Analysis of fragment isotope yields from ^{20}Ne+^{197}Au at 400 MeV in terms of liquid-gas phase transitions

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(Received 24 August 1984)

Total fast particle yields for 33 isotopes ranging from protons to ^{19}F emerging from the bombardment of ^{197}Au with 400 MeV ^{20}Ne ions are analyzed in terms of Fisher's theory for phase transitions from liquid to gas. The parameters obtained are close to those from GeV proton bombardment of heavy nuclei. The data infer a critical temperature of 5.0 MeV.

I. INTRODUCTION

Recently there has been interest in the fragmentation of big nuclei from the bombardment with medium energy projectile particles.[1] Three different scenarios have been proposed for the process:

Statistical emission from a hot system—the process is governed mainly by the available phase space.[2–4]

The passage of energetic nucleons from a hot spot leads to random shattering of the cold spectator matter.[5]

The heated nucleus expands leading to smaller density and a phase transition from liquid to vapor.[6–9]

The third possibility is especially fascinating because, if this process is the real physics, fragmentation could provide useful information about the equation of state in a new parameter range.

In this paper we want to investigate the question of whether at energies of 20 MeV/nucleon there are indications of a phase transition. For this purpose we have chosen the system ^{20}Ne+^{197}Au for which a large set of data is available.[10,11]

II. THE REACTION ^{20}Ne + ^{197}Au AT 400 MeV

In the experiments reported in Ref. 11 fast light charged particles were identified with respect to their charge Z and mass number A and were spectroscopied by a stack of solid state detectors. Total fast particle yields for the different isotopes were obtained by fitting Maxwell-Boltzmann distributions in a moving frame to the data, thus allowing integration from threshold to the maximum energy. The measured cross sections span the region $1 \leq Z \leq 3$ and $1 \leq A \leq 9$. Cross sections for heavier species with $4 \leq Z \leq 9$ and $7 \leq A \leq 19$ have been reported by Egelhaaf *et al.*[10] for the same system. The yields as function of the fragment mass number are shown in Fig. 1. The yield for $A=1$ has been obtained by adding the unobserved neutron yield Y_n estimated by the proton yield Y_p times the ratio of the number of neutrons to the number of protons in the system under consideration ($Y_n = Y_p \times N/Z$). Obviously, there are structures in the mass yield curve: maxima occur at $A=4$ (α particles), $A=12$ (mainly from ^{12}C), and $A=16$ (mainly from ^{16}O); minima are to be seen for $A=8$, 14, and 18.

The data with small mass numbers show a behavior similar to that from high energy proton-nucleus interaction.[6] We have fitted the function

$$f(A) = \exp\left[\sum_{j=0}^{r} b_j (\ln A)^j\right] \tag{1}$$

to the data. Independently where the truncation of the data set occurs in the range from $A=8$ to 12 we find the smallest χ^2 for $r=1$. This is just the power law

$$\sigma = CA^{-K} \tag{2}$$

as has been proposed by Fisher[12] for a phase transition. The critical exponent $K=2.5$ shown in Fig. 2 is close to the one proposed for real gases: 2.1–2.3 (Ref. 6). On very general theoretical grounds K is expected to lie at the critical point between 2 and 2.5 (Refs. 12–14). However, the critical exponent is a function of the temperature, as

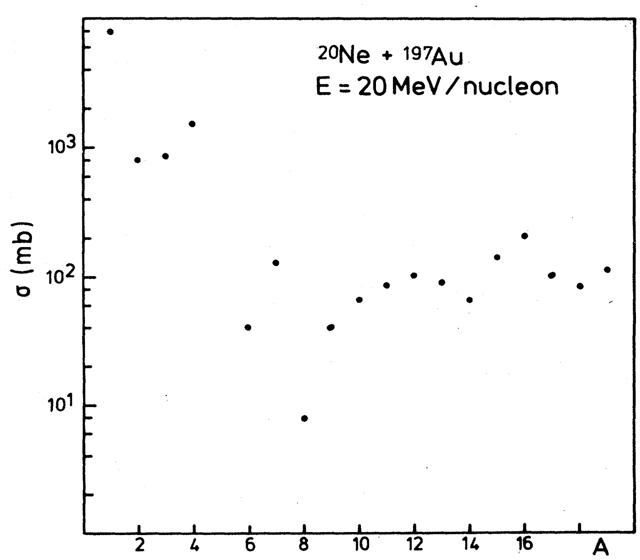

FIG. 1. The total isobaric yields for the reaction indicated. For $A=1$ the neutron yield has been added, which has been estimated as discussed in the text.

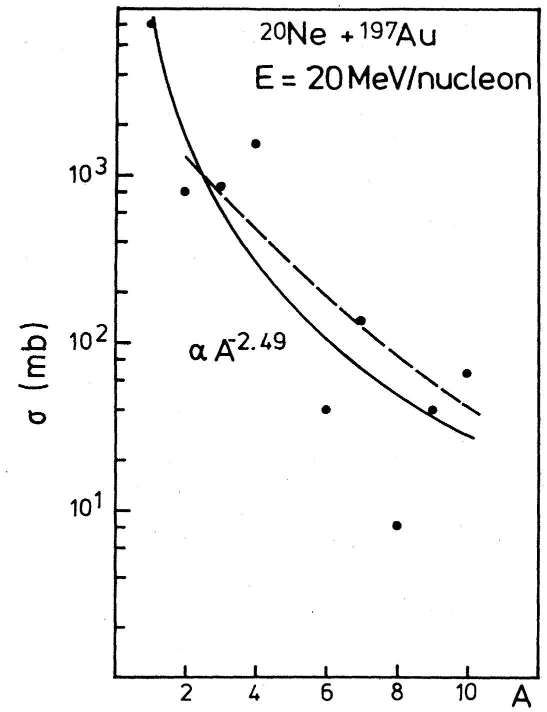

FIG. 2. Isobaric yields for mass numbers $A \leq 10$. Data (dots) are compared with a power law fit [Eq. (2)] denoted by the label $A^{-2.49}$ and by fitting Eq. (6) (dashed line).

has been pointed out by Panagioutou *et al.*,[8] and we will therefore call it an apparent exponent. They argue that—according to Fisher's theory[12]—the probability for fragment formation of size A depends not only on the apparent exponent K, but also on the surface free energy per particle, the volume free energy per particle, and the chemical potential per particle. In the region with temperature below the critical temperature T_c, where gas and liquid phases coexist, the volume energy per particle in the liquid phase is equal to the Gibbs free energy per particle in the gaseous phase. Then, the fragment formation probability depends not only on the apparent exponent, but also on the surface, resulting in maxima for $A=1$ and $A=A_{\text{target}}+A_{\text{projectile}}$.[6] Only for $T=T_c$ is the pure power law valid.

Since we cannot expect to be exactly at the critical exponent, we have taken the chemical potentials per particle μ_N and μ_Z for neutrons and protons, respectively, as well as the Helmholtz free energy, into account. Following Hirsch *et al.* (Ref. 6) we employ a liquid drop expansion

$$f(Z,A)=a_v A-a_s A^{2/3}-a_C Z^2/A^{1/3} -a_a(A-2Z)^2/A-\delta\ , \tag{3}$$

with

$$\begin{aligned}\delta&=a_p/A^{3/4} \text{ for odd-odd nuclei}\\ &=0 \text{ for odd-even and even-odd nuclei}\\ &=-a_p/A^{3/4} \text{ for even-even nuclei .}\end{aligned}$$

The coefficients in (3) represent the volume, surface, Coulomb, symmetry, and pairing contributions to the free energy. The function fitted to the data then reads

$$\sigma(Z,A)=CA^{-K}\exp\{[f(Z,A)+\mu_N N+\mu_Z Z]/T +N\ln(N/A)+Z\ln(Z/A)\}\ , \tag{4}$$

with N the neutron number and C an overall normalization as in Eq. (2). The parameters obtained from the best fits, i.e., leading to smallest χ^2 values, are shown in Table I.

To make our results comparable to previous ones,[6] we have kept the value $a_v=14.1$ MeV fixed to the ground state liquid drop value. Examples for the quality of the fits are given in Fig. 3. The fits follow only the gross behavior of the data; they cannot reproduce the measured yields in detail. However, we know that the Weizsäcker mass formula is not capable of reproducing the exact variations in binding energy for very light nuclei. Therefore, one cannot expect perfect fits. However, neglect of the helium and hydrogen isotopes improves the fits for the heavier elements only slightly. It is interesting to note that the deduced temperature is lower in that case than fitting Eq. (4) to the full set of data. The parameters obtained show some similarities with those from Ref. 6.

TABLE I. Values for the parameters in the fits to the isotopic yields. The volume free energy has been set equal to 14.1 MeV as has been done in Ref. 6.

Parameter		^{20}Ne + ^{197}Au	p + Kr (Ref. 6)	Nominal value
Volume	a_v (MeV)	14.1	14.1	14.1
Surface	a_s (MeV)	5.21	6.61	13.0
Coulomb	a_C (MeV)	0.17	0.400	0.595
Symmetry	a_a (MeV)	10.63	23.30	19.0
Pairing	a_p (MeV)	10.60	5.28	33.5
Proton chemical potential	μ_Z (MeV)	−10.73	−11.01	
Neutron chemical potential	μ_N (MeV)	−7.85	−7.62	
Temperature	(MeV)	3.26	3.24	
Apparent exponent		3.44	2.65	

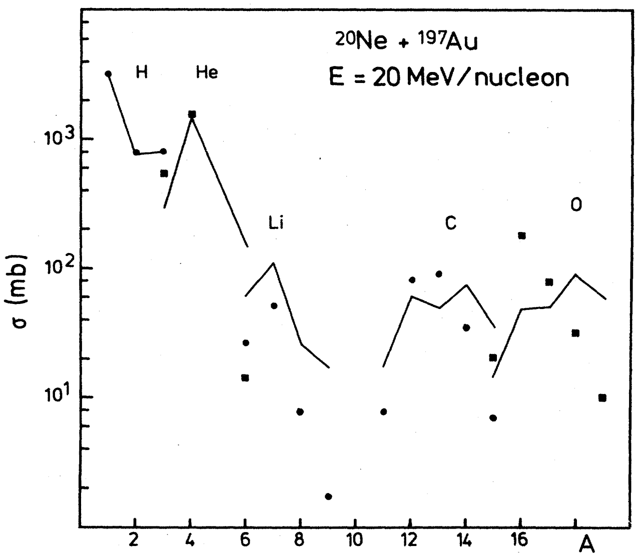

FIG. 3. Measured isotopic yields for selected elements (dots and squares) are compared with fits of Eq. (4) and parameters in Table I.

The temperature T is very close to the value of Hirsch *et al.* However, the apparent exponent is much larger. This finding—small temperature and large apparent exponent—is in qualitative agreement with the findings of Panagioutou *et al.*[8] for the case $T \leq T_c$. This critical temperature may be obtained from the parameters in Table I with the help of the parametrization for the surface tension as being proposed by Goodman *et al.* (Ref. 13)

$$a_s(T)=a_s(T=0)(1+1.5T/T_c)(1-T/T_c)^{1.5} . \qquad (5)$$

Our result is $T_c=5.0$ MeV, close to 5.6 MeV which the parameters of Ref. 6 yield.

In a recent paper Lopez and Siemens[9] investigated the fragmentation process in a vapor-liquid mixture by invoking a master equation. They take into account the transition rates for one nucleon exchange between droplets through their surface. From this ansatz Lopez and Siemens can describe the evolution in time of the numbers of droplets having A nucleons. For equilibrium, i.e., the transition rates for gaining or losing a nucleon are equal, they obtained the distribution

$$\sigma^{\mathrm{eq}}(A)=\sigma^{\mathrm{eq}}(1)\exp(-a_s A^{2/3}/T) . \qquad (6)$$

We have fitted Eq. (6) to the data by adjusting the ratio a_s/T. For the mass region $2 \leq A \leq 10$ we obtain $a_s/T=1.13$ and for $2 \leq A \leq 19$ a value $a_s/T=0.859$. These values can be compared with the results given in Table I: $a_s/T=1.60$. The fit to the low mass interval is much better than the fit to all experimental data, and is also shown in Fig. 2. Obviously, an exponential like Eq. (6) cannot reproduce a mass distribution as shown in Fig. 1 very well.

III. DISCUSSION

Total fragment cross sections from the bombardment of ^{197}Au with 400 MeV ^{20}Ne are presented. The low mass region shows a decrease of the fragment yields similar to those previously obtained from proton-nucleus interaction in the GeV regime.[6] This is not true for the yields of fragments having mass numbers $A \geq 10$. The data reveal signs of a fragmentation process in terms of a liquid-vapor phase transition below the critical temperature T_c. A fit of Fisher's theory using the liquid-drop expansion for the free energy per particle leads to a set of liquid-drop parameters at a certain temperature. These parameters are close to the ones derived from the high energy data.[6] This is especially true for the temperature, chemical potentials, and surface tension. However, the apparent exponent is larger than the previous value.[6] The Coulomb contribution and the symmetry energy term are strongly reduced, especially when compared to the ground state values. The temperature achieved in the medium energy nucleus-nucleus collision of 3.26 MeV is not too far away from the critical temperature of $T_c=5.0$ MeV.

It should be noted that these values are much smaller than those recently calculated from the different types of Skyrme interactions.[15] For the force $ZR\,1$ and a system of 200 nucleons the critical temperature was calculated to be 19.1 MeV without Coulomb corrections and 15.7 MeV when Coulomb corrections are taken into account.[15]

However, the fits to the data are not perfect. The reason for this shortcoming may be twofold: As mentioned above, the Weizsäcker mass formula is not a good parametrization for the masses of light nuclei; the data are total yields. They contain contributions from the participant region as well as from the spectator nucleons and are therefore contaminated by sequential decay from the projectile nucleus.[11,16]

If the underlying picture of the physical process is correct, then the study of fragment yields offers a new possibility to study the nuclear equation of state at higher temperatures and lower density than the nuclear ground state.

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