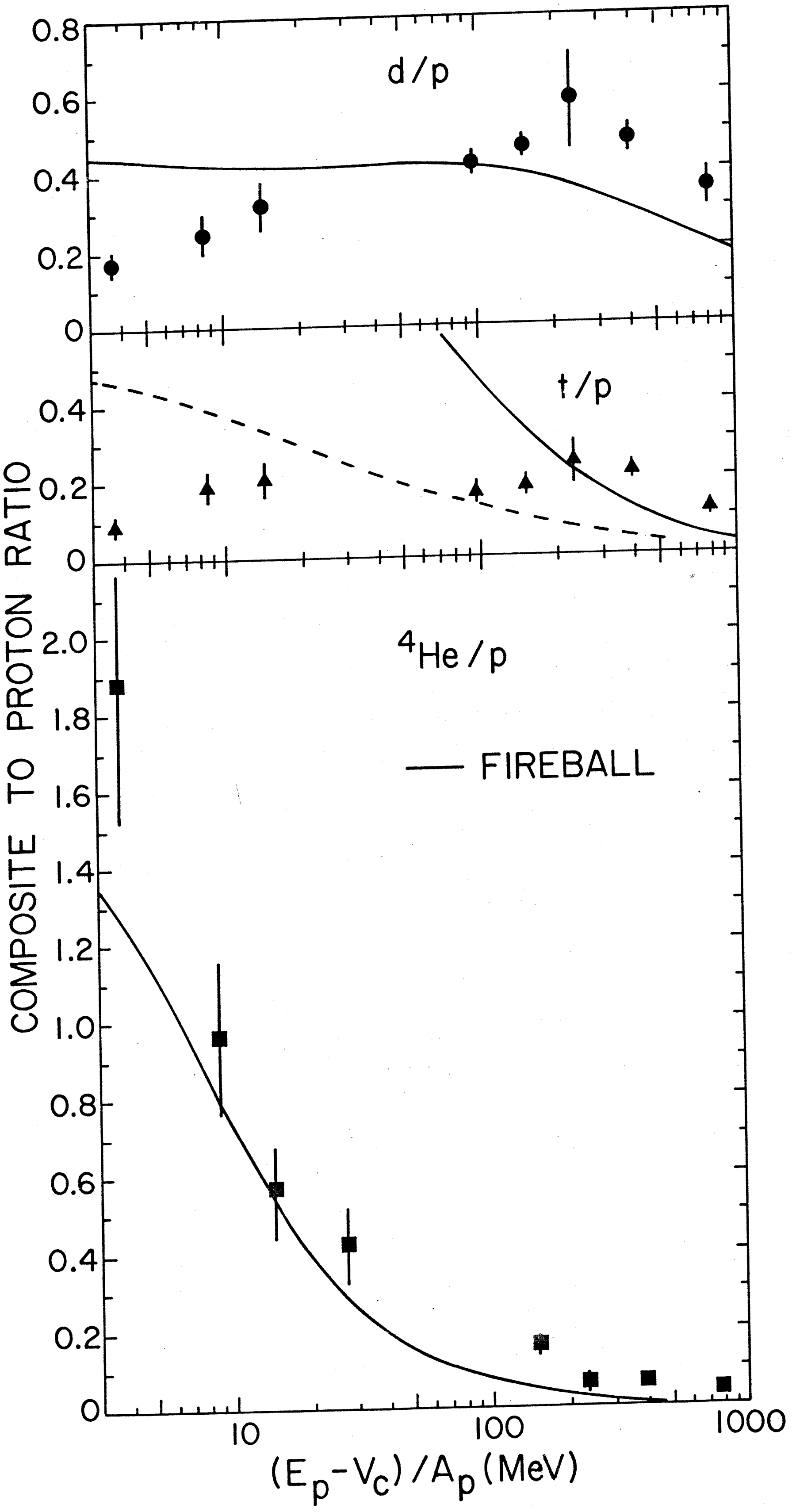
COMPOSITE TO PROTON RATIO
d/p
0.8
0.6
0.4
0.2
0
t/p
0.4
0.2
0
^{4}He/p
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
— FIREBALL
10
100
1000
$(E_p-V_c)/A_p$ (MeV)

FIG. 2

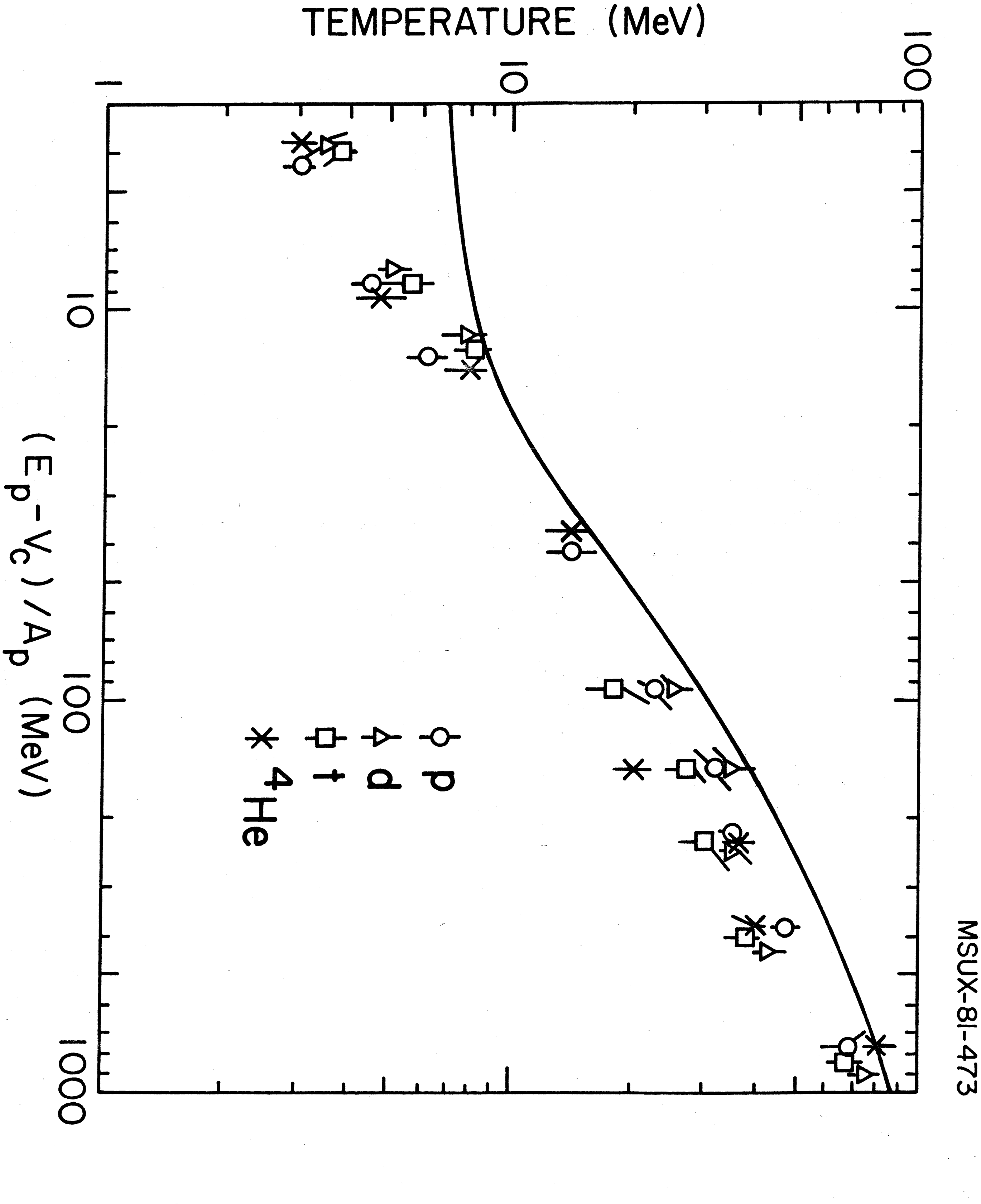
TEMPERATURE (MeV)
1
10
100
$(E_p - V_c)/A_p$ (MeV)
10
100
1000
p
d
t
^{4}He
MSUX-81-473

FIG. 3