Isotopic-Yield Ratios of Complex Fragments from Intermediate-Energy Heavy-Ion Reactions

R. Wada,[a] K. D. Hildenbrand, U. Lynen, W. F. J. Müller,[b] H. J. Rabe, H. Sann, H. Stelzer, W. Trautmann, and R. Trockel
Gesellschaft für Schwerionenforschung Darmstadt, mbH D-6100 Darmstadt, West Germany

N. Brummund, R. Glasow, K. H. Kampert, and R. Santo
Universität Münster, D-4400 Münster, West Germany

E. Eckert and J. Pochodzalla
Universität Frankfurt, D-6000 Frankfurt, West Germany

and

I. Bock and D. Pelte
Universität Heidelberg, D-6900 Heidelberg, West Germany
(Received 25 November 1986)

Isotopically resolved yields of intermediate-mass fragments from ^{12}C- and ^{18}O-induced reactions on ^{58,64}Ni, ^{nat}Ag, and ^{197}Au at $E/A=84$ MeV were measured. The systematic variation of the yield ratios with projectile and target shows that these fragments are produced by a mechanism that involves the whole target nucleus. It is demonstrated that, within a statistical interpretation, the isotope-yield ratios are a measure of the entropy and determine a relation between temperature and density at breakup.

PACS numbers: 25.70.Np, 25.70.Gh, 25.70.Lm

The emission of complex fragments in intermediate- and high-energy heavy-ion collisions is a phenomenon whose dynamics is not yet satisfactorily understood. The range of suggested interpretations extends from conventional compound emission or fission[1] over statistical emission from a hot subsystem[2] to more novel mechanisms such as cold breakup of nuclear matter[3] or breakup due to dynamical instabilities in the coexistence region of liquid and gaseous nuclear matter.[4] These models differ in rather basic ingredients such as the size and the state of the emitting system or the mechanism by which the fragments are accelerated. It is the purpose of this Letter to demonstrate that the measurement of isotopic yields of complex fragments offers unique opportunities to study some of these questions.

The rapid equilibration of the N/Z degree of freedom, i.e., of the ratio of the neutron number N to the proton number Z of emitted fragments, is well established for dissipative heavy-ion collisions.[5] But also in heavy-ion reactions at higher energies including fission of spallation the isotopic composition of the fragments is a function of the N/Z ratio of the emitting system.[6,7] We will make use of this property to identify the system from which the complex fragments originate or, more precisely, the system taking part in the N/Z equilibration prior to fragment emission. Secondly, we will show that, within a statistical description,[8] the isotope-yield ratios are a measure of the entropy and thus determine a relation between the breakup temperature and density. We deduce these quantities for the studied reactions, thereby complementing measurements of the breakup temperatures from population ratios of excited resonances.[9]

We report inclusive data from experiments performed with heavy-ion beams provided by the CERN synchrocyclotron. Targets of ^{58,64}Ni, ^{nat}Ag, and ^{197}Au with areal densities between 0.5 and 3.0 mg/cm^2 were bombarded with ^{12}C and ^{18}O beams of $E/A=84$ MeV. Intermediate-mass fragments were detected and identified by telescopes placed at angles $\theta_{lab}=40°$, 51°, 63°, 73°, and 120° and subtending solid angles of $\Delta\Omega=2.63$ msr. Each telescope consisted of an axial-field ionization chamber followed by three silicon detectors of thicknesses 50, 300, and 1000 μm, respectively, and was backed by a 1-cm$^2\times$1-cm bismuth germanate detector. Full isotope separation for ions up to carbon was achieved at $E/A\geq 3$ MeV which was the threshold for particles to pass through the 50-μm detector. The recorded energy-loss signals from the ionization chamber allowed us to distinguish lithium isotopes and to separate ^{7}Be from $^{9-11}$Be at even lower energies. The misidentification of the two α particles from the ^{8}Be ground-state decay as ^{7}Li required corrections of the measured ^{7}Li yields of 3% to 6%, depending on the reaction.[10]

The measured energy spectra were typical for the intermediate-energy regime with maxima corresponding to Coulomb repulsion and exponentially decreasing slopes at higher energies.[11] Energy-integrated isotope yields were obtained by extrapolation from the isotopically resolved parts of the spectra with the help of fitting functions. The analytic form of the fitting functions was that of a Maxwellian source moving in beam direction.[11]

The parameters controlling the shapes were determined by fits to the mass-integrated element spectra since elements could be separated over a wider energy range, in particular at the more backward angles. Only the normalization parameters were adjusted by fits to the individual isotope spectra. The uncertainty associated with this procedure is included in the quoted errors of the data.

The isotope-yield ratios vary little with the detection angle. This permitted an extrapolation over the full angular range in order to determine 4π averaged ratios. For the following comparison of the various projectile target systems, however, we choose the data measured at the most forward angle, $\theta_{lab}=40°$, since they have the smallest experimental uncertainties. This angle is sufficiently backward to avoid contributions from projectile fragmentation, and the measured ratios are close to the 4π-averaged values.

Three yield ratios, of lithium, beryllium, and boron isotopes, for all the investigated reactions are shown in Fig. 1, plotted as functions of the neutron-over-proton ratio N/Z of the combined system of projectile and target nuclei. This way of representing the data was motivated by the following observations: The isotope-yield ratios vary strongly with the choice of the target. The relevant property of the target, however, is neither the mass A nor the charge Z but rather the ratio N/Z; the yield ratios are different for the ^{58}Ni and ^{64}Ni targets but, apparently, the same for the ^{64}Ni and ^{nat}Ag targets which have equal N/Z. Furthermore, the different N/Z of the ^{12}C and ^{18}O projectiles seem to have little influence except in the reactions with the ^{58}Ni target. The fact that in this case the ratios measured with the ^{12}C projectiles are significantly smaller than those with ^{18}O suggests that the N/Z of the combined system rather than that of the target nucleus alone is the most significant ordering parameter. Plotted in this way, all three isotope-yield ratios follow smooth curves and increase monotonically, i.e., the relative intensity of neutron-rich isotopes increases, with increasing N/Z of the combined system (Fig. 1). We therefore conclude that the combined system of the projectile and the whole target is involved in the emission of the complex fragments.

The significance of this result may be seen in a comparison to projectile fragmentation where, at this bombarding energy, isotope-yield ratios were observed to depend very little on the target N/Z.[12] The situation is also quite different in the case of preequilibrium light-particle emission as will be illustrated in the following. Figure 2 shows yield ratios for hydrogen isotopes measured for the same reactions. Here the energy spectra were decomposed into the contributions from target evaporation and from an intermediate-velocity source by a two-source fit extended over the measured angular range; projectile fragmentation can be neglected at these angles.[13] The energy-integrated yields of the intermediate source at $\theta_{lab}=40°$, which amount to about 80% of the total yield at this angle, were used to form the ratios

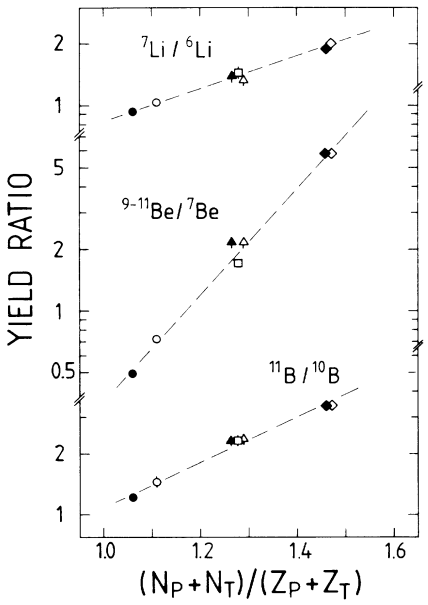

FIG. 1. Ratios of energy-integrated isotope yields, measured at $\theta_{lab}=40°$, as functions of the N/Z ratio of the combined system of projectile and target. Closed and open symbols denote ^{12}C and ^{18}O projectiles, respectively; circles, squares, triangles, and lozenges stand for ^{58}Ni, ^{64}Ni, ^{nat}Ag, and ^{197}Au targets, respectively. The dashed lines are meant to guide the eye.

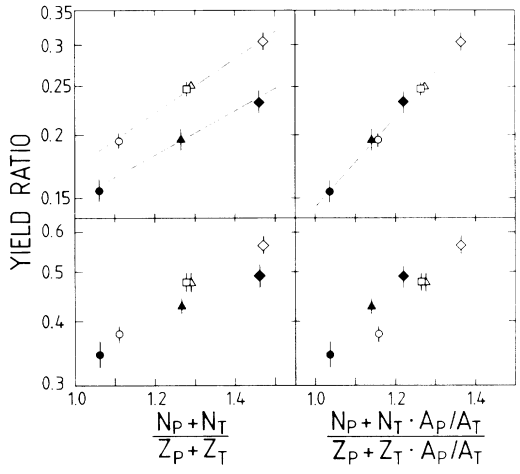

FIG. 2. Ratios of triton to proton yields (top) and triton to deuteron yields (bottom), measured at $\theta_{lab}=40°$, and plotted as functions of the N/Z ratios of the combined system (left-hand side) and of a source consisting of equal numbers of nucleons from the projectile and from the target (right-hand side). The symbols are chosen as in Fig. 1, the dashed lines are meant to guide the eye.

shown in Fig. 2.

With the postulate that the observed ratios should be a unique function of the N/Z ratio of the emitting source, the light-particle data are inconsistent with emission from the combined system (Fig. 2, left panels). The t/p ratios can be reconciled with this postulate if the emitting source is assumed to consist of equal numbers of nucleons from the projectile and from the target, chosen according to their respective N/Z ratios (Fig. 2, upper right). For the t/d ratios the assumption of a 1:1 mixing ratio of projectile and target nucleons in the emitting source overcorrects the deviations (Fig. 2, lower right) but also in this case a source can be identified that leads to a unique and monotonic increase of the measured isotope ratios as a function of its N/Z. The mixing ratio has to be chosen as 1:2. Both examples show that preequilibrium light particles originate from a subsystem much smaller than the combined system of projectile and target.

In order to assess the quantitative information contained in the measured isotope-yield ratios of intermediate-mass fragments we have performed calculations with the quantum-statistical-model code of Hahn and Stöcker.[8] In this model thermal and chemical equilibrium is assumed at the breakup point where the system is characterized by a density ρ, a temperature T, and a total proton-to-neutron ratio (including the nucleons bound in the composite particles). The model respects fermion and boson statistics but does not make provisions for the finite size of nuclear systems. One may expect, however, that for yield ratios of isotopes most of the finite-size effects resulting from different exit-channel dynamics should cancel. In particular, the effects of different Coulomb penetrabilities are of no concern for the following discussion. We estimate that they amount to 20% in the most unfavorable cases (e.g., for the ratio of $^{9-11}$Be/^{7}Be at low temperature) and therefore are of the same order as the experimental uncertainties (see below). On the other hand, the correct treatment of the sequential decay of excited fragments by the code turned out to be an essential feature since the calculated yield ratios of the primary and the final populations were found to differ by factors of up to about 2.

Calculations for fixed temperature and density approximately reproduce the observed strong dependence of the isotope-yield ratios on the N/Z ratio of the combined system. For example, with T and ρ chosen to give the values measured for ^{18}O+^{197}Au, slopes $d(\ln R)/d(N/Z)$, where R is a yield ratio, of 60% to 70% of those displayed in Fig. 1 are obtained. So, although the calculated variation is somewhat smaller, one may conclude that the main physical basis of the N/Z dependence is contained in the model.

Figure 3 shows the results of calculations for ^{12}C+^{197}Au, i.e., for $N/Z=1.46$ in the combined system. The solid lines are the calculated isentropes in the temperature-versus-density plane. The hatched areas indicate the regions where the calculated isotope-yield ratios are equal to the experimental values obtained from the extrapolation and integration over the full 4π solid angle. The widths of these regions correspond to the experimental uncertainties (5% to 20%) which include estimates of possible systematic errors associated with the integration procedure. We first observe that these loci approximately follow isentropes. This is less so in the beryllium and boron than in the lithium cases but all values deduced from the four isotope ratios consistently fall within $1.5 \leq S/A \leq 2.5$. We further note that, at low temperature T and density ρ, the four regions exhibit a high degree of overlap as required by the assumption of thermal and chemical equilibrium, and in support of the argument that the disregard of finite-size effects in the model may cause little concern for isotope-yield ratios. Here all measured ratios are consistent with a common entropy of $S/A \sim 2.2$. The divergence at high T and ρ does not necessarily constitute a contradiction since it is conceivable that this region may be beyond the physically relevant range of breakup parameters.

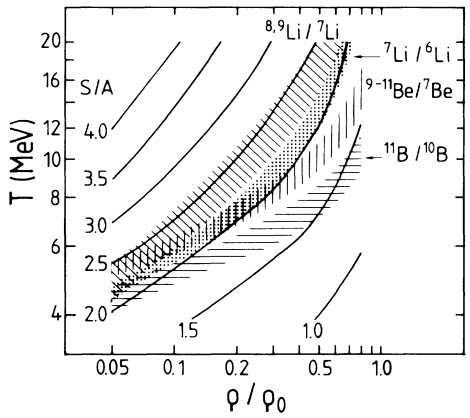

FIG. 3. Results obtained from calculations with the quantum-statistical-model code (Ref. 8) for the combined system of ^{12}C+^{197}Au. The solid lines are the isentropes in the temperature T vs density ρ plane ($\rho_0=0.16$ fm^{-3}). The shaded areas mark the regions where the calculated and the experimental values of the indicated isotope-yield ratios agree.

The isotope-yield ratios or, equivalently, the corresponding isentropes determine a relation between temperature and density (Fig. 3). Common expectations for the breakup density, derived on various grounds, extend from about $\rho_0/3$ (Csernai *et al.*,[14] Bondorf *et al.*[15]) down to $\rho_0/8$ (Sa and Gross[16]). The corresponding temperatures are 6 to 12 MeV in the former and 5 to 8 MeV in the latter case (Fig. 3). These numbers are in the range of the compound-nucleus temperature of about 6 to 8 MeV and, particularly with the latter assumption, compare well with the temperatures $T \sim 5$ MeV that were derived from the relative population of excited reso-

nances.[9] (The spectral temperatures of about 12 to 15 MeV obtained from moving-source fits to the spectra are believed to have a partly nonthermal origin.[11]) On the other hand, if we adopt these experimentally determined temperatures of about 5 MeV as values applying to a wider range of bombarding energies and reactions, then the measured isotope-yield ratios restrict the breakup densities to $\rho < \rho_0/5$. This would place the point of breakup into the region of dynamical instability in the coexistence region of liquid and gaseous nuclear matter but at temperatures considerably below estimated values of the critical temperature.[4] Clearly, the dynamical evolution of the system into this region[17] has to be considered in a further-reaching interpretation of these parameters.

We are highly indebted to Dr. B. Allardyce and the staff of the CERN Synchrocyclotron for their effort in preparing the heavy-ion beams. We would like to thank Dr. D. Hahn and Dr. H. Stöcker for making their code available to us and for valuable discussions. This work was supported in part by the Bundesministerium für Forschung und Technologie.

[a]Present address: Texas A&M University, College Station, TX 77843.

[b]Present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720.

[1]R. J. Charity *et al.*, Phys. Rev. Lett. **56**, 1354 (1986).

[2]W. A. Friedman and W. G. Lynch, Phys. Rev. C **28**, 16 (1983).

[3]J. Aichelin and J. Hüfner, Phys. Lett. **136B**, 15 (1984).

[4]R. W. Minich *et al.*, Phys. Lett. **118B**, 458 (1982); for reviews see L. P. Csernai and J. I. Kapusta, Phys. Rep. **131**, 223 (1986); D. H. Boal, Nucl. Phys. **A447**, 479c (1986).

[5]See, e.g., A. Gobbi and W. Nörenberg, in *Heavy Ion Collisions,* edited by R. Bock (North-Holland, Amsterdam, 1980), Vol. 2, p. 127.

[6]N. T. Porile and L. B. Church, Phys. Rev. **133**, B310 (1964).

[7]B. Ludewigt *et al.*, Phys. Lett. **108B**, 15 (1982).

[8]H. Stöcker *et al.*, Nucl. Phys. **A400**, 63c (1983); D. Hahn and H. Stöcker, to be published.

[9]J. Pochodzalla *et al.*, Phys. Rev. Lett. **55**, 177 (1985); C. B. Chitwood *et al.*, Phys. Lett. **172B**, 27 (1986).

[10]The primary ^{8}Be(g.s.) yield was taken from the quantum-statistical-model calculations described below.

[11]R. Trockel, in *Progress in Particle and Nuclear Physics,* edited by A. Faessler (Pergamon, New York, 1985), Vol. 15, p. 225; R. Trockel *et al.*, in *Hadronic Matter in Collision,* edited by P. Carruthers and D. Strottman (World Scientific, Singapore, 1986), p. 291.

[12]J. Mougey *et al.*, Phys. Lett. **105B**, 25 (1981).

[13]N. Brummund *et al.*, Nucl. Phys. **A453**, 349 (1986).

[14]L. P. Csernai *et al.*, Phys. Rev. C **28**, 2001 (1983).

[15]J. Bondorf *et al.*, Nucl. Phys. **A444**, 460 (1985).

[16]Sa Ban-Hao and D. H. E. Gross, Nucl. Phys. **A437**, 643 (1985).

[17]See, e.g., A. Vicentini *et al.*, Phys. Rev. C **31**, 1783 (1985).