NUCLEAR REACTION STUDIES

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November 1, 1994

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Period of proposed budget: April 1, 1995 to March 31, 1996

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Research Outline for 1995

Roy A. Lacey

(December 27, 1994)

Over the past year we have maintained our focus on the statistical and dynamical properties of "hot" nuclei formed in symmetric heavy ion collisions. Two major experiments were successfully completed at the National Superconducting Cyclotron Laboratory (NSCL) in January (1994), and analyses of these experiments are currently underway. In 1995 we will continue the analyses of these experiments with an eye toward the identification and characterization of possible signatures for nuclear expansion at intermediate energies.

Our collaborative effort with the MSU FourPI group, continues to focus on flow measurements and the mechanism for multifragment disassembly. Recently, an experiment was performed to study the impact parameter dependence of the disappearance of flow for the Ar + Sc system. Analysis of this experiment is underway. Our Stony Brook group will contribute to the completion of this analysis during 1995. Similarly we will continue to contribute to ongoing efforts to perform model calculations for comparison with new flow data obtained for the reactions C+C, Ne+Al, Ar+Sc, Kr+Nb, and Xe+La. Initial calculations [performed in 1994] based on the Boltzmann Uehling Uehlenbeck (BUU) model have shown trends which are in good agreement with these new data. However, a large number of additional calculations are needed to set more stringent constraints on the extracted values of K and σ_{nn} . We plan to continue this effort with the FourPi group in 1995.

In recent work we have been investigating the utility of multifragment correlation functions as probes for collective flow, rotational collective motion, and the space-time extent of nuclear systems that undergo nuclear disassembly. Initial results from these investigations have been recently published (in letter format). In 1995 we will prepare and submit full-length manuscripts of these works.

Earlier this year we joined the EOS collaboration with a view toward active participation in E895 (at BNL) as well as the analysis of existing EOS data. Subsequently, we have begun

an upgrade of our computer hardware/software commensurate with this new initiative. We have not yet completed the hardware upgrades (in 1995 we plan to acquire additional disks, additional fast CPU's, and improve our local-area network). However, a large number of the EOS analysis and simulation codes have been installed [a valuable prerequisite for the experimental planning associated with E895]. In early 1995, we will assist with the installation (at Brookhaven), configuration, testing, etc., of the EOS TPC in preparation for a possible experimental run in November 1995.

We have also presented a number of analysis themes [for existing EOS data] to the EOS collaboration which have all been accepted. In 1995 we will begin the analysis of EOS data by using previously developed multifragment correlation techniques to probe the time-scale for multifragment disassembly in central Au + C collisions (1 A GeV). This work will be carried out in collaboration with the Purdue group.

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Research Outline for 1995

by J. M. Alexander

In January 1995 we are scheduled for a two-week run in Michigan in collaboration with the M.S.U. four pi group, Hope College, Iowa and a group from Lyon. This experiment and the initiation of its analysis will constitute a major part of our work in 1995. The proposal to the M.S.U. P.A.C. is attached.

During 1994 doctoral degrees were granted to both Carl Gelderloos and Eric Bauge. Manuscript preparation is in progress for parts of their work, and additional calculations are being performed to flesh out some aspects. The results are very exciting as previewed in preprints included in our annual report. The new M.S.U. experiment will be trying to track the same kind of incomplete fusion reactions to even higher energies. If they persist as identifiable mechanistic pathways, then one might be able to study and to characterize nuclei excited to and above their total binding energy.

In a new and separate initiative three Stony Brook groups (Alexander, Lacey, and McGrath) have joined the EOS collaboration. Mark Gilkes from Purdue has recently joined us as a post-doc and has already got much of the relevant software into operational form on a DEC alpha workstation. He is also participating in the analysis code upgrades at Berkeley to be used in all future EOS analyses. Stony Brook has conceived of a series of analysis projects based on the existing EOS data and is also looking toward participation in experiment E895 at BNL in November of 1995.

Analysis ideas were presented at the last EOS collaboration meeting by each of the three Stony Brook groups; each was well received and accepted into the fold. The Gilkes software work and alpha implementation was of direct interest to many in the EOS group. We feel that we are well positioned to contribute in important ways. For example, we will test for equilibration in these relativistic energy collisions, a test that is essential for the phase-transition interpretations from the Purdue group. During

1995 the nuclear chemistry group wants to develop and expand this new initiative into experiment E895. We feel that our participation can be of great importance to the success of this experiment, and to this end we request the addition of a post doctoral appointment. Our proposed budget holds the 1994 level with this one post doc added.

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Central Collisions, Incomplete Fusion, "Poof or Porosity":

^{40}Ar Reactions from 27 to 115 MeV/nucleon

Heavy ion reactions at near-barrier energies (< 10 MeV/nucleon) have been studied for several decades. The central collisions proceed by essentially complete fusion to give hot composite nuclei that decay by evaporative particle emission leading to evaporation residues (ER's) or by fission leading to two fragments of similar mass. More recent studies at energies from ≈ 10 to ≈ 25 MeV/nucleon have shown that complete fusion yields to incomplete fusion in which a sizable fraction of the mass is fused, but there is a substantial spray of direct forward-peaked particle emission (i.e. in the direction of the light collision partner). With the present generation of intermediate energy accelerators of ≈ 25 to 250 A MeV, physicists are still in the process of feeling out the basic picture for the energy dissipation processes in the most violent entrance channels along with their associated exit channels.

This proposal builds on a series of three recent experiments that focused on central collisions for ^{40}Ar reactions over the wide energy span of 7 - 34 MeV/nucleon. Many of the results have been published as cited below; others are well along in analysis. Probes were the charged particles and fragments, i.e. H and He or LCP's, Li, other IMF's, and also the heavier fragments such as fission fragments and ER's. The three runs were as follows: (a) $^{40}\text{Ar} + \text{Ag}$ ($E/A = 7$ & 17 MeV), small-angle and large-angle correlations [1-5]. (b) $^{40}\text{Ar} + \text{Au, Ag, Cu, Al}$ ($E/A = 7, 17, 27, 34$ MeV), survey with AMPHORA 4π multidetector [6-13]. (c) $^{40}\text{Ar} + \text{Ag}$ ($E/A = 17, 27$ and 34 MeV), small-angle and large-angle correlations [14].

To our surprise many of the characteristics of well studied fusion reactions persist from the near-

barrier domain [15] to the Fermi energy domain [3,6]. Violent central collisions have been selected by use of the charged particle multiplicities. As the ^{40}Ar beam energy is increased, one finds that the hot nuclear emission sources clearly exhibit their increasing temperature in the shapes of their particle spectra and their LCP multiplicity [6]. For 34 A MeV ^{40}Ar the energy deposition reaches ≈ 5 MeV/nucleon ($E^* \approx 600$ MeV) [6,7,13,16,17] for nuclei with initial mass ≈ 130 [8,10,11]. Binary fission has been essentially replaced by multifragment emission at 27 and 34 A MeV [9], which is often cited as a signpost for entry into a new mechanistic domain. Particle and fragment emission times have decreased to the order of 10^{-22} s [3,5,9,11] i.e. the traversal time. Nevertheless, one still observes many signatures of incomplete fusion. Notable among these, as shown in Fig. 1, are heavy residual nuclei that are observed at small angles ($\theta < 12^\circ$) with velocities somewhat less than $V_{c.m.}$ (i.e. 1-2 cm/ns) [13,18]. Fig. 2 shows average excitation energies for central collisions as estimated from these velocities by the commonly used incomplete fusion approximation.

In this proposal we focus on these heavy residual nuclei and their correlations with light charged particles (LCP's) and intermediate mass fragments (IMF's). Possibly the term "collision residues" is preferable for 34 A MeV ^{40}Ar as compared to "evaporation residues" for 7 A MeV ^{40}Ar . In any case we wish to follow their production (or disappearance) for $^{40}\text{Ar} + \text{Ag}$ ($E/A = 25-115$ MeV). It is often thought that such heavy residues will be completely blown away into showers of IMF's and LCP's for the most violent collisions for $E/A \geq 34$ MeV. One might expect this from the values and trends of the energy deposition shown in Fig. 2. It is also possible, however, that the collision zones may become so porous for $E/A > 34$ MeV that the energy dissipation processes become essentially saturated [16,17]; in this case, beam energy increases may have little or no effect in giving additional heat to the heavy residual nuclear system. Therefore, the measurement of heavy residues at forward angles can be a good probe for nuclear porosity and energy deposition. The additional association of such residues with LCP and IMF multiplicity can locate their production on the scale of collision violence. (For 34 A MeV ^{40}Ar

+ Ag we note that it is indeed these residues, rather than IMF's, that are associated with the highest LCP multiplicities [7,13].)

Another important probe of the hot nuclear matter in the early life of the collision zone is the "apparent recoil effect" [8,10] as determined by right-left shifts in the transverse momenta of particle pairs. We have developed a method that uses these recoil effects to obtain the effective mass of emission sources for such particle pairs. For example, for 34A MeV $^{40}\text{Ar} + \text{Ag}$ the effective mass number for the source of ^4He - ^4He pairs is 115 ± 10 [8,10] compared to a final residue mass of ≈ 70 [18] and an initial mass of ≈ 130 as estimated from the linear momentum transfer [13]. These average masses along with average neutron [16,17] and LCP multiplicities [7] give the possibility for a much clearer view of the life history of the collision zone and its acceptance and disposal of energy [8]. We propose to combine these measurements as tests for continued growth or saturation in the deposition energy.

We also propose to continue exploitation of the azimuthal correlations between particle and IMF pairs in the most central collisions [11,19]. These have great power in several important ways: (a) to signal rotational collective motion and even to indicate the spin zone of the emitters [6,9,11]. (b) to obtain the average emission time between IMF's [5,9,20] and (c) to provide a possible signature for explosive multifragmentation [11,19,20]. Each of these techniques has been a subject of measurements and model calculations [1-14,19,20] in our series from 7-34 A MeV.

In short we will measure these changes in particle and/or fragment correlations that would signal the explosive disappearance of bound composite nuclei, i.e. "poof", or the persistence of bound nuclei, which would demand great "porosity" and strong limits on energy deposition.

The experimental details for this current proposal are conceptually very simple; we would use the MSU 4π array with gas counters [21], the Maryland forward array, and the high-rate forward array now in preparation. With these arrays one can register heavy (but slow) nuclear fragments at forward angles. With Si detectors we would measure time of flight (tof) and energy; with plastics (and PPAC's)

we would get tof (at least) and possibly energy even for the slowest heavy fragments (as in our earlier experiments [13]). The first reaction to be observed would be for 27 A MeV $^{40}\text{Ar} + \text{Ag}$ to gain a good consistency test with the earlier work cited above. These data also give a basis for verification of the energy calibrations. We have energy spectra for LCP's and IMF's from 17 A MeV $^{40}\text{Ar} + \text{Ag}$ measured in an LBL experiment with Si detectors [14]. These were used as one basis for calibrations in the three experiments cited above.

The meat of the experiment would employ beams of ^{40}Ar of 44, 55, 75 and 115 A MeV on Ag targets (along with comparisons to Cu and Al). For 4π detection the beam time needed is fixed by the acceptable counting rate rather than by the cross sections. Counting rates allowable for the 4π array at MSU are comparable to those allowed by AMPHORA [22]. Our time request of 240 hours is calculated to give a data set for 44, 55, 75 and 115 A MeV ^{40}Ar that has the same number of events as the set of proven merit for 7, 17, 27 and 34 A MeV ^{40}Ar [6-13]. Inter comparisons between data from different energies and different targets give great strength to the consistency of results as well as to the efficient use of manpower for setup, calibration and analysis. Therefore we strongly prefer to make all measurements in one long run.

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Figure Captions

Fig. 1 Velocity distributions for heavy fragments registered in plastic scintillators at 7.9° [13].

Solid (dashed) curves are the subset of these data gated by the highest (lowest) third of the LCP multiplicity distribution.

Fig. 2 Calculated excitation energy densities for fusion reactions. For incomplete fusion, the average mass, energy and linear momentum transfer were taken to be 100, 85, 80 and 60% respectively.

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$^{40}\text{Ar} + ^{108}\text{Ag}$ Central Collisions