FRAGMENT PRODUCTION IN INTERMEDIATE ENERGY HEAVY ION REACTIONS

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ABSTRACT

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The emission of fragments with A $\leq$ 14 has been studied in intermediate energy argon and neon-induced reactions. The energy spectra were observed to be approximately Maxwellian and the high energy region was fitted assuming emission from a single moving source. The source was found to move with a velocity intermediate between that of the projectile and the target, and its temperature was approximately independent of the mass of the emitted fragment, suggesting that complex fragments as well as light particles are emitted from a thermalized subsystem in the reaction.

A quantum statistical model of the disassembly of the thermalized region was used to infer information about the entropy of the system from the observed fragment distribution. This method yields lower values for the entropy per nucleon than derived from the production of protons and deuterons alone. The entropy extracted from target-like fragments observed in other experiments was found to be lower than the entropy from intermediate rapidity fragments, and was independent of the projectile energy. The complex fragment spectra through nitrogen were

also well described by the coalescence model, yielding source radii of 4.5-5.5 fm, in agreement with experiments measuring two-proton correlations.

The light particle data were used to test two models for the collision dynamics. A solution of the Boltzmann equation, incorporating a mean field and Pauli blocking as well as two-nucleon collisions, described the proton spectra from Ar + Ca for bombarding energies as low as 42 MeV/A. A conventional intranuclear cascade model, developed for high energy collisions, was unable to reproduce the data, underlining the importance of nuclear mean field and Pauli blocking effects in this energy regime. Nuclear fluid dynamical calculations were also compared with the data. The agreement was fair above 100 MeV/nucleon, but the model did not describe the lower energy data.

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CHAPTER I

INTRODUCTION

A. MOTIVATION

Heavy ion reactions have provided a unique opportunity to study the chemistry of nuclear matter. Chemists and physicists have used low energy beams to study the nuclear response in relatively gentle collisions, and reactions at high bombarding energies to heat and compress nuclear matter and study its bulk properties. Very different theoretical frameworks for understanding the reaction mechanisms in these two energy regimes have been developed, but a complete description of the transition from low to high energy reactions does not yet exist. Historically, the development of heavy ion accelerators has focussed on beams at the extremes in energy; only recently have machines been constructed to address the intermediate energy transition region. The new accelerators have allowed measurements at bombarding energies between 20 and 200 MeV/nucleon, thus testing existing reaction models at the limits of their applicability. The data presented in this work give a survey of the intermediate energy domain and provide a testing ground for new theories. The theory presented here is a first attempt at incorporating both low and high energy phenomena and applying the result at intermediate energy.

Figure I-1 schematically illustrates the mechanisms of nuclear reactions as a function of incident energy and impact parameter [SC 81]. At low energies (a few MeV/nucleon), the duration of the collision is much longer than the transit time of a nucleon at the Fermi energy, and the whole nucleus responds to the collision. Central collisions lead to complete fusion [RE 65, LE 74, BI 79], while more peripheral collisions proceed by deeply-inelastic scattering, where the nuclei rotate about each other, exchanging nucleons and excitation energy [SC 77, VO 78, GO 80, BR 79]. The division appears to be set by a critical separation,

$$d_c \approx 1.0 \, (A_1^{1/3} + A_2^{1/3}) \qquad (I-1)$$

where the nuclei overlap at their half-density points [GL 75]. In this region, an additional reaction mechanism of fast fission of the binary nuclear system may occur [GR 81] on a time and impact parameter scale between the other two mechanisms. The excited residual nuclei deexcite by emitting neutrons, gamma rays or charged particles, or in the case of heavy target nuclei, by fission.

Above 10 MeV/ nucleon neither the entire projectile mass nor the entire projectile momentum is absorbed by the target. In central collisions, only some of the projectile nucleons may be captured by the target; the rest escape

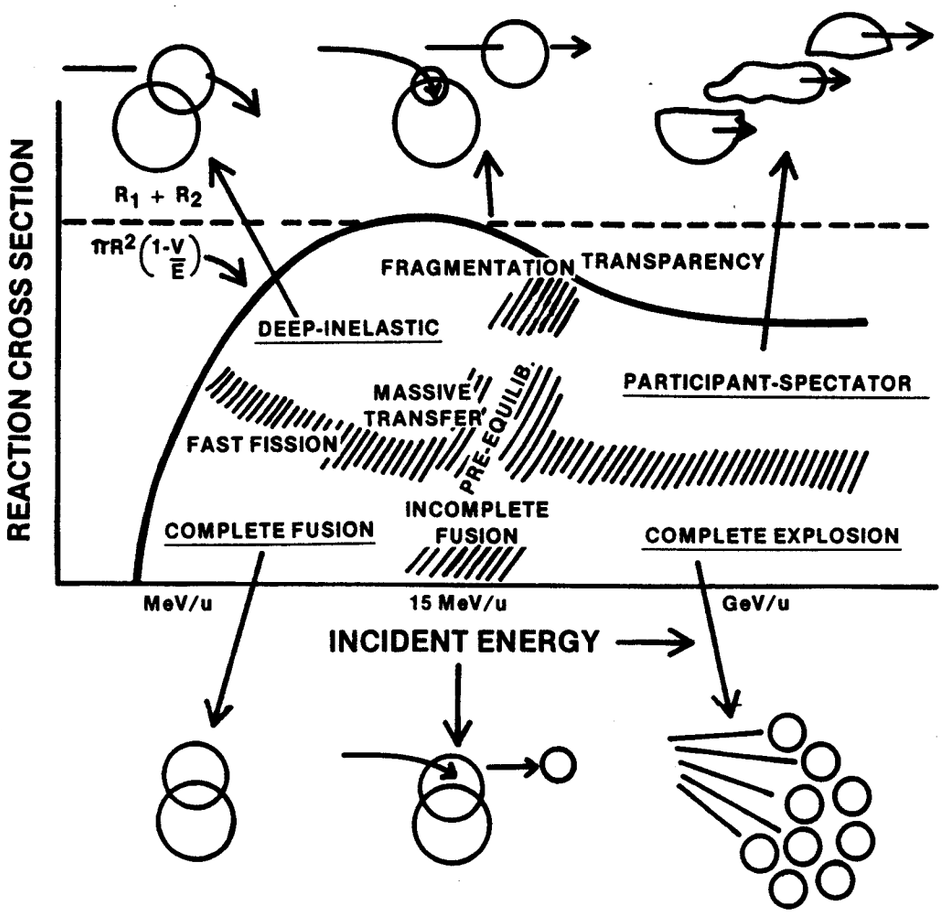

FIGURE I-1. Schematic illustration of heavy-ion collision processes, as a function of impact parameter (vertical scale) and bombarding energy (horizontal scale).

giving rise to incomplete fusion reactions [SI 79, WI 80, WU 80]. In more peripheral collisions, part of the projectile may be sheared off and interact with the target, leaving a relatively undisturbed fragment of the projectile moving at the original velocity [GE 78].

Collisions in the low energy regime are dominated by the nuclear mean field. The nucleons involved in the reaction interact with the rest of the nucleons in the system via a potential field. Dynamical models which address such collisions often use a time-dependent Hartree-Fock (TDHF) approach [BO 76, WO 77, CU 80, NE 82, WO 82] in which the motion of quantum-mechanical particles in a mean field is followed as the reaction proceeds in time. The Pauli principle prevents two-body scattering at low energies, but above 20 MeV/nucleon two-body collisions do take place, and a pure mean-field approach becomes inadequate [ST 80].

At very high energies, at the right in Figure I-1, the contact time between projectile and target is shorter and they may become somewhat transparent to one another [JA 78]. Central collisions result in breakup of the system into many fragments, and are characterized by a high multiplicity of light charged particles [GO 77, SA 80, NA 81, CE 81] and large, slow target fragments [WA 83]. Such reactions produce highly excited, compressed nuclear matter [GO 79, PR 83, PR 83a, NA 84], and have been studied in 4π

experiments, which measure all emitted particles simultaneously [GU 83, SA 83].

An important concept for the description of peripheral collisions is the separation of the observed fragments into participants and spectators [GU 76]. When the relative velocity of the two colliding nuclei is higher than the speed at which information is propagated through nuclear matter, the early stage of the reaction is localized to the overlapping volume of the target and projectile nuclei. The remaining fragments of the target and projectile retain much of their original velocity and are only slightly excited. At forward angles, cold projectile fragments accompanied by few emitted light particles are observed [GR 75]. Inclusive neutron [CE 81], light particle [PO 75, ME 80, SA 80, SY 80, NA 81, NA81a] and complex fragment [GO 77, ST 77, LE 79, WA 83] spectra measured at larger angles were analyzed with thermal models based on the participant and spectator concept. Fragment data from proton-induced reactions [HY 71, WE 78, GR 80, GR 84a] have been compared to those from heavy ion-induced reactions, and the spectra also appear thermal in origin.

In the intermediate energy region between 15 and 200 MeV/nucleon, a transition is expected to occur from the mean field description of low energy interactions to the two-body scattering behavior typical of high energies [SC 81]. A rather long mean free path is typical of the TDHF approach, but as the two-body collisions become more important, the