ABSTRACT

MEASUREMENT OF

LIGHT PARTICLE-COMPLEX FRAGMENT

COINCIDENCE CROSS SECTIONS

By

Bruce Earl Hasselquist

Light particle ($Z \leq 2$) inclusive and coincidence spectra have been measured for the reactions 92 MeV/A ^{40}Ar+Au and 30 MeV/A ^{12}C+Al,Au at angles from 45 to 90 degrees. Coincidence triggers for the light particle spectra were intermediate mass fragments ($3 \leq Z \leq 7$) at -30 degrees, near projectile velocity fragments ($3 \leq Z \leq 18$) at -13 degrees, and light particles ($Z \leq 2$) at -45 and -90 degrees. The Ar+Au inclusive spectra are compared to hydrodynamics and firestreak model calculations. A coalescence model calculation is used to extract coalescence radii for d,t,^{3}He, and ^{4}He from the Ar+Au spectra. Triple differential cross sections predicted by hydrodynamics are compared to the intermediate mass fragment triggered light particle spectra. A single moving source parameterization is employed throughout to depict the relevant trends in the data. Simple conservation laws are considered for the coincidence spectra in the context of a thermal moving source.

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CHAPTER I

INTRODUCTION

Much work has been done in the field of heavy ion nuclear physics, both experimental and theoretical. In the past decade, the interest has been concentrated in the projectile energy regimes below 20 MeV/nucleon and above 200 MeV/nucleon. As a result of studies in the lower energy regime, theories of compound nucleus production and mean field theories of the nucleus such as the Time Dependent Hartree-Fock theory (TDHF) have been developed. Theories such as hydrodynamics, cascade, and fireball/firestreak have been developed as a result of studies in the higher, relativistic energy regime. Theories developed for a particular energy regime tend to give agreement with the experimental data in that energy regime. But because of the differences in their underlying assumptions, none of them can be extrapolated into the other regime. It would seem that the projectile energy range from 20 to 200 MeV/nucleon should provide a transition region in which these disparate theories can be joined. Only recently, with the inauguration of the K500 superconducting cyclotron at NSCL and the availability of beams from the low energy beam line at Lawrence Berkeley Laboratory (LBL), has this transition region been open to experimental exploration. Other new

facilities such as the GANIL national facility at Caen, France, the SARA accelerator in Grenoble, France, and the HHIRF at Oak Ridge are also beginning to produce results in this energy regime. The present study is a preliminary look at two energies in this region.

Most of the experimental work that has been done at intermediate energies with heavy ions has involved the measurement of inclusive double differential cross sections from carbon, oxygen, and argon induced reactions on Au or other heavy targets [Ab 83, Fi 84, Ja 81, Ja 83, We 82, and We 84]. Some work has also been done using more symmetric systems [Ab 83, Ja 81, and Jc 84]. In general, it has been found that, the resulting double differential cross sections for light particles with $1 \leq Z \leq 2$ and for intermediate mass fragments with $3 \leq Z \leq 10$ give indications of the existence of a thermalized region in the combined projectile-target system moving at a velocity near the velocity of the center of mass. Other reaction mechanisms are known to exist as shown, for example, by the results of projectile fragmentation experiments [Bo 83, Gu 84, Mo 81, Ra 84, Va 79, and Vi 79]. Borrel, et al. observed fragments of the projectile with $3 \leq Z \leq 16$ at laboratory angles less than 12 degrees from ^{40}Ar induced reactions on Au and Ni at 44 MeV/nucleon. The velocity distributions for these fragments were found to be gaussian in shape with centroids near the projectile velocity. The reaction mechanism is thought to be a fragmentation process whereby the projectile nucleus is

excited by the target nucleus and subsequently breaks up into smaller fragments. Whether the breakup occurs almost immediately after the collision or only after a partial thermal equilibrium of the projectile is established, is a topic of current research. In order to better understand a given reaction mechanism, it is necessary to constrain the dynamics of the reaction under investigation. To this end, a number of investigators have undertaken complex coincidence measurements, each concentrating on a particular aspect of the reaction. A typical coincidence measurement is the detection of light charged particles with $Z \leq 2$ in coincidence with slow, heavy target-like fragments [Br 83, Me 80, Wa 83]. Examination of the fragment yields as a function of the light particle multiplicity indicates that the lighter fragments are associated with high multiplicity, while the heavier fragments are associated with low multiplicity. The high multiplicity events have in turn been identified as indicators of central collisions. The most ambitious coincidence experiments are the work of the "Plastic Ball" group at LBL . The "Plastic Ball" 4π detector allows detection of light charged particles with nearly a full 4π acceptance. Analysis of events based on a calculated energy flow tensor as a function of light particle multiplicity by Gustafsson, et al. [Gu 84] has given indications of what are termed non-trivial collective nuclear flow effects, namely, the bounceoff of the projectile fragments for peripheral collisions, and the

side-splash of fragments from the disintegration of the projectile and target nuclei for central collisions. The reactions studied were Ca+Ca and Nb+Nb at 400 MeV/nucleon. The present work seeks to observe the dependence of the light particle spectra ($Z \leq 2$) on fragment production. Observed fragments are projectile-like fragments with $3 \leq Z \leq 18$ at forward angles and intermediate mass fragments with $3 \leq Z \leq 7$ at angles away from the projectile direction. An estimate of the direct knock out contribution to the light particle spectra, proposed for the higher energy regime,is also sought in coincidence measurements with other light particles ($Z \leq 2$).

Four models are widely accepted today-cascade, hydrodynamics, fireball/firestreak, and coalescence. These models all have their origins in the relativistic regime and have been applied in the intermediate energy regime with varying degrees of success. The cascade model [Cu 81, Cu 82, Ki 84, Kr 84, Ya 79] assumes that high energy heavy ion collisions proceed via individual nucleon-nucleon collisions within the overlap zone of the two nuclei. The nucleons follow straight-line trajectories between collisions. As the collisions continue, particles whose energy exceeds the binding energy are considered to be emitted, until a minimum collisional density is achieved or until a predetermined collision time is reached. Effects due to the Pauli principle and pion production have more recently been included [Ki 84, Kr 84]. A cascade

calculation was unavailable for inclusion in this work. Most applications of the cascade model have been restricted to energies above 400 MeV/nucleon. Comparisons of the early cascade models with experimental data at these relativistic energies [Bc 84, Gu 84, St 68, St 82] show that the cascade model fails to reproduce the trends in the 400 MeV/A Nb+Nb data of Gustafsson, et al. [Gu 84]. A more recent cascade calculation by Kitazoe et al. [Ki 84], has had more success in describing the Nb+Nb data by including the effects due to Pauli blocking and pion production. It remains to be seen whether or not the cascade formulation can be successfully extended down into the intermediate energy region.

The hydrodynamic or nuclear fluid dynamic model [Bu 81, Bc 84, St 68, St 79, St 80, St 81, St 82, St 83] requires the assumption of a short mean free path relative to the size of the interaction region. This is in contrast to the necessary assumption of a long mean free path used in the cascade model. For peripheral collisions involving only a few interacting nucleons, the mean free path is likely to be long. Since inclusive measurements contain contributions from all impact parameters, it is likely that inclusive measurements are not a good test of hydrodynamics. Although hydrodynamics predicts regions of extreme temperature and density during the reaction, at later times in the reaction the density becomes so small that the nucleons rarely collide. At this point hydrodynamics no longer applies because of the requirement of a short mean free path and an