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EMISSION OF HIGH-ENERGY, LIGHT PARTICLES FROM INTERMEDIATE-ENERGY HEAVY-ION REACTIONS

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Introduction

With heavy ion beams now or soon to be available for research, we have the opportunity to study nuclear matter under stresses that cannot be produced with any other probes. At the lower projectile energies the nuclear structure and reaction dynamic effects of high angular rotation stresses are being studied to better define the collective and single particle behavior of nuclear matter. As we push to higher energies, we introduce the possibility of compressional forces that may produce nuclear densities greater than those normally present in the nucleus of an atom. It is with such studies that we can hope to derive information about the behavior of the nuclear-matter equation of state.

At collision energies of one to two times the Coulomb barrier energy, the relative velocities are less than the typical Fermi velocities of the bound nucleons. In this domain, we expect the mean field properties of the nuclei to dominate the reaction process. At the other extreme, at relativistic collision energies, we expect the reaction to proceed as an incoherent superposition of individual two-particle collisions. Before we can obtain information on the behavior of the nuclear equation of state it seems clear that we must understand the processes which lead to this transition from mean field to independent particle dominance of the nuclear reaction.

If high nuclear-matter densities are produced during reactions in this transition region, the lifetime of this hot, dense aggregation will be very short - the order of the reaction time. Thus, whatever we can deduce about this state of nuclear matter will have to be reconstructed from our examination of the nuclear debris remaining after the reaction.

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One of the early surprises in examining reaction products from heavy ion reactions at 10 MeV/nucleon and above was the large yield of light particles emitted and the high energies to which the spectra of these particles extended. At Oak Ridge, a group of us have been involved actively in studying light charged particle emission from heavy ion reactions since about 1976. This paper is intended as a progress report on that work and a look at our present interpretation of this phenomenon.

Reactions Below 20 MeV/Nucleon

This research program began, curiously enough, with a measurement performed to test predictions of a cascade-evaporation code[1] used to generate neutron spectra for radiation shielding calculations. Calculations for heavy ion projectiles at energies of 100 MeV/nucleon and above had produced predicted neutron spectra extending to energies significantly above the energy/nucleon of the projectile. At issue was the actual existence of such high energy neutrons accompanying a heavy ion reaction.

Because there were no 100 MeV/nucleon heavy ion beams available at that time, the cascade-evaporation calculations were repeated for incident 16 MeV/nucleon carbon ions. This ion-energy combination represented the highest energy/nucleon available to us with ion beams from the Oak Ridge Isochronous Cyclotron utilizing its internal Penning source. Surprisingly, the calculations predicted that the spectra of neutrons and protons emitted would extend to several times the energy/nucleon of the incident carbon ions.

Since there was little difference between predicted spectra of neutrons and protons, we chose to perform the easier measurement of the charged-particle spectra.[2] The results, shown in Fig. 1, confirmed the existence of light particles emitted with very high energies. There were, to us, two additional surprises in these results: First, the similar cross sections observed for emission of high-energy protons and composite Z=1 particles - deuterons and tritons. This is in sharp contrast to the more familiar order of magnitude differences seen in direct reactions and low-energy compound nuclear reactions. Second, the large magnitude of the observed cross sections for energetic particles. The proton spectra, as shown in Fig. 2, have an instrumental cut-off at about 15 MeV. The observed integrated yield above this energy is about 0.8 barns. Such a large cross section implies that processes leading to the emission of these light particles must play a major role in the reaction mechanism at these energies.

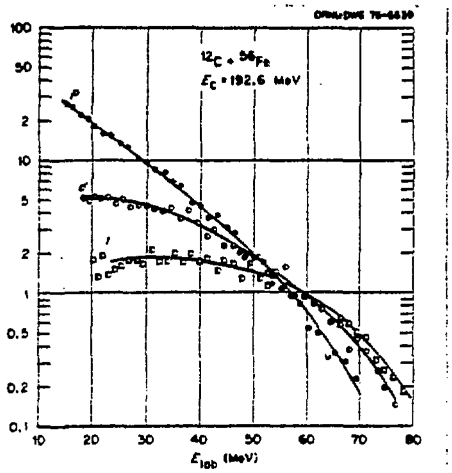

Fig. 1. Energy spectra observed at a laboratory angle of 15° for Z=1 particles emitted following the reaction of 16 MeV/nucleon ^{12}C ions with a target of ^{56}Fe.

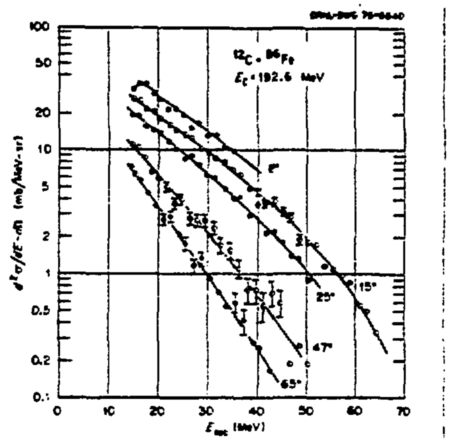

Fig. 2. Energy spectra of protons emitted at several angles from the reaction of 16 MeV/nucleon ^{12}C with ^{56}Fe.

This experiment was not the first identification of possible non-equilibrium emission of light particles from heavy-ion induced reactions. In 1961, Britt and Quinton reported a forward-peaked component in proton spectra from reactions at 10.5 MeV/nucleon.[3] They proposed that this direct component was produced by breakup of the incident particle during a grazing collision with the target. However, in their experiment, the high energy nature of the proton spectrum was not identified. Since the breakup mechanism will produce laboratory energies for the light particles that will not differ greatly from the energy/nucleon of the incident ion, this mechanism cannot account easily for the results obtained with ^{12}C ions at 16 MeV/nucleon where the proton spectra extend almost to 5 times this energy.

The results of the cascade-evaporation calculation discussed in the previous section are compared to the 16 MeV/nucleon induced proton spectra in Fig. 3. Although somewhat deficient at the higher energies, the

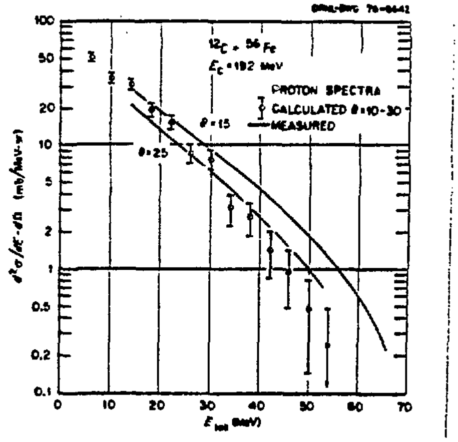

Fig. 3. Comparison of observed proton spectra with results of the cascade-evaporation calculation. The lines are those drawn through the experimental points on Fig. 2. The error bars on the calculated points represent the statistical uncertainties introduced by use of the Monte Carlo method of the calculations.

calculation gives a quite reasonable account of the data. How much of this is fortuitous is difficult to say. In particular, the calculations employ the impulse approximation which is difficult to justify at such low energies. Even so, it seems worthwhile to use the calculations as a guide. An examination of the details of the calculations[4] shows that, at these energies, essentially all of the predicted high-energy light ions arise from the excitation of the projectile and subsequent evaporation from the excited projectile-like fragment. Such a mechanism had been proposed earlier[5] as a means to produce high energy light ions in heavy ion collisions. In this picture, the high-energy components of the light particle spectra are produced by the addition of the velocity of the evaporated particle in the rest frame of the moving projectile fragment to the laboratory velocity of this source. Note that there is a subtle distinction here with the time scale of the reaction and the instant at which the light ions are produced. For the projectile breakup mechanism, the production takes place prior to projectile-target separation. For the projectile evaporation mechanism, the production takes place at some time following the separation. One inference would be that the particles formed by the latter mechanism would carry very little information about the collision process. This point will be returned to below.

If projectile evaporation is an important mechanism for producing the high-energy light ions, then we should be able to detect a correlation between the fast light particles and their associated projectile-like fragments.

At Oak Ridge, Robinson and co-workers have performed such a measurement[6] for reactions induced by 16 MeV/nucleon ^{12}C ions on a ^{60}Ni target. This experiment involved 16 detectors and observed a limited angular distribution of emitted light ions in coincidence with 1) projectile-like fragments, 2) Z=1,2 particles, 3) γ-ray multiplicities, and 4) discrete γ-rays. The experimental arrangement utilized four light ion detector telescopes at laboratory angles of 17°, 38°, -23°, and -49°. The telescope at 17° was preceded by a heavy ion telescope. Two Ge(Li) gamma-ray detectors were located in the scattering plane at 90° and -145°. Four NaI(Tl) detectors above the scattering plane were used for determining gamma-ray multiplicities.

The angular yields of energetic alpha particles in coincidence with He, Li, and C fragments are shown in Fig. 4. For all gating fragments, the angular distribution of the alpha particles exhibits a single peak and

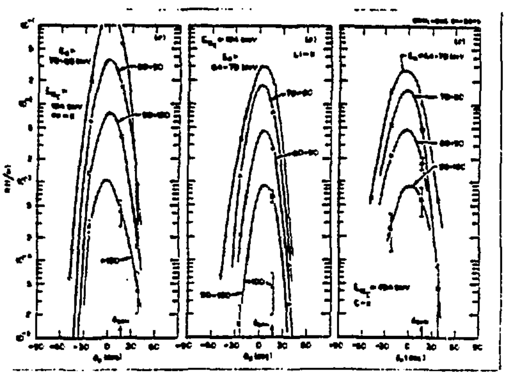

Fig. 4. Angular yields of the energetic alpha particles in coincidence with a) He, b) Li, and c) C from the interaction of 16 MeV/nucleon ^{12}C with ^{60}Ni. The coincident alpha particles are divided in the energy bins noted in the figure. The angle of the gating particle is 17°.

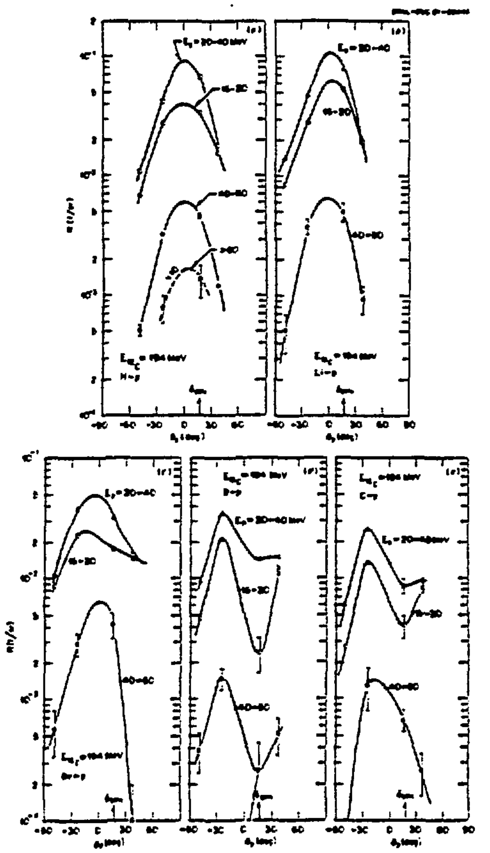

Fig. 5. Angular yields of energetic protons in coincidence with a) H, b) Li, c) Be, d) B, and e) C for the same conditions as the data of Fig. 4.

appears symmetric about the beam axis. No obvious correlation with the gating detector is observed.

For protons, as shown in Fig. 5, the result is more complex. For the heavier fragments, a drop in the coincidence yield appears to correlate with the position of the gating detector. Thus it would appear that the heavy projectile-like fragments are acting as a shield—essentially the opposite effect we would expect from the picture of projectile evaporation.

Another possibility is that, following evaporation of a light particle, the projectile fragment and target fuse. Such a process has been observed by the Texas A&M group and termed "massive transfer."[7,8] In the present experiment, the coincident gamma-ray spectra were used to identify the fusion residues. The distributions were found to center about the ^{60}Ni target. It is interesting to compare this with similar measurements made with 11.3 MeV/nucleon carbon ions. At the lower energy, the centroid was found to be a few masses higher. The implication, then, is that as the reaction energy is increased, more particles are emitted from the reacting system. Even at the centroid of the distribution, the maximum yield for any channel never exceeded about 5% to 8% of the total. The heaviest mass observed would correspond to the compound system less an alpha particle.

The yield for this channel was measured to be less than 1/2%. It thus appears that while the process of "massive transfer" may be present, it does not play a dominant role in the reactions at these energies.

A Moving Source

One of the most successful models applied to the interpretation of relativistic heavy ion collisions involves the assumption of an excited assembly of nucleons moving at a velocity intermediate between those of the target and incident projectile.[9,10] Pictorially, such a source would be formed from the overlap region between the incident projectile and the target nucleus. Various versions have gone by such exotic names as "nuclear fireball," "firestreak," etc.

The resulting parameterization, that of an excited moving source emitting particles at some equilibrated temperature, has been interestingly applied to data in the 20 MeV/nucleon region.[11,12] An example[13] of such a treatment of data from ^{12}C-induced reactions is shown in Fig. 6 for incident ion energies of 7.5 and 15.8 MeV/nucleon. The form of the parameterization utilized the assumption of surface emission of the particles. The parameters extracted at these and intervenient energies exhibit a marked consistency and show a rather smooth energy dependence.

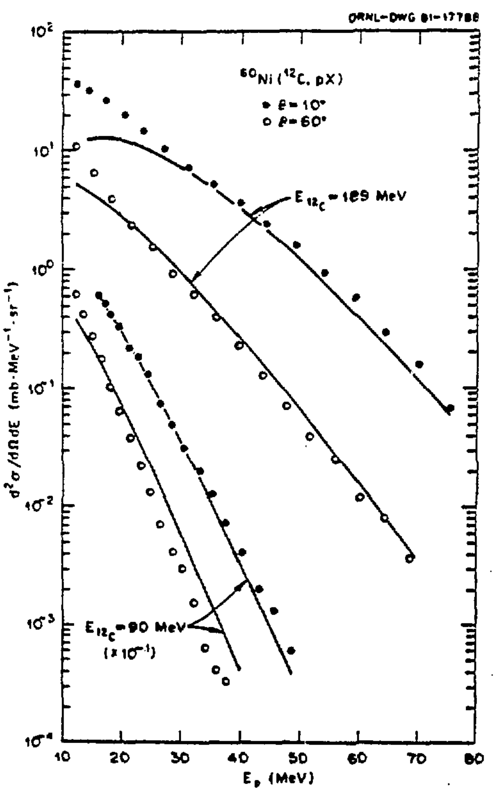

Fig. 6. Comparison of proton spectra at 7.5 and 15.8 MeV/amu incident energy (solid and open points) with fits obtained assuming light-ion emission from a moving, excited source (solid curves).

One question to be asked is whether or not the light particles emitted during heavy ion induced reactions are purely statistical in origin. If so, can anything be learned from the systematics of the observed spectra? Are there any discontinuities in these systematics that might signal the introduction of new degrees of freedom in the emitting source?

To Higher Energies

Given a parameterization, the moving source, that can be fit to data in the 10 to 20 MeV/nucleon energy region as well as to data[9] at relativistic energies, an obvious question is can anything be learned by following the systematics of this parameterization through the intermediate "transition" region. In particular, will there be any discontinuities that could signal the onset of compressional modes, thermal saturation, etc.

To study light particle emission in this intermediate energy region, measurements were made using 50, 100, and 147 MeV/nucleon oxygen ion beams at the low-energy beam line of the LBL Bevalac.[14] An example of proton spectra observed from a nickel target is shown in Fig. 7. The data extend over an angular range from 6° to 115°. Alpha particle spectra observed from this same reaction are shown in Fig. 8. At forward angles, the particle spectra are seen to peak at an energy near the energy per nucleon of the projectile. This general behavior is observed at all three energies.

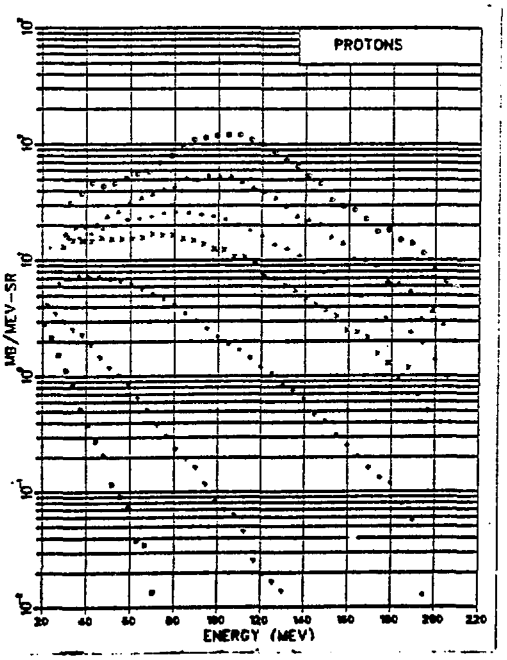

Fig. 7. Proton spectra observed from the reaction of 100 MeV/amu ^{16}O ions with a natural nickel target. The angles of observation are (from top to bottom): 6, 12, 18, 24, 45, 85, and 115 degrees.

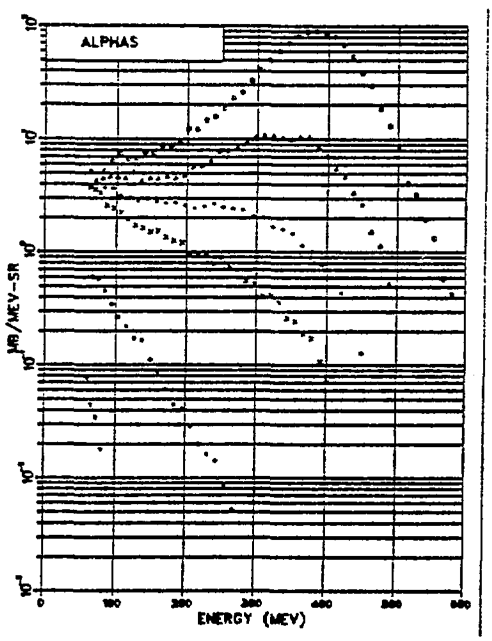

Fig. 8. Alpha particle spectra observed from the reaction of 100 MeV/amu ^{16}O ions with a natural nickel target. The angles of observation are (from top to bottom): 6, 12, 18, 24, 45, and 85 degrees.

Typical proton spectra at 100 MeV/nucleon for a range of targets are shown in Fig. 9. The spectral shapes are seen to be independent of target mass. Moving source parameterization of the data was obtained for the angular range from 24 to 115 degrees. Velocity and temperature parameters were found to be insensitive to the target mass. In all cases, surface emission has been assumed. A plot of the parameters deduced, including the lower energy ^{12}C data, is shown in Fig. 10. The insensitivity of the ratio of source velocity to projectile velocity and the smooth variation of the "temperature" parameter are quite striking. Certainly one does not find any evidence for discontinuities in such a parameterization through this energy region.

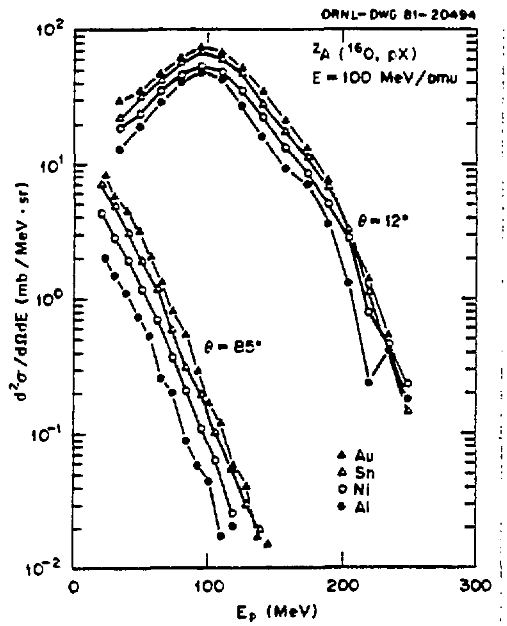

Fig. 9. Proton spectra from reactions induced by 100 MeV/amu 16O ions with various targets.

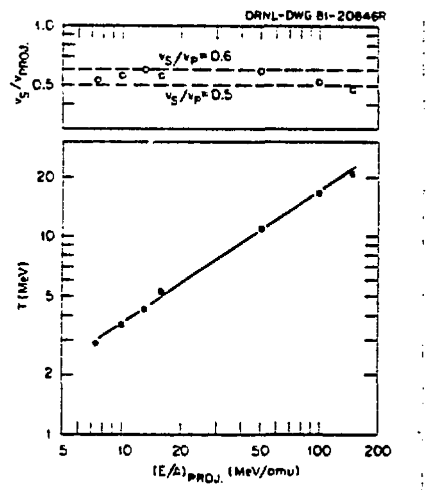

Fig. 10. Systematics of moving source parameters obtained from fitting proton spectra at incident projectile energies from 7.5 to 147 MeV/amu.

It may be worth remarking that the concept of a "temperature" as defined here is not clear. In particular, there is no *a priori* reason for assuming that the emission of the particles observed is from an equilibrated source. More likely, we are observing the momentum distribution of an interaction region with a rest frame different from the projectile or the compound system. This point will be returned to in the last section.

There is another interesting feature that emerged from the 100 MeV/nucleon data. If the energy integrated yields at each angle are plotted as a function of target mass, the behavior as shown in Fig. 11 is found. At the forward angles, the yield is seen to vary as $A^{1/3}$ and to change smoothly to an $A^{2/3}$ dependence as the angle is increased. This suggests a change from predominately peripheral interactions at forward angles to predominately central collisions contributing to the larger angles. This may suggest that the most forward angle spectra, where the cross sections peak at or near energies corresponding to the projectile velocity, could be due primarily to projectile fragmentation.[15] A predominately thermal mechanism may be responsible for the particle spectra observed at larger angles. The moving source parameterization used to extract the values shown in Fig. 10 did not include the most forward angles for the high energy data. The inability of this parameterization to account for the forward angle data is illustrated in Fig. 12. The 12° spectrum was calculated using parameters derived from fitting $\Theta \geq 24°$ spectra. The rapid increase in observed yields at more forward angles is clearly not reproduced by this parameterization and is the reason for excluding these angles from the fitting discussed in connection with Fig. 10.

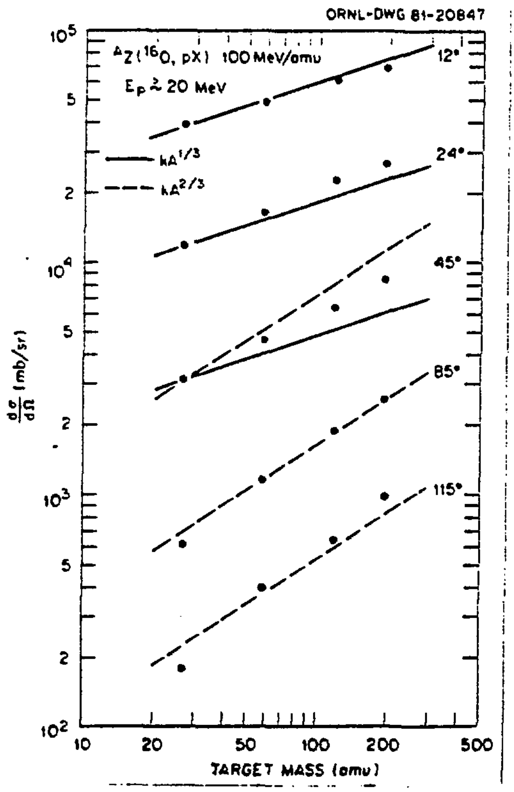

Fig. 11. Energy integrated yields of protons produced by the interaction of 100 MeV/amu 16O ions with targets of Al, Ni, Sn, and Au. The solid and dashed lines indicate the expected slopes for $A^{1/3}$ and $A^{2/3}$ dependence, respectively.

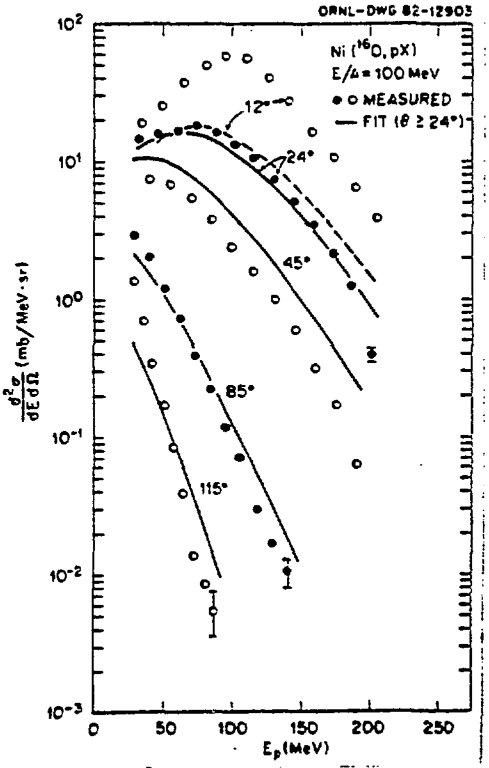

Fig. 12. Measured proton spectra compared to emission from an excited source moving at 0.54 of the projectile velocity with a temperature of 17.2 MeV.

Composite Particles

In examining the systematics of proton spectra for reactions induced at incident ion energies between 7.5 and 147 MeV/nucleon, no change in qualitative behavior has been observed that might signal a change in reaction dynamics over this "transition" region. It may be that we are not using an appropriate analysis to see signs of such a transition. Another possiblity is that we are looking in the wrong place or at the wrong thing. Siemens and Kapusta have suggested[16] that the composite particles may carry important information about details of the collision process. In particular, the relative yields of composite particles to protons may carry information about the entropy associated with the hot, dense emitting source. An increase of entropy would be expected from the introduction of new degrees of freedom such as excitation of more mesonic degress of freedom, or more exotic modes such as pion condensation.

The same general features as have been discussed here for the Oak Ridge studies have also been observed in the studies of Awes et al., with oxygen ions at 8.75, 13.4, and 19.4 MeV/nucleon.[17] In that study, the yield of composite particles has been related to the yield of protons through a coalescence model.[18,19] Here the composite particles are assumed to be formed from an aggregation of independent nucleons which find themselves in the same region of phase space. This gives rise to a simple power law relating the composite particle spectra to the proton spectra. In general, rather good agreement is observed[17] although there is a disturbing variation in the deduced coalescence radii with projectile energy and projectile-target combination. One implication of this may be that the composite particles observed at these energies do not represent equilibrium yields formed during the initial collision but are modified in later stages of the interaction. An open question is how much information is retained that relates to the properties of an initial emitting source.

An example of composite particle spectra observed from 100 MeV/nucleon ^{16}O on ^{60}Ni is shown in Fig. 13. Again, at these forward angles the spectra peak at energies associated with the velocity of the incident projectile. A notable exception to this behavior is seen for the tritons. An example of the application of the coalescence model to the deuteron data is shown in Fig. 14. It is interesting to note that while the fit to larger angles is rather remarkable, this model also fails to reproduce the data observed at the forward angles. It is also clear, from Fig. 13, that the triton spectra will not be well accounted for in terms of a coalescence picture.

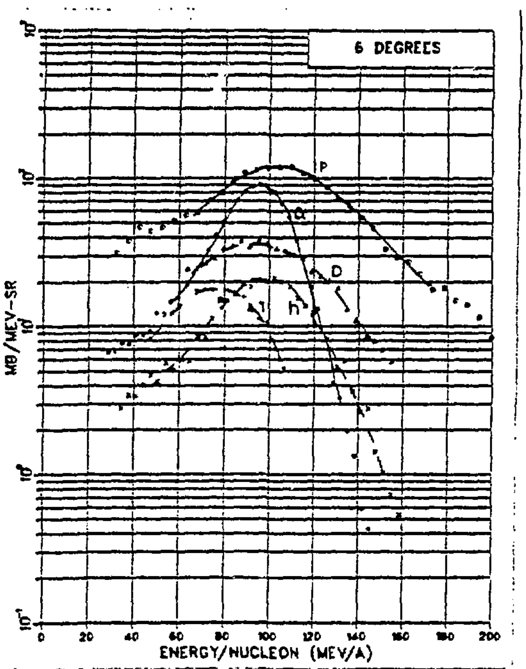

Fig. 13. Energy spectra observed at a laboratory angle of 6 degrees for protons, deuterons, tritons helium-3, and helium-4 from the interaction of 100 MeV/amu 16O ions with a nickel target. Spectra are plotted as a function of the energy per nucleon of the observed ejectile. Note the dissimilarity of the t and ^{3}He spectra.

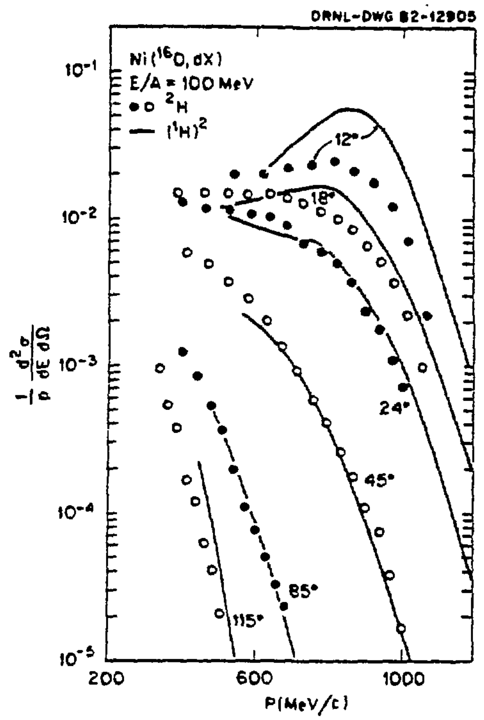

Fig. 14. Measured deuteron spectra compared to predictions of a coalescence model based on the observed proton spectra.

The target mass dependence of the integral yields for protons and composite particles is shown in Fig. 15 for the data at 100 MeV/nucleon. Note the sharp increase in deuteron and triton yields observed between the Ni and Sn target. This may be related to the neutron excess associated with the heavier targets.

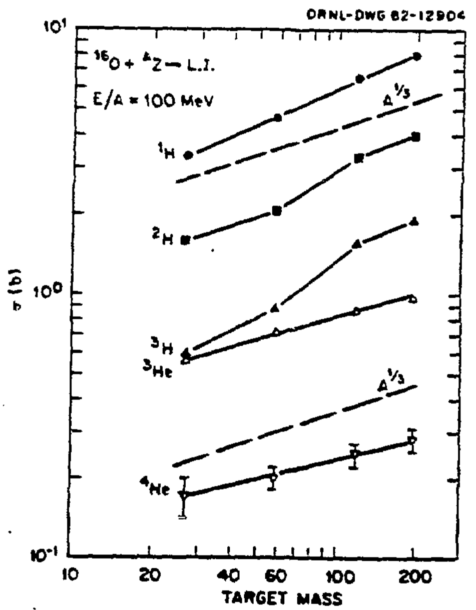

Fig. 15. Integral cross sections for particles with energy greater than the lower detection limit for 1.6 GeV 16O on Al, Ni, Sn, and Au targets.

Moving source parameters have been extracted from the proton and composite particle spectra for the Bevalac data. The ratio of proton to deuteron to triton yields seem to have stabilized at these higher energies at about 1.0:0.3:0.1. As was found for the lower energies, the fits derived from this parameterization seem quite consistent and well-behaved. No evidence is observed for any discontinuities in the observed behavior of the composite particles.

Present Status

This paper has concentrated on results from the program at Oak Ridge. There have also been major efforts in this field by groups at Texas A&M University, Lawrence Berkeley Laboratory, and Michigan State University. Some of these results have been referenced here, but for additional information the reader is referred to the excellent review paper by Scott.[20]

In the present work, the interpretation of the origin of the high energy light ions has evolved from a picture of projectile excitation and subsequent evaporation to one of pre-equilibrium (or nonequilibrium) emission. The "time scale" for particle emission has thus moved from one that occurs following the initial collision to one that occurs at the very early stages of the collision.

At low energies the observed light ion spectra can be reasonably well reproduced by the assumption of emission from a heated source moving at a velocity corresponding to approximately half the projectile velocity. At higher energies, the larger angle data are also well reproduced by such a parameterization which extrapolates smoothly from the lower energies. At the smaller angles, however, the higher energy data shows a peaking around the projectile velocity characteristic of a projectile fragmentation process. This duality of processes at higher energies is consistent with the observed change of target mass dependence between small and large angles of observation leading to the conjectured change from peripheral to central collision dominance. One obvious next step is to utilize this angular dependence to try to disentangle these two processes and examine their individual behavior.

The moving source picture which has been used to parameterize the existing data has a certain appeal in its simplicity and ability to account qualitatively for a rather large range of data with a minimum of parameters. Obviously, this picture is too simplistic and merely a convenience. We need to replace such a treatment with an approach which deals more directly with momentum distributions of particles in the interacting system. One such formulation has been proposed by Wong.[21] The momentum distribution is generalized in such a way that it gives the thermal distribution, if indeed thermal equilibrium is established. The light particle spectra are treated as arising from two distinct momentum distributions, a central distribution and a fragmentation distribution. In both portions of this distribution the transverse and longitudinal momentum components are treated separately. In addition, in analyzing the experimental data, it is found necessary to allow a "Wood-Saxon" shape for the momentum distribution of the central source. A Gaussian distribution is used for the fragmentation source. The resulting formulation has, then, eight parameters which are fit to the data. An example of the results of such a fit is shown in Fig. 16 for the protons observed from 100 MeV/nucleon ^{16}O on nickel. Constraining the number of parameters to less than eight compromises significantly the quality of the fits achieved.

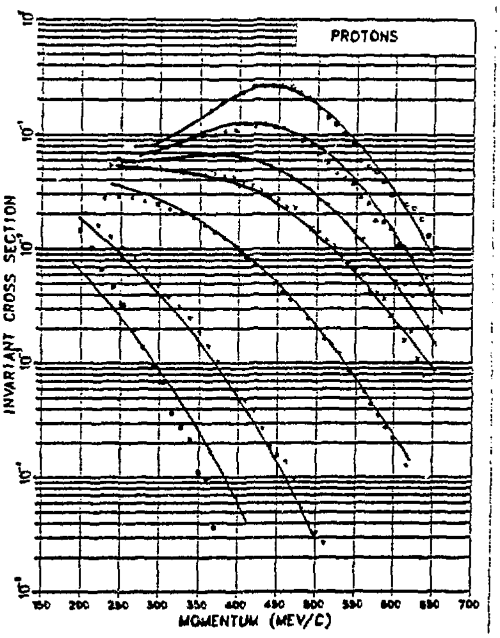

Fig. 16. Proton spectra of Fig. 11 (100 MeV/amu ^{16}O on natural nickel) fit with the two-source, unconstrained momentum formulation of Wong.[21]

Although analysis of the light particle inclusive spectra with this more complete parameterization is very preliminary, some interesting features seem to be emerging. The velocity of the central source is seen to center about 0.55 of the velocity of the projectile, in agreement with the simpler moving source picture. At 100 and 147 MeV/nucleon projectile energies, the longitudinal momentum component of the central source exceeds the transverse component. This is interpreted as indicating the particles are being emitted prior to equilibration of the source. Using the parameters derived from fitting the 100 MeV/nucleon data, integration may be performed to obtain the total yield from each source. The emission from the central source is found to vary as $A^{2/3}$ of the target while that from the fragmentation source varies as $A^{1/3}$ in good agreement with the interpretation given to Fig. 11.

If we are correct in our assumption that a significant number of the high energy light ions emitted from heavy ion reactions are created during the early states of the collision, then these particles should in fact carry information about the processes involved. The challenge remains for us to design the appropriate experiments and interpretations to understand the reaction processes involved and use this understanding to deduce such information.

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