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THE RAPID ONSET OF FRAGMENTATION IN PERIPHERAL HEAVY-ION COLLISIONS

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Abstract:

A study of the isotope yield and momentum distributions of fragments produced in peripheral collisions of ^{16}O on heavy targets as a function of energy from 5 MeV/nucleon to 2.1 Gev/nucleon indicates a rapid transition from equilibration to fragmentation between 10 and 20 MeV/nucleon.

Our knowledge of collisions between complex nuclei comes mainly from two extremes of incident energy, each dominated by characteristic reaction processes. Below 10 MeV/nucleon, the collision time is longer than the transit time of nucleon at the Fermi level; consequently the whole nucleus responds coherently to the collision, and the dominant phenomena are characteristic of the mean field.[1] At relativistic energies of GeV/nucleon, on the other hand, the reaction processes are dominated by independent collisions of individual nucleons. The transition between the two regimes is expected to occur when the incident energy allows the complete disjunction of the two nuclei in momentum space, at a few tens of MeV/nucleon.[1] In this letter we show that, in approaching 20 MeV/nucleon, a rapid transition takes place between low-energy, deeply-inelastic processes and high-energy abrasion or fragmentation phenomena in peripheral collisions.

Our approach is to measure the production cross sections and energy spectra of projectile-like fragments from ^{16}O-induced reactions on targets of Pb, Au and Ni as a function of incident energy. Typical spectra for outgoing ^{12}C products at incident energies of 140, 218, 250 and 315 MeV are shown in Fig. 1. The experiments used ^{16}O beams (up to charge state 6^+) from the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory, as described previously.[2,3] The spectra peak at an energy corresponding to a velocity close to that of the projectile (E_p). The widths of the spectra increase rapidly with energy, which is a manifestation of the transition in the nature of the reaction mechanism.

First we use the concept of temperature to find systematic trends in the data. At low energies ($<$ 10 MeV/nucleon), the production cross sections of isotopes in reactions of the type reported here have an exponential dependence,[2] $\sigma \propto \exp(Q_{gg}/T)$, which is explained by a statistical model of partial equilibration in the dinuclear system at temperature T. The two-body, ground state Q-value, Q_{gg}, determines the relevant excitation energy.[4] For our data the associated temperatures are shown as a function of the incident energy (top scale) in Fig. 2 by filled circles. The variation of the temperature initially follows the trend of the Fermi gas equation of state, $(E_c-V) = aT^2$, where E_c is the center of mass energy and V the Coulomb barrier in the incident channel (Q-values are neglected); the level density parameter a is set equal to A/8, with A the mass number of the intermediate complex. Hence, T is proportional to $\sqrt{E_c-V}$, the variable appearing on the bottom scale. Data from the analysis[5] of ^{16}O, ^{15}N + ^{232}Th reactions, at incident energies similar to the present work, are included with square symbols.

At relativistic energies the concept of temperature has also been useful in explaining isotope production cross sections, where the "emitter" is the projectile rather than the dinuclear complex.[2,6] Then $\sigma \propto \exp(Q_F/T)$, with Q_F equal to the appropriate fragmentation Q-value, and T is the projectile temperature. This approach was previously adopted for the data at 315 MeV[2] ($\approx$ 20 MeV/nucleon) and at 2.1 GeV/nucleon.[7,8] These values of T are also shown in Fig. 2 by the filled circles. Following the initial trend of the Fermi gas equation, a rapid rise sets in between 10 and 20 MeV/nucleon, after which the temperature appears to remain constant in the region of 8 MeV. Above 15 MeV/nucleon, where the curve departs from the prediction of the Fermi gas for heating the entire intermediate complex, only a part of the total system can be heated. One interpretation of the saturation of T at 8 MeV is that $A'(\ll A)$ nucleons participate, and carry less than $B*A'$ of excitation energy, for the system to survive to emit a complex fragment. Here B is the binding energy of a nucleon ($\approx$ 8 MeV). If this subsystem is excited like a Fermi gas, the result that $T \approx 8$ MeV follows immediately from the equation $8A' = (A'/8)T^2$. Since higher temperatures would result in a disintegration of the fragment, it is natural to refer to this temperature as the "boiling point of nuclear matter".[9]

Although temperature is a useful concept for understanding the limiting behavior in the high-energy region, an alternative interpretation comes from the abrasion model[10] in which the primary fragments emerge by the sudden shearing of the projectile without prior excitation. We show that the dependence $\sigma \propto \exp\,(Q_F/T)$ can also be derived analytically with this model. For the primary distribution of fragments in neutron number N about the mean N_0, we use the formulation of the abrasion model in Ref. 11:

$$\sigma \propto \exp\left[-(N-N_0)^2\left(\frac{1}{2\sigma_a^2}+\frac{1}{8\sigma_{t_3}^2}\right)\right] = \exp\left[-\frac{(N-N_0)^2}{\alpha}\right] \qquad (1)$$

where σ_a, σ_{t_3} are the dispersions in particle number and isospin, which are derived from a model[11] with correlations built into the nuclear ground state, viz. $\sigma_{t_3} \approx 0.24\ A^{1/3}$, $\sigma_a \approx 4.9\ \sigma_{t_3}$. In the production of a series of isotopes, the changes in Q_F are determined primarily by the N-dependent terms in the liquid drop mass formula. For small excursions in N from the mean, it follows that the sum of the fragment masses exceeds that of a symmetric division ($N=N_0$) by the amount:

$$Q_F \approx 4\left(\frac{a_s}{A} - \frac{a_{ss}}{A^{4/3}}\right)(N-N_0)^2 = \beta(N-N_0)^2 \qquad (2)$$

where a_s and a_{ss} are the symmetry and surface symmetry coefficients, respectively.[12] From Eqs. (1) and (2) we get, $\sigma \propto \exp\,(Q_F/\alpha\beta)$, which is equivalent to the result of the thermal excitation model, with T replaced by $\alpha\beta$. By inserting the values[11] σ_a, σ_t and the mass formula coefficients,[12] we deduce that T = 9 MeV (or 5 MeV with values of σ_a, σ_{t_3} neglecting[11] correlations). This derivation of isotope distributions ignores the subsequent redistribution of isotopes by nucleon capture and evaporation,[12] but the value of 9 MeV is close to the required saturation value of 8 MeV shown in Fig. 2. This parameter in the exponential dependence of σ on Q_F is, however, identified with the onset of the fast abrasion mechanism, rather than with the saturation of nuclear temperature in the slower process of local equilibration.

In the saturation region above 20 MeV/nucleon, the abrasion model also accounts consistently for the momentum distribution of fragments in the projectile rest frame.[8] For the energy distribution in the laboratory frame at angle Θ, the model predicts[3]:

$$\frac{d^2\sigma}{dE d\Omega} \propto \sqrt{2A_F E}\ \exp\left[-\frac{A_F}{\sigma^2}\,(E-2\varepsilon E^{1/2}\cos\Theta+\varepsilon^2)\right] \qquad (3)$$

where $\varepsilon^2 = 1/2\, M_F v_P^2$, v_P is the velocity corresponding to the peak of the energy distribution, $\sigma^2 = \sigma_o^2\ \frac{A_F(A_P-A_F)}{A_P-1}$, A_F and A_P are the mass numbers of the observed fragment and the projectile, and $\sigma_o = P_F/\sqrt{5}$, where P_F is the Fermi momentum of the projectile. The value σ_o = 86 MeV/c, appropriate[3,7] for the data at 20 MeV/nucleon, 1.05 GeV/nucleon and 2.1 GeV/nucleon, corresponds to P_F = 192 MeV/c (0.97 fm^{-1}) which is close to the measured Fermi momentum[13] of a nucleus as light as ^{16}O. The predicted energy distribution at 20 MeV/nucleon is shown in Fig. 1. (The parameters used differ slightly from Ref. 3, since isotope rather then element distributions are now described).

The energy distribution in Eq. 3 is also expected from a statistical model of fragment emission.[8] Therefore, the formula can be applied equally well to the lower energy spectra in Fig. 1, where we have already shown that equilibration processes at temperature T are relevant. By conservation of energy and momentum, T and σ_o are related[8] by $\sigma_o^2 = Tm \frac{A_P - 1}{A_P}$, where m is the nucleon mass in MeV. (For σ_o = 86 MeV/c, T ≈ 8 MeV, consistent with the two interpretations of the isotope yield distributions in the high-energy region). The values of T required to fit the data at all energies are shown in Fig. 2 by the open circles. Also included are data for oxygen on nickel at 315 MeV and on tantalum[14] at 96 MeV. Although results for only ^{12}C fragments are presented, similar trends were observed in the energy spectra of other particles. At low energies ($<$ 10 MeV/nucleon), the temperatures extracted from the momentum (open circles) and isotope yield distributions (filled circles and square symbols) are in agreement, supporting the temperature model. At high energies ($>$ 20 MeV/nucleon), the saturation of the widths of the momentum and isotope distributions with T = 8 MeV is consistent with a fast abrasion mechanism.

If we adopt the abrasion model for the description of the high energy data, then the sudden transition from equilibration to fragmentation must contain information on characteristic properties of nuclear matter, such as the relaxation time for spreading the localized deposition of energy, or "hot-spot",[15] over the nucleus. The initial excitation may be in the form of uncorrelated particle-hole excitations, in which case this relaxation time is related to the Fermi velocity. On the other hand, if the initial excitation is carried by coherent, collective compressional modes, then this time is related to the frequency of these modes, which in turn depends on the speed of sound in nuclear matter.[16] Recent experiments,[17] determining the frequency of the monopole mode, lead[18] to a value of the compressibility coefficent K $\approx$ 300 MeV, and an implied velocity of sound, $v_s = \sqrt{K/9m}$, of 0.19c (m is the nucleon rest mass). This velocity and the Fermi velocity in nuclear matter (equivalent to 36 MeV/nucleon) are marked in Fig. 2, but it would be premature to specify which defines the change of mechanism without a detailed model.

Our study of single particle inclusive peripheral reactions over a broad range of incident energy demonstrates the rapid transition from equilibration to abrasion or fragmentation above 20 MeV/nucleon. This transition implies an increased localization of the nuclear response as the time scale of the reaction becomes faster. If a quantitative treatment of this behavior can be developed, it may be possible to extract interesting information on the tensile strength of nuclear matter,[18] as the healing properties of the nucleus disappear under the stress of the collision. Although the rapid abrasion mechanism is consistent with the data in the high energy region above 20 MeV/nucleon, the alternative interpretation based on localized excitation cannot be ruled out, and through the transtion region both approaches certainly must hold some validity.

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FOOTNOTES AND REFERENCES

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1. G. Bertsch, Lecture Notes for the Les Houches Summer School, 1977.
2. M. Buenerd, C. K. Gelbke, B. G. Harvey, D. L. Hendrie, J. Mahoney, A. Menchaca-Rocha, C. Olmer and D. K. Scott, Phys. Rev. Lett. 37, 1191 (1976).
3. C. K. Gelbke, D. K. Scott, M. Bini, D. L. Hendrie, J.-L. Laville, J. Mahoney, M. C. Mermaz and C. Olmer, Phys. Lett. 70B, 415 (1977).
4. J. P. Bondorf, F. Dickmann, D. H. E. Gross and P. J. Siemens, J. de Phys. 32, C 6 (1971).
5. V. V. Volkov, Sov. J. Nucl. Phys. 6, 240 (1976).
6. V. K. Lukyanov and A. I. Titov, Phys. Lett. 57B, 10 (1975).
7. D. E. Greiner, P. J. Lindstrom, H. H. Heckman, B. Cork and F. S. Bieser, Phys. Rev. Lett. 35, 152 (1975) and LBL Preprint 3650 (1975).

8. A. S. Goldhaber, Phys. Lett. 53B, 306 (1974).

9. It is intriguing that a similar saturation of the temperature at ≈ 140 MeV is predicted for hadronic matter: see R. Hagedorn, Cargèse Lectures in Physics, Vol. 6, ed. E. Schatzman (Gordon Breach, N.Y., 1973); N. K. Glendenning and Y. Karant, Phys. Rev. Lett. 40, 374 (1978).

10. J. Hüfner, C. Sander and G. Wolschin, Phys Lett 73B, 289 (1978).

11. J. P. Bondorf, G. Fai and O. B. Nielsen, Niels Bohr Institute Preprint 78-6.

12. M. A. Preston and R. K. Bhaduri, Structure of the Nucleus , Addision Wesley, 1975), p. 202.

13. E. J. Moniz, I. Sick, R. R. Whitney, J. R. Ficenec, R. D. Kephart and W. P. Trower, Phys. Rev. Lett. 26, 445 (1971).

14. F. Videbaek, R. B. Goldstein, L. Grodzins, S. G. Steadman, T. A. Belote and J. D. Garrett, Phys. Rev. C 15, 954 (1977).

15. P. A. Gottschalk and M. Weström, Phys. Rev. Lett. 39, 1250 (1977).

16. P. J. Johansen, P. J. Siemens, A. S. Jensen and H. Hofmann, Nucl. Phys. A288, 152 (1977).

17. D. H. Youngblood, Bull. Am. Phys. Soc. 23, 42 (1977).

18. V. R. Pandharpande, Phys. Lett. 31B, 635 (1970).

19. G. Bertsch and D. Mundinger, Phys. Rev. C 17, 1646 (1978).

FIGURE CAPTIONS

Fig. 1 Energy spectra of ^{12}C fragments produced in the collision of ^{16}O + ^{208}Pb and ^{197}Au at several energies. The arrow g.s. corresponds to a two-body reaction forming residual nuclei in the ground state. If two-body processes are dominant, the spectra imply high excitation energies. The arrow E_p denotes the energy of a fragment travelling with beam velocity. This energy is characteristic of two-body processes at low energy and of fragmentation at high energy. The dashed curves are theoretical predictions using Eq. 3, as discussed in the text.

Fig 2 The variation of temperature with incident energy in the collision of ^{16}O with ^{208}Pb, ^{197}Au, ^{58}Ni and Ta (the lowest energy point). The open circles correspond to the widths of momentum distributions. The filled circles and square blocks are derived from isotope production systematics. The hatched line is the prediction of a statistical equilibrium model, based on the Fermi gas equation of state. The arrows v_s and v_F mark the characteristic velocity of sound and the Fermi velocity in nuclear matter. The solid line is drawn to guide the eye.

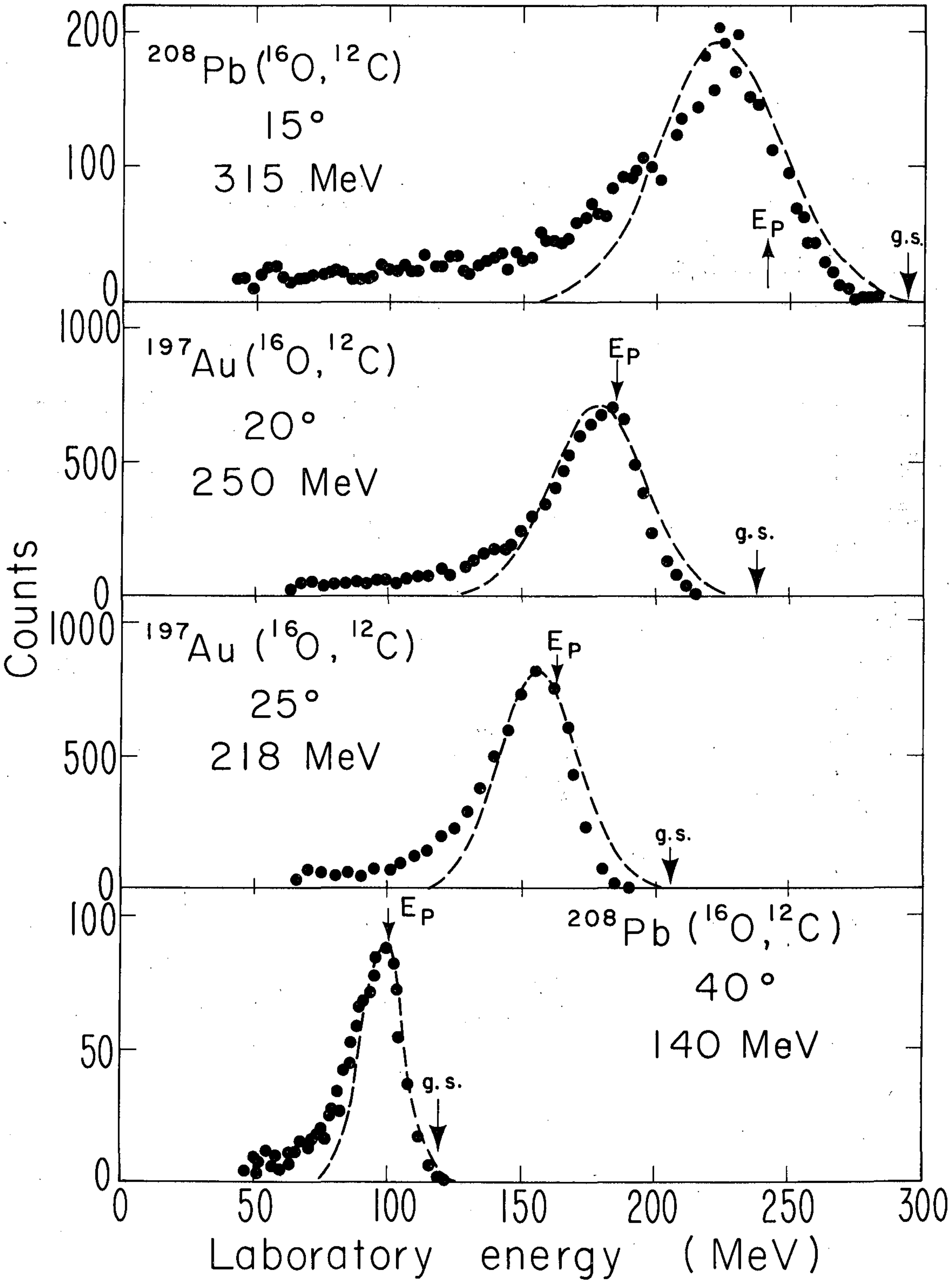

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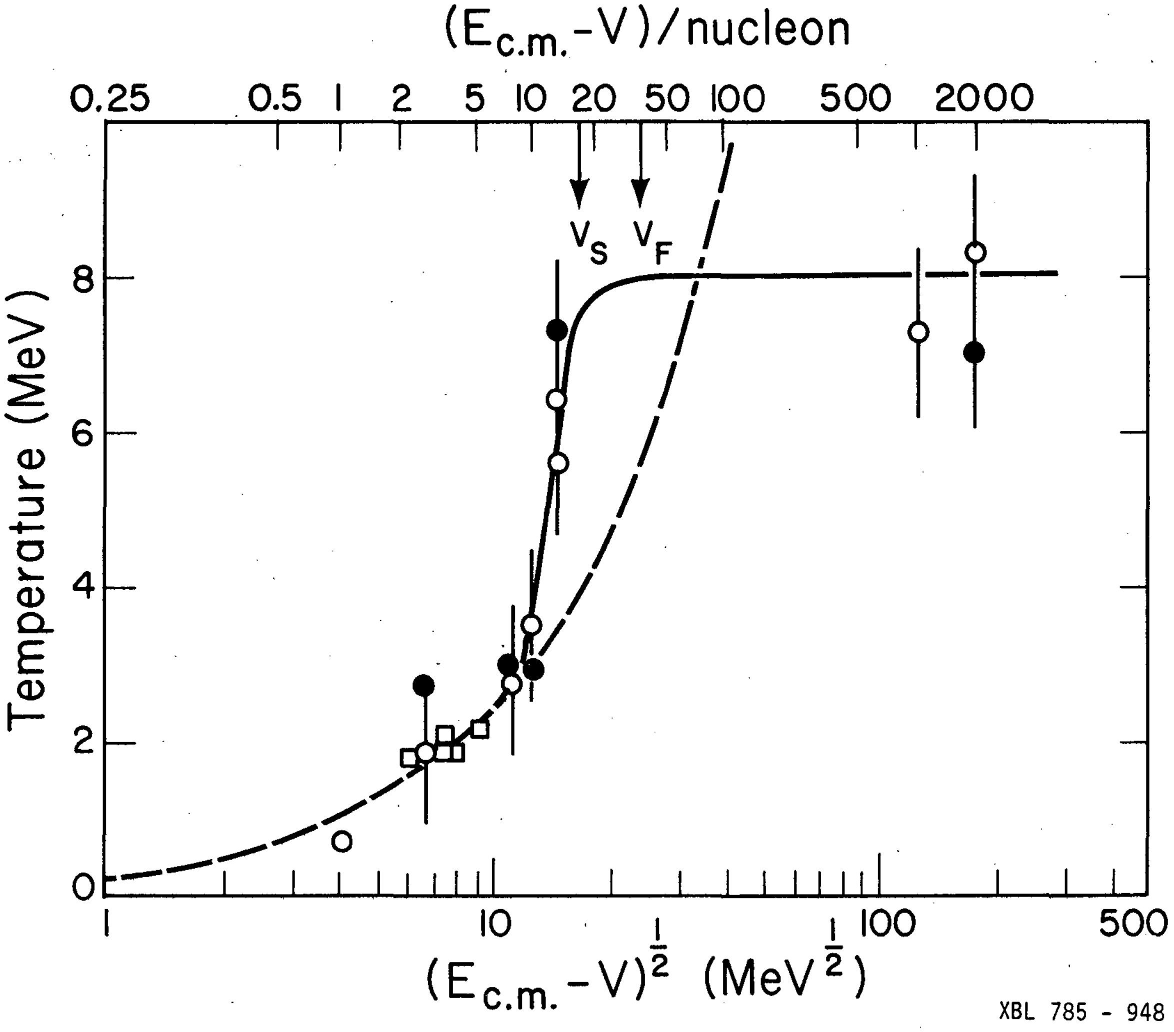
Fig. 1



(E$_{c.m.}$-V)/nucleon
0.25
0.5
1
2
5
10
20
50
100
500
2000
V$_S$
V$_F$
Temperature (MeV)
0
2
4
6
8
1
10
100
500
(E$_{c.m.}$-V)$^{\frac{1}{2}}$ (MeV$^{\frac{1}{2}}$)
XBL 785 - 948

Fig. 2

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