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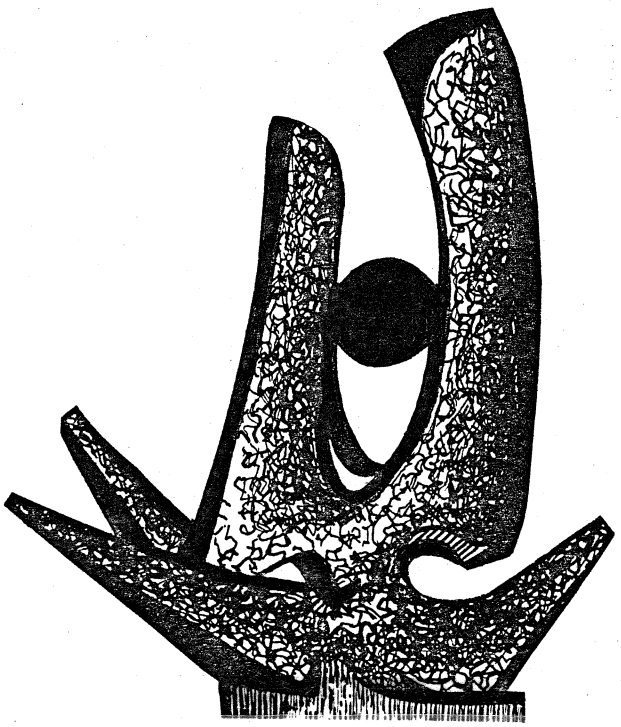

SEPTEMBER 1983

MSUCL 433

EXPERIMENTAL EVIDENCE FOR A LIQUID-GAS PHASE TRANSITION IN NUCLEAR SYSTEMS *

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ABSTRACT

At a certain combination of temperature and density, nuclear matter may exist as a liquid-gas mixture exhibiting phase instabilities, a characteristic signature of which may be found in the emission of intermediate-mass fragments in nuclear collisions. Our analysis of fragment distributions from proton and heavy ion induced reactions, in the framework of a theory of condensation, is suggestive of the possible occurrence of such phase transitions with a critical exponent, $k \sim 1.7$ and a critical temperature, $T_c \sim 12$ MeV.

PACS number: 25.70.Np, 21.65.+f, 25.40.-h, 24.60.-k

Through the study of high energy nuclear collisions, it may become possible to determine the nuclear equation of state (1), and to create new forms of nuclear matter. Although most attention has been directed towards phase transitions to a pion condensate or a quark-gluon plasma, conjectured to develop at high density and temperature,it is also possible that a liquid-gas phase instability may set in at a critical temperature and density (2,3). This instability may be encountered during the expansion of the initially heated zone, formed in a nuclear collision. In this letter we discuss experimental evidence for such a critical phenomenon from a study of the formation of complex fragments, in a variety of proton and heavy ion induced reactions. Such studies are of intrinsic interest in yielding information on the equation of state at high temperatures and at densities below normal and also for the insight into the hydrodynamical behavior, necessary for the occurrence of more exotic phase transitions, and for the astrophysical ramifications with regard to neutron stars and supernovae (4,5).

The possibility of a phase transition in an equilibrated nuclear system was previously considered theoretically in a number of papers (5-10). Examination of light ion production cross sections over a wide range of incident energies has indicated that, to obtain an unambiguous experimental signature of phase transitions, it is necessary to measure intermediate-mass fragment cross sections (8). It has already been suggested in a number of recent papers (2,11,12), that the power law dependence, $Y(A) \sim A^{-\tau}$, of the fragment distributions may constitute a signature for the occurrence of phase transition phenomena near a critical point. The widely differing

systems, which exhibit this characteristic power law dependence, suggest that phase transitions are global in origin, dependent only on the energy imparted to the system and not on the details of the reaction. However, the temperatures of the reported systems vary between about 8 MeV (12), and 18 MeV (11). Clearly, not all these systems can be near the critical point.

To understand the temperature dependence of the data, we first fitted the available fragment distributions with a power law dependence of the form: $P(A) \sim A^{-\tau}$, where τ is the "apparent" exponent. In this approximation, the effects of any temperature-dependent factors are absorbed into the power exponent, . Therefore, this apparent exponent will vary with temperature.

For some of the analysed data the temperature of the system has been extracted from moving source fits to the fragment energy distributions, as reported in ref (2,11,14-16). Where the temperature was not given, we determined it either from the slope of the tail of the 90^{o} fragment energy distributions (13), or from the ideal Fermi gas, assuming the size of the emitting system to be in the range of 2 to 4 times the largest fragment mass (12,20). The fragment masses used to determine the power law exponent were in the range of $3 \leq Z \leq 22$ for all systems; care was taken to avoid contributions from the tail of possible fission fragments. Table I summarizes the data used and the values obtained by the fit.

In Fig. 1 we plot the apparent exponent, τ, determined from a least squares fit to the fragment distributions, as a function of the temperature of the emitting system. We observe a dramatic temperature

dependence of the apparent exponent, which decreases as the temperature increases up to about 11 MeV, after which the trend is reversed. The exponent appears to reach the minimum value of about 1.7 at a temperature of about 11 MeV. If we assign the critical temperature, Tc, corresponding to the minimum value of the apparent exponent, i.e, corresponding to the maximum probability for fragment emission, then from Fig. 1 we may conclude that Tc~11 MeV. This indication is in dissagreement with the result Tc=3.3 MeV (3), obtained from the isotope distributions, but is in agreement with calculations for finite nuclear systems (10), which predict Tc in the range of 8-13 MeV.

Since the de-excitation processes of the emitted fragments may make it difficult to obtain information from lighter fragments, we restricted the range of the fragment mass to $Z \geq 5$ and used only data with integrated total cross sections to obtain the power law apparent exponent,(see Table I). This new set of data produced the same dramatic features as the full set shown in Fig. 1. This behavior of the temperature dependence of the fragment yield distribution prompted us to fit the fragment distributions with expressions obtained from a theory of condensation in excited nuclear matter (17,5), in which the probability for fragment formation of size A is given by :

$$P(A) \sim A^{-k} \exp\{[-a_s'(T)A^{2/3} - a_v'(T)A + \mu(T)A]/T\}$$

where k is the critical exponent, $a_s'(T)=a_s(T)-TS_s$ is the surface free energy per particle, $a_v'(T)=a_v(T)-TS_v$ is the volume free energy per particle and $\mu(T)$ is the chemical potential per particle.

The above relation can be written in the following form :

$$P(A) \sim A^{-k}\ X^{(A**2/3)}\ Y^{A}$$

where :

$$X = \exp[-a_s'(T)/T]$$

$$Y = \exp\{-[a_v'(T) - \mu(T)]/T\}$$

In the region T<Tc, where gas and liquid phases coexist, the sum of the volume energy per particle in the liquid phase and the Gibbs free energy per particle in the gaseous phase is equal to zero, $[a_v'(T)-\mu(T)]=0$. Therefore, the exponential factors are Y=1 and X<1, and the probability P(A) can be written as :

$$P(A) \sim A^{-k} \exp\{-[a_s'(T)A^{2/3}]/T\} \qquad [1]$$

At the critical point, determined by T=Tc, the surface free energy term is equal to zero, $a_s'(T)=0$, and in addition $[a_v'(T)-\mu(T)]=0$. Therefore, both exponential factors are X=1 and Y=1, and the probability assumes the pure power law form:

$$P(A) \sim A^{-k} \qquad [2]$$

Finally for T>Tc, corresponding to a gas phase, we assume that the surface free energy is very small, $a_s'(T)\sim 0$, while $[a_v'(T)-\mu(T)]>0$. Therefore, the exponential factors are X~1 and Y<1, and the probability P(A) assumes the form:

$$P(A) \sim A^{-k} \exp\{-[a_v'(T)-\mu(T)]A/T\} \qquad [3]$$

We note that the exponential factors X and Y, at temperatures T<Tc and T>Tc, respectively, modulate the pure power law dependence of the fragment distribution. Furthermore the form of expression [3] has an A-dependence (power of A) similar to the coalescence formula, which is applicable to composite fragment emission in high energy collisions

(18,19).

We parameterised the temperature dependence of the surface free energy as :

$$a_s'(T) = 18.4(1- T/Tc)^2 \qquad [4]$$

since: $a_s'(T=0)=18.4$ MeV, the cold nuclear matter surface energy, and $a_s'(T=Tc)=0$. For the volume and Gibbs free energies we take:

$$a_v'(T)-\mu(T) \sim b^*(1- T/Tc)^2 \qquad [5]$$

where b is a coefficient not known apriori; a value in the range 7-10 MeV was determined by the fitting routine (21). A least-squares fit to the fragment distributions was undertaken using the expressions:

$$P(A)=C\ A^{-k}\ \exp\{[-a_s'(T)A^{2/3}]/T\} \qquad \text{for } T<Tc$$

$$P(A)=C\ A^{-k}\ \exp\{-[a_v'(T)-\mu(T)]A/T\} \qquad \text{for } T>Tc$$

letting the exponent, k, take successively the values 1.6, 1.7, 1.8, 2.0, and 2.33 to yield the corresponding Tc-values. For the temperature of each system we used $T = T' \pm 1.$ MeV, where T' is the temperature over all emitted fragments used in each fit. This variance in T, resulting from the uncertainty in establishing the average temperature of the source, produced a variance in the calculated Tc.

Figure 2 shows the extracted critical temperature as a function of the exponent, k. We observe that for k between 1.7 and 1.8 the calculated Tc values for both T<Tc and T>Tc coincide, while for both lower and higher k values they strongly diverge. We are, therefore, inclined to accept $k \sim 1.7$ as the critical exponent and $Tc=12.0\pm0.2$ MeV as the critical temperature. The uncertainty in the critical temperature allows the possibility that the exponent k may take on a value between 1.7 and 1.8, which is lower than the value 2.33 for a

macroscopic Van der Waals system. Calculations of thermal properties of nuclei (22), using the thermal Hartree-Fock aproximation and the Skyrme III interaction, yield a critical temperature Tc=12.58 MeV for the liquid drop surface free energy, close to the temperature extracted by our analysis.

The similarity of the power law dependence ($2.6<\tau<2.7$) of the fragment distributions (2,11,12), at very different temperatures (8<T<18 MeV) can now be understood in our picture; these points lie on either side of the critical temperature and the power law is about equally modified by the temperature dependent exponential factors X and Y.

In this work it has been essential to assume the formation of thermalized hot matter of nuclear dimensions in the temperature range of 5 to 20 MeV. We have further to rely on the global freezeout concept, which ensures that the experimentally observed mass distribution reflects the configuration at the freezeout density of matter. Although both of the above concepts are generally accepted at very high energies (E/A>500 MeV), they have to be confirmed by careful examination of experimental data. It is very encouraging, however, to find that the simple ansatz, taken from the theory of condensation, works very well in this wide energy range and for very different systems.

Our analysis made use of fragment distributions from widely different systems and with appreciable uncertainty in the temperature of the fragments. To circumvent this inherent difficulty one should choose one system, such as Ar+Ag and measure an excitation function of

the fragment distributions, (trigering on central collisions) to span the region of critical temperature of about 9 to 14 MeV. From such a study one may also be able to infer more accurately the form of the T-dependence of the free energies very close to Tc, providing information concerning the equation of state of nuclear systems.

The evidence presented by our analysis leads us to conclude that critical phenomena associated with phase transitions occur in equilibrated nuclear systems, which are manifested by the formation of intermediate-mass fragments. This state of nuclear matter must be distinctly different from the one observed in normal nuclei.

We would like to thank F. Sottile for writing the fitting code and the authors of ref (12) for permission to use unpublished data. One of the authors (A.D.P.) acknowledges the hospitality of the NSCL at Michigan State University.

* Work supported by NSF under Grand No. PHY-80-17605

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*** Supported in part by NSF under Grand No. PHY-81-09019

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TABLE

I. Summary of the data used and the values of the apparent exponent obtained from the power law fit to the fragment distributions.

FIGURE CAPTIONS

FIG. 1. The apparent exponent, τ, of the power law fit to the fragment distributions as a function of the temperature, T. The error in T denotes the assumed uncertainty in the temperature for all systems. The systems are: CIR-p+Ag(.21-4.9GeV), DOT-Ne+Au(5-20GeV), X-p+U(4.9,5.5GeV), SQR-p+Xe(80-350GeV), TRI-C+Ag,Au(180,360Mev). The insert shows a typical power law fit to the fragment distributions.

FIG. 2. The extracted critical temperature, Tc, as a function of the exponent, k, for $T < Tc$ and $T > Tc$.

TABLE I

SYSTEM	ENERGY (GEV)	A or Z RANGE	TEMPERATURE (MEV)	ANGULAR RANGE (degrees)	EXPONENT τ # (+/-.2)	REFERENCE
p + Ag	0.21	3 < Z < 8	6.0 +/- 1	20, 90, 160	4.07 (4.75)	13
p + Ag	0.30	3 < Z < 8	6.5 +/- 1	20, 90, 160	3.69 (4.35)	13
p + Ag	0.4	3 < Z < 8	7.8 +/- 1	20, 90, 160	3.19 (3.83)	13
p + Ag	1.0	3 < A < 11	8.4 +/- 1	60, 120	2.51	14
p + Ag	4.9	6 < Z < 18	14.5 +/- 1	90 **	2.40	15
p + Xe	80-350	12 < A < 30	14.7 +/- 1	34 **	2.64* (2.86)	2
p + U	4.9	3 < Z < 11	14.0 +/- 1	20, 90, 160	2.03 (2.35)	15
p + U	5.5	3 < Z < 11	12.6 +/- 1	20 - 160	1.70 (1.80)	16
Ne + Au	5-20	3 < Z < 12	18.0 +/- 1	90	2.70	11
C + Ag	0.36	4 < Z < 22	8.5 +/- 1	40 - 70	2.56 (2.59)	12
C + Ag	0.18	3 < Z < 13	7.0 +/- 1	50 - 70	2.96 (3.24)	12
C + Au	0.36	3 < Z < 11	7.5 +/- 1	50 - 120	2.75 (2.81)	12
C + Au	0.18	4 < Z < 11	6.0 +/- 1	50 - 120	3.77 (3.66)	12

\# The apparent exponent, obtained with the restricted range of masses, $5 \leq Z$, is shown in parenthesis.
* The masses A=1,4 are also included in the fit.
** An almost isotropic (to about 20%) angular distribution was assumed in obtaining the integrated total cross section (15,2).

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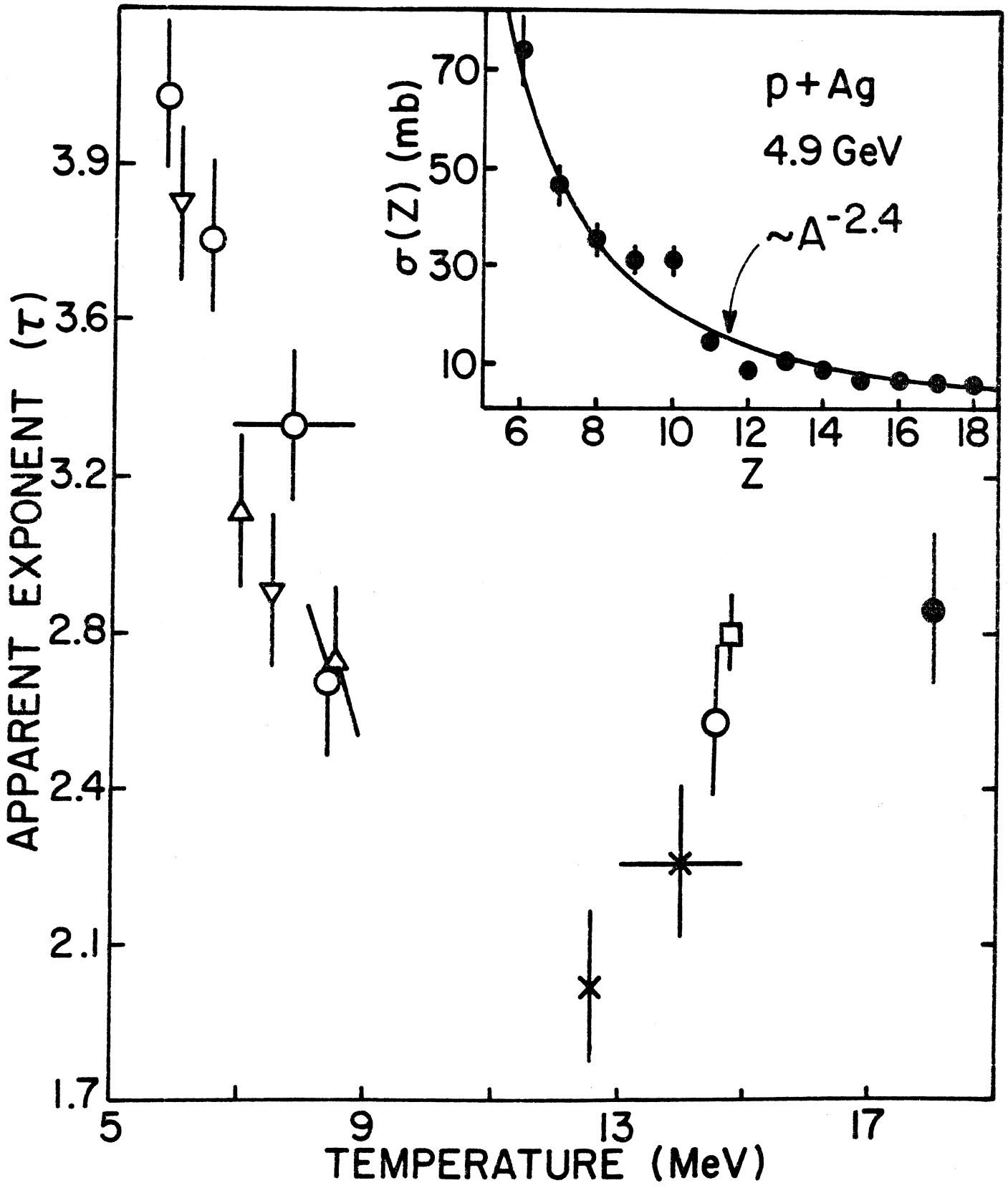

FIG 1

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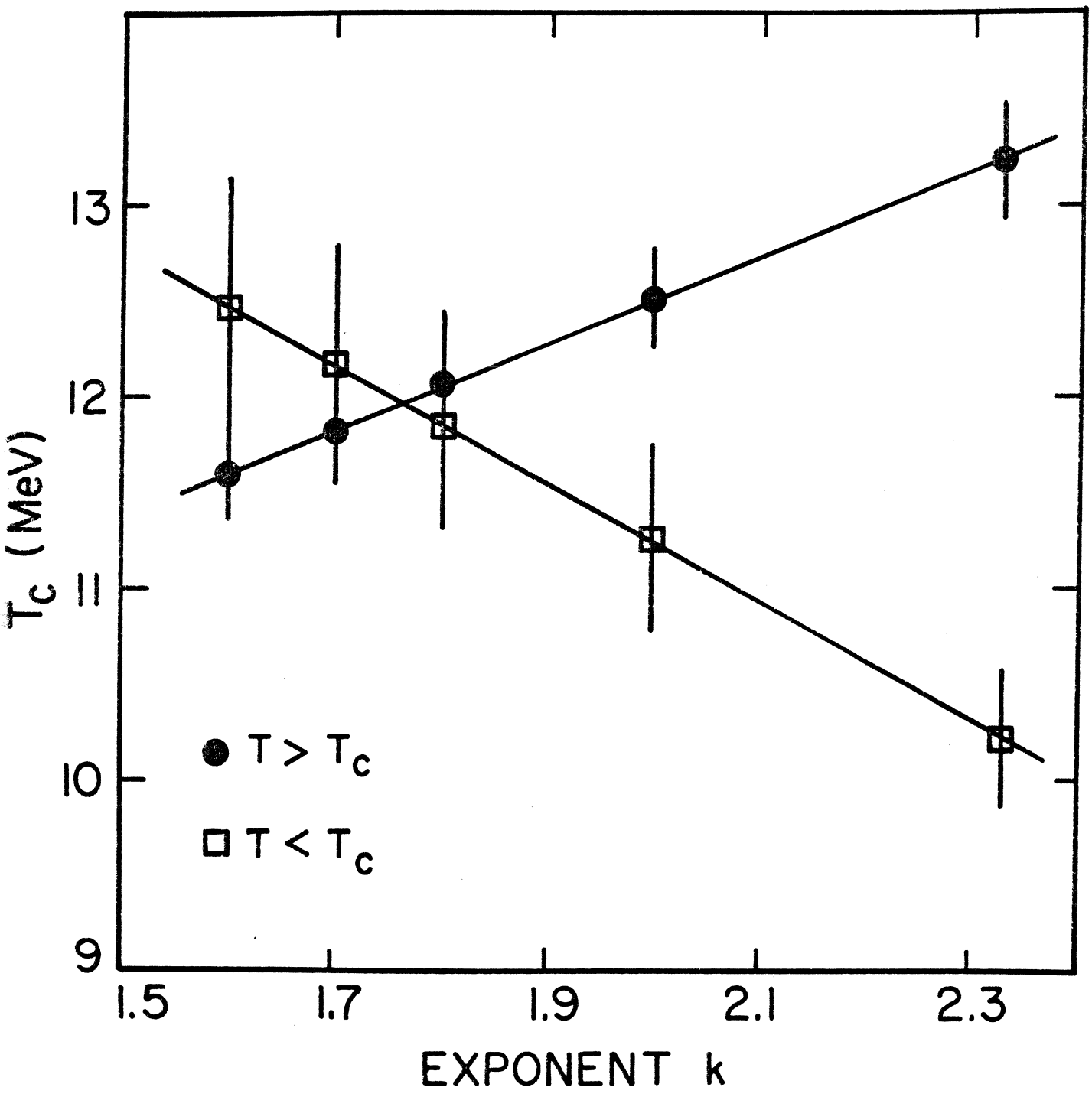

FIG. 2