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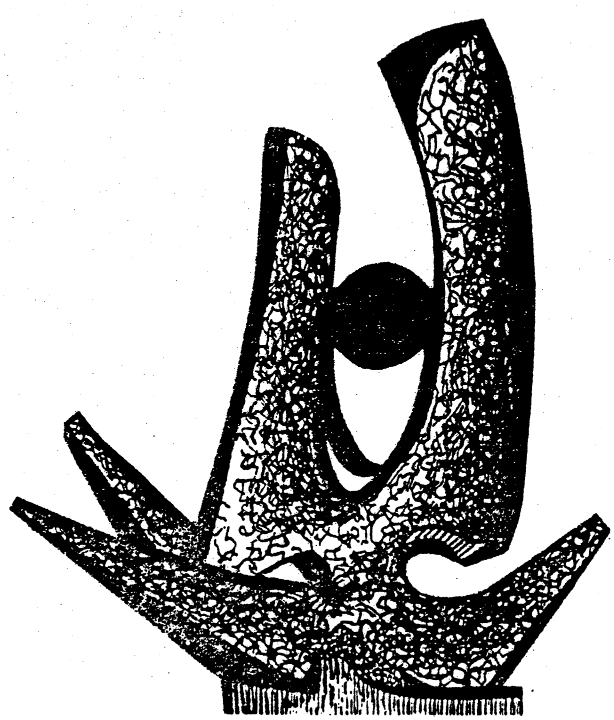

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Abstract

Characteristics of intermediate mass fragment emission data claimed to be experimental evidence of a hadronic gas to liquid phase transition are reviewed. The data are shown to be compatible with conventional nuclear physics models which do not incorporate such a phase transition.

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The internucleon separation dependence of the nucleon-nucleon interaction, attraction at long distances and repulsion at short, opens up the possibility that there may be a nuclear liquid-gas phase transition. Studies[1-5] of models for the nuclear equation of state show that the critical temperature of nuclear matter is probably in the 10-20 MeV range (with some estimates outside this range). This may allow such a nuclear gas to liquid phase transition to be observable experimentally, since thermal model analyses of intermediate energy nuclear reactions show that these temperatures can be achieved.

The search for experimental signals of the phase transition largely has concentrated on intermediate mass fragment emission in proton induced reactions, as researchers in this field were among the first to apply phase transition ideas to their data.[6-8] The yield of intermediate mass fragments $Y(A_F)$ is observed to decrease smoothly as a function of fragment mass A_F for $A_F \gtrsim 10$. Among other functional forms which approximate this decrease, the simple expression $Y(A_F) \propto A_F^{-\tau}$ has been used extensively. The exponent τ found in fitting the data was typically 2-3, in the range predicted by the thermal liquid drop model[9] for condensation around the critical point.

Of course, the whole idea of treating this kind of nuclear reaction as a phase transition has to be approached with caution. A sharp phase transition requires firstly a large number of particles, secondly a long time scale relative to the time required for the phase transition to take place, and lastly, of course, an equilibrated system. Thermal model analysis of intermediate mass fragment data in proton induced reactions[10] typically shows that the number of nucleons in the system which produces the fragment is about double A_F. For the fragment mass range often examined, $10 \leq A_F \leq 20$, this implies a system of the order 40 nucleons. Density flutuations for such a small number of particles are quite substantial, and will certainly tend to soften the sharpness of the transition. Consider, for example, a part of the Van der Waals-like equation of state shown in the inset of Fig. 1. In the Maxwell construction, states A are thermodynamically favored over states B and C. The probability for being in these other states can be calculated[5,11] and is shown in Fig. 1 for a 40 nucleon system and, for comparison, a 10,000 nucleon system. Clearly, one must go to temperatures well below the critical temperature before the transition becomes at all sharp for small systems.

Similarly, the time scale involved is fairly short. Hydrodynamical[12] and other calculations[13,14] give estimates for the lifetime of the hot region in the 10 to 20 MeV temperature range of 5 to 10×10^{-23} sec. These results are supported by analysis[15] of nucleon emission in muon and proton induced reactions. On the other hand, the disassembly time in the liquid-gas transition is estimated[16] to be in the 10^{-22} sec. regime. In other words, the time for the phase transition to occur is calculated to be comparable to the cooling time of the system.

Of course, the fact that the mass yield curve can be described by a parametrized function is not confirmation of a phase transition. Several other[12,17-20] models which have nothing to do with phase transitions are equally successful in describing the data. The author has shown,[17] for example, that the mass distribution of a system of interacting nucleons which is allowed to form clusters will evolve to a form similar to that observed experimentally in about 5 to 10×10^{-23} sec. In another approach,[12,19] the entropy per nucleon extracted from the mass yield curve is about what one would expect for the minimum entropy characteristic of the disassembly of a system in thermal and chemical equilibrium, without the extra entropy expected from a phase transition. Evaporative models[20] and ones involving the break-up of cold nuclear matter[18] can also reproduce the data.

In a recent paper,[21] the temperature dependence of the exponent τ was investigated and the results from this analysis of several data sets[6,7,10,22-26] are shown in Fig. 2a along with some other results. From this figure, there are indications that there may be unusual behavior of the exponent in the $T = 11$ MeV region, perhaps indicating critical behavior. However, there are sufficient ambiguities in the way the data points were chosen for this graph that they are worth commenting on. First, a dramatic point at $\tau = 1.7$ included in Ref. 21 is not included in Fig. 2a. This point was generated from data[26] which was later included in a more complete[25] data set, used to generate point U.

Hence, we omit the earlier data to avoid "double counting". Similarly, a data set[27] from a silver target at 5.5 GeV incident proton energy is omitted here (as it was in Ref. 21) because the data are included in the more complete experiment of Ref. 25. The point labelled U on the graph is an experiment with a uranium target, whereas all of the other data points are from lighter targets, predominantly silver. The Q value for fragment production is substantially larger with uranium, of course, and this leads to greater fragment production. A more consistent approach would be to use only the silver target data from the same reference as point U as has been done in Fig. 2b.

There are also difficulties in determining the relevant temperature to be used. The temperature used in plotting points P_1 (which was not included in Ref. 21; see Ref. 8) and P_2 are not actual fragment temperatures determined by a thermal model analysis of the fragment data, but rather are the intercepts of a straight line fit to that temperature plotted as a function of A_F. (This is an attempt to take recoil effects into account, although the temperature decrease may also have to do with an increasing source size as a function of fragment mass.) Often this intercept temperature is not too different from the actual fragment temperatures, but in this case the fragment temperatures are considerably lower, shown as points P_1' and P_2'. Similarly, a new extended data set[28] allows a better determination of τ and the intercept temperature in 500 MeV $p + Ag$ reactions. The older data are denoted by point S, which becomes S' with the more complete experiment. Of course, one is always wary of the fact that the fitting procedures used by Refs. 21 and 28 may be different, resulting in the large displacement of S (illustrating the difficulty of combining so many data sets together, as Fig. 2 does); however, we will take the results at face value and include S' in Fig. 2b. The error bars the authors of Ref. 21 have assigned to their temperature and exponent estimates are also restored to Fig. 2b, although it should be emphasized that the actual variation in temperature over the mass range of fragments considered is much larger than is indicated by the error bars.

One sees from Fig. 2b that the dip structure hinted at in Fig. 2a has disappeared. Nevertheless, the interesting rise in the exponent at low temperatures remains. Is this evidence for a phase transition, or is it explicable in terms of more conventional ideas? The yield curves used in determining the exponents in Fig. 2 are found by numerically integrating the inclusive differential cross section $d^2\sigma/dEd\Omega$. The differential cross section has its largest value at relatively low energies, in the region of the coulomb barrier. For example, the authors of Ref. 28 show that coulomb effects strongly cut off their heavy fragment yields in this energy region.

To see if coulomb effects can quantitatively explain the behavior shown in Fig. 2, we perform the following simple calculation. Suppose that there is a mass distribution given by $Y(A_F) = CA_F^{-\delta}$ (where C is a normalization constant) which describes the yield independent of temperature before coulomb effects are included. The individual fragment spectra we will characterize by a Maxwell-Boltzmann distribution in energy. Now, at high temperatures, the existence of the coulomb barrier will only have a major effect on the lowest energy part of the fragment spectrum. As the temperature is lowered, an increasing fraction of the large Z fragments will be subject to a coulomb barrier in leaving the nucleus. The calculation consists of taking the spectrum inside the coulomb barrier and modifying it by multiplying by a barrier penetration factor $P_A(q)$, where q is the fragment momentum. In other words,

$$\left.\frac{d^3\sigma_A}{d^3q}\right|_{\text{outside}} = P_A(q) \left.\frac{d^3\sigma_A}{d^3q}\right|_{\text{inside}} \tag{1}$$

where the integral of the "inside" distribution obeys $Y = CA_F^{-\delta}$. The integral of the left hand side then gives the yield. The penetration factor will be approximated by $\exp(-2\int \kappa dx)$ where $\kappa = \sqrt{2m(V(x)-K)}$, V(x) being the coulomb barrier and K the kinetic energy.

The change in the apparent exponent for the $10 \leq A_F \leq 20$ region is shown as the curve on Fig. 2. The high temperature exponent is chosen as $\delta \equiv 2.2$ here, although it can be obtained from the calculations of Refs. 17-20. The results depend upon the charge and mass of the emitting system, chosen to be 25 and 50 respectively here, similar to what is found in analysis of the fragment differential cross sections.[8,10,28] No attempt was made to tailor the coulomb barrier to get a "best fit" to the data. The point of this calculation has not been to present a complete description of fragment yields, but rather to show that the observed behavior of the yield curve at low temperatures is what one expects from coulomb barrier effects.

In summary, in spite of the growing calculational evidence that nuclear gas to liquid phase transitions should be expected in large, long lived assemblies of nucleons, there are indications that the nuclear interaction region involved in intermediate mass fragment emission is both too small and too short lived to support a sharp transition. The mass yield curves themselves can be explained by several models which do not invoke a phase transition. The change of the yield curves with temperature is consistent with what one expects from the necessity of the higher Z fragments to tunnel through a substantial coulomb barrier at low temperature.

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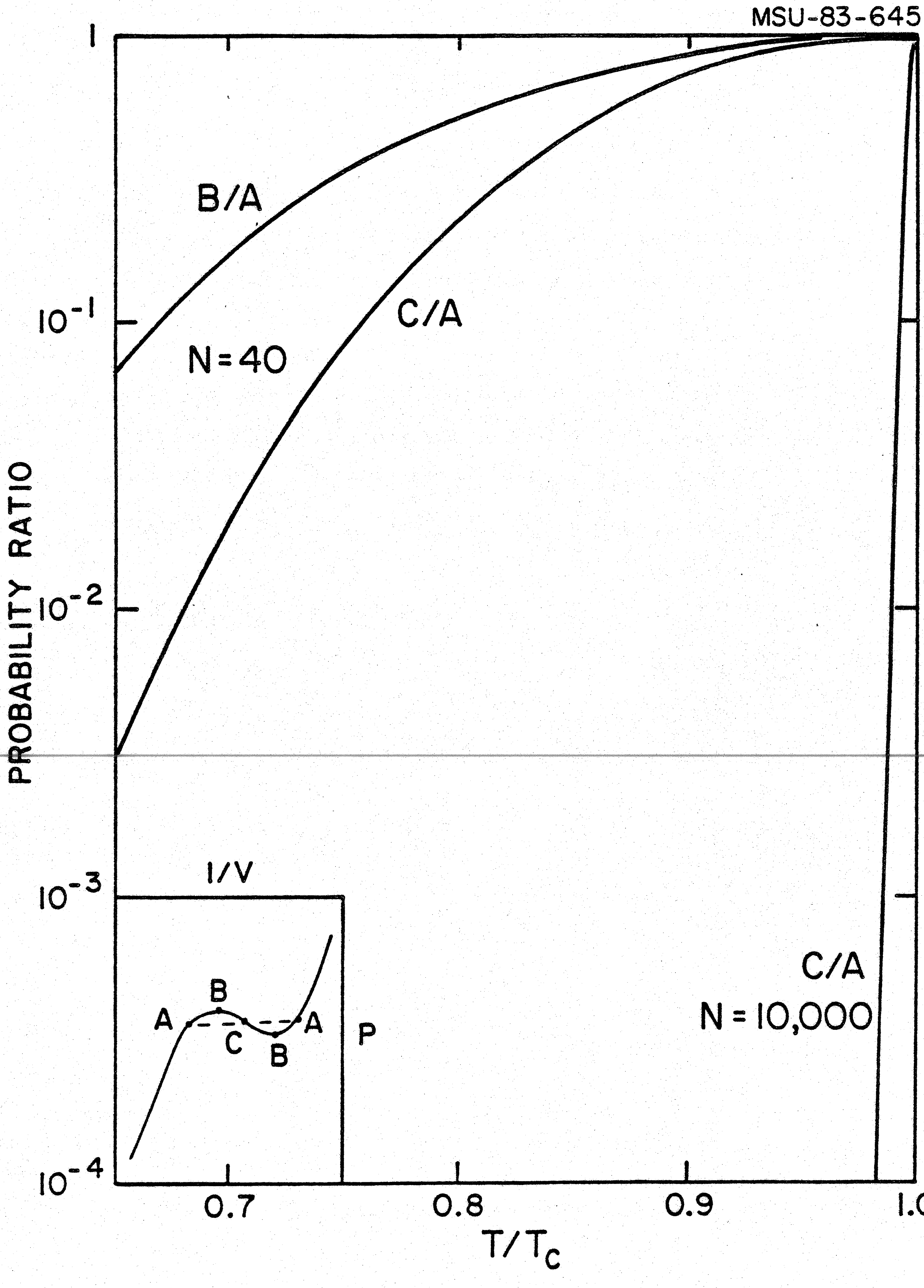
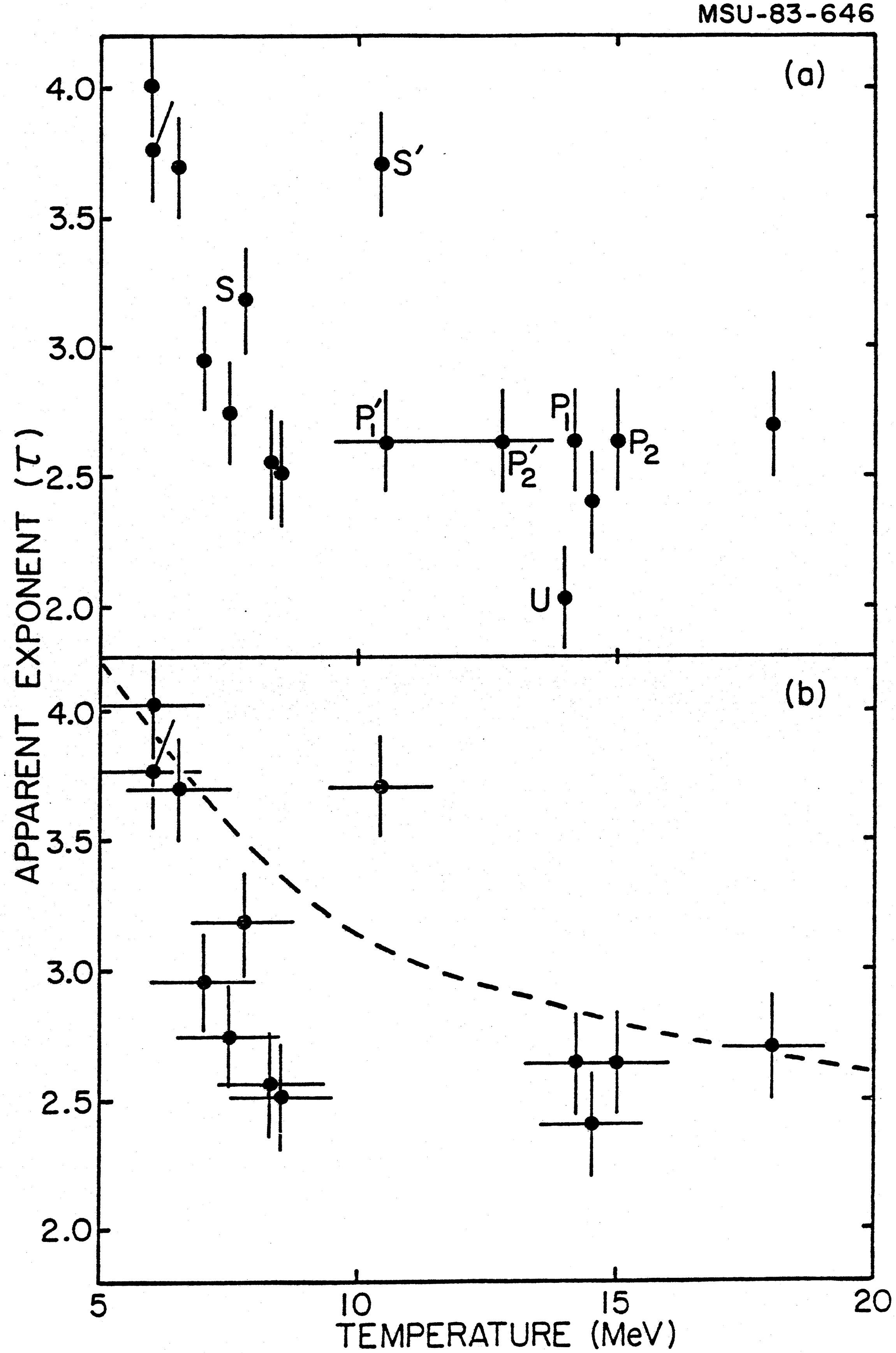
Figure Captions

Fig. 1. Ratio of probabilities for a 40 nucleon system being in the states B and C compared to the thermodynamically favored states A. The inset shows the state labels in the Maxwell construction in a liquid-gas equation of state.

Fig. 2. a) Temperature dependence of the exponent τ as given in Ref. 21. See text for explanation of labels.
b) Estimated dependence of τ on tunnelling through the coulomb barrier is given by the curve through the data.



MSU-83-645
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PROBABILITY RATIO
B/A
C/A
N=40
1/V
B
A
A
C
B
P
C/A
N = 10,000
0.7
0.8
0.9
1.0
T/T_c



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(a)
(b)
S′
S
P′1
P′2
P1
P2
U
4.0
3.5
3.0
2.5
2.0
APPARENT EXPONENT (τ)
5
10
15
20
TEMPERATURE (MeV)