Multifragmentation Induced by Light Heavy-Ions with GeV Energy

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and

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ABSTRACT

We have extended our investigations on nuclear multifragmentations induced by GeV-energy light projectiles. By using light heavy-ion beams (^{16}O, ^{20}Ne and ^{28}Si) provided from the Heavy-Ion Medical Accelerator in Chiba (HIMAC) at the National Institute for Radiological Science (NIRS) we studied similarities and differences among various fragment formation reactions in the same total energy domain. We found there are noticeable differences in spectrum shapes of Intermediate-Mass Fragment (IMF) and their magnitudes depending upon the projectile mass, but all of their angular distributions clearly exhibit the existence of sideward-peaked components, indicating fragment formations are mainly governed by a total energy of the projectile, not by a incident energy per nucleon.

1. Introduction

Our collaboration, the MULTI, has been exploring thermo-dynamical nature of highly excited nuclear system produced in GeV-energy nuclear reactions for last few years.[1,2,3] We selected the GeV-energy domain as a region of interest, because possible precursor phenomena of liquid-gas phase transition in the nuclear matter have been reported for light-projectile induced reactions in this energy domain. For example, (i) the production cross section for an Intermediate Mass Fragment (IMF) as a function of the beam energy clearly shows plateau above 10 GeV.[4] (ii) The energy spectra of IMFs qualitatively change their shapes at around 5 GeV.[4,5,6] (iii) The IMF angular distributions show the transition from forward to sideward-peaking in the energy domain of 3 to 11.5 GeV.[7,8,9,10,11,12](iv) The power-law index τ for the inclusive element-distribution, $\sigma(Z) \propto Z^{-\tau}$, as a function of the incident energy exhibits minimum at about 4 GeV.[4] There is, however, no direct evidence that these phenomena strongly link to the phase-transition.

In order to understand those phenomena several groups in the world have initiated research projects on the multifragmentation in the GeV-energy domain. Recently the ALADIN collaboration at GSI successfully extracted a so-called "nuclear caloric curve," namely temperature as a function of the average excitation energy of the decaying system, obtained from measurements of the isotope yield ratios for the highly excited nuclear system produced through a Au + Au reaction at 600 MeV/nucleon. Their caloric curve behaves just like the one of water at normal pressure of 1 atmosphere[13]. More recently the IUCF group demonstrated that nuclear liquid-gas phase transition does occur in the GeV-energy light-projectile induced multifragmentation reactions[14,15] by using 5.0-14.6 GeV/c proton and π^- beams, and 8.0 GeV/c anti-proton and π^- beams at AGS together with their powerful Indiana Silicon Sphere (ISiS) 4π array[16]. Our group also extracted a caloric curve from 8 and 12 GeV proton induced target multifragmentation (TMF) data, which suggested that the existence of nuclear liquid-gas phase transition[17]. All these findings seem to suggest that the multifragmentation is a statistical decay process from a thermally equilibrated system.

There are, however, still several unresolved questions. For example we still do not know why the character of the IMF angular distributions evolves from forward-peaked to sideways-peaked in the energy regime of 3 to 12 GeV. Appearance of sideward peaking angular distribution could be very disturbing because it might imply that the emission source of IMFs is not thermally equilibrated or not spherical as usually assumed in many theoretical models for the multifragmentation. Although a great deal of efforts has been made on explaining this phenomenon in the past (shock wave formation[18], nuclear-doughnuts formation[19], significant transverse momentum of remnant from intra nuclear cascade[12]), there is little agreement on the origin of the sideward peaking. Considering the fact that 5.5 GeV proton induced TMF did not show sideward peaked nature[20] while our 20 GeV α data did exhibit clear sideward peaked character similar to the one observed in the 12 GeV proton data[1], we suspect that the interpretation proposed by Hsi *et al.*[12] is not well-founded.

Last year a nuclear theory group at the Hokkaido University reported results of their calculations based on both transport model and non-equilibrium percolation model[21] to account for our 12 GeV proton data. They suggested sideward peaking angular distribution might arise from a "doughnut shape" of the IMF emission source. Inclusion of Coulomb expansion seems to be essential to account for a sideward-peaked angular distribution of IMFs. They also urged us to accumulate more systematic data on the incident energy dependence of the IMF angular distribution. In order to obtain data in the wider incident energy range and to investigate a possible scaling rules[22,23,24,25] and/or density effect in the TMF reaction, we moved our entire experimental setup to the HIMAC after the completion of the experiments at the KEK-PS.

2. Experimental Procedure

New experiments were performed with ^{16}O and ^{20}Ne beams of 8 GeV, ^{28}Si beams of 8.12 GeV, ^{20}Ne beams of 12 GeV, and ^{28}Si beams of 22.4 GeV accelerated by the HIMAC at the NIRS. Typical beam intensity was about a few times 10^8 particles/sec. with a beam-spot size of roughly 10 mm in diameter. A metallic Au target of about 0.6 mg/cm^2 was mainly used for the measurements. Intermediate Mass Fragments (IMFs; $3 \leq Z \leq 20$) were detected and particle-identified with the 37 Bragg Curve Counter (BCC) array, which was almost the same as the one used for the previous experiments with 8- and 12-GeV proton beams at the KEK-PS. As counter gas we used the P10 (Ar 90% and $CH_4$10%) gas of 300 Torr instead of 200 Torr. In order to measure angular distributions of the IMFs 12 BCCs were placed in the horizontal plane including the target and the other 25 were set in upper hemisphere in order to measure the IMF multiplicity. They covered an angular range of θ_{lab}= 30°-150° in 20° steps and a solid angle of nearly 20% of 4π. The technical details of our BCCs have been published in Ref. 25. The data were taken under the minimum bias condition; i.e. a sum of 37 self-triggers from individual BCC.

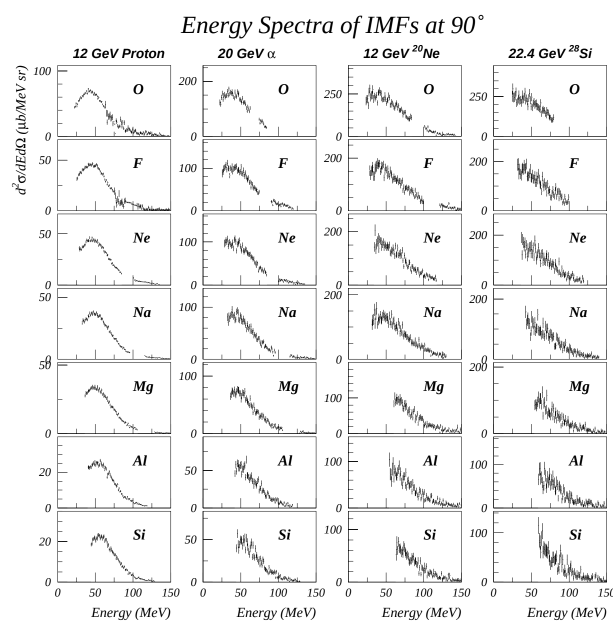

Figure 1: Inclusive energy spectra of IMFs for 12 GeV proton, 20 GeV α, 12 GeV ^{20}Ne and 22.4 GeV ^{28}Si induced TMFs at 90°.

3. Experimental Results

Inclusive IMF energy spectra for the GeV-energy light heavy-ion induced TMFs are shown together with those for the proton and α induced ones at the similar beam energies in Fig. 1 and 2. In order to avoid a shape-distortion arising from a movement of emission-source we select the data at 90° in the laboratory system. As can be seen in the figures all spectra show usual Maxwell-Boltzmann distribution-like shapes, but absolute cross sections for the ^{16}O, ^{20}Ne and ^{28}Si induced TMFs are about 4-5 times larger than those for the proton induced ones. Coulomb peaks become wider and high energy tails become longer as the projectile mass increases.

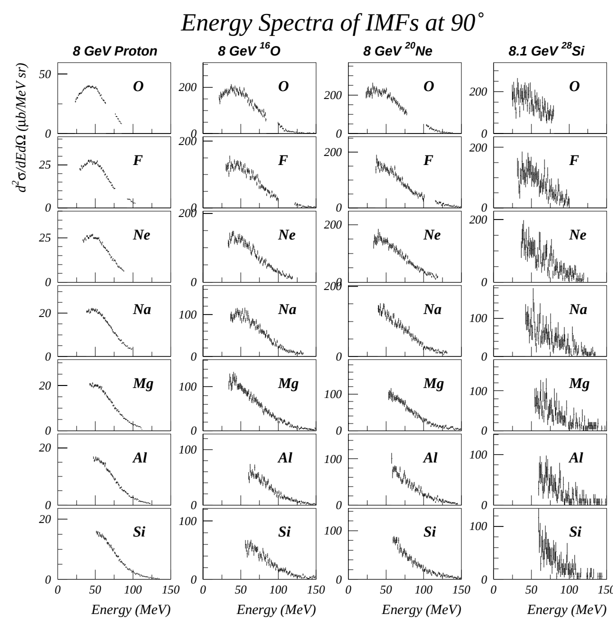

Figure 2: Inclusive energy spectra of IMFs for 8 GeV proton, 8 GeV ^{16}O, 8 GeV ^{20}Ne and 8.12 GeV ^{28}Si induced TMFs at 90°.

In Fig.3 inclusive angular distributions of Na for 8 GeV proton, 8 GeV ^{16}O, and 8 GeV ^{20}Ne induced TMFs are shown. The location of the Coulomb peaks shifts more rapidly as a function of the emission angle for the ^{16}O and ^{20}Ne induced TMFs than for the proton induced one, indicating the emission sources of IMFs move faster for the ^{16}O and ^{20}Ne projectile cases than for the proton beam case. In fact results of the moving source analysis suggest that the velocity of the moving source increases as the mass of projectile increases. It was also found that the moving source model always underestimates yields at sideward angles even for the ^{16}O and ^{20}Ne induced TMFs, especially for heavy IMFs ($Z \geq 10$).

To see this underestimation more clearly, we integrated the IMF yields within a

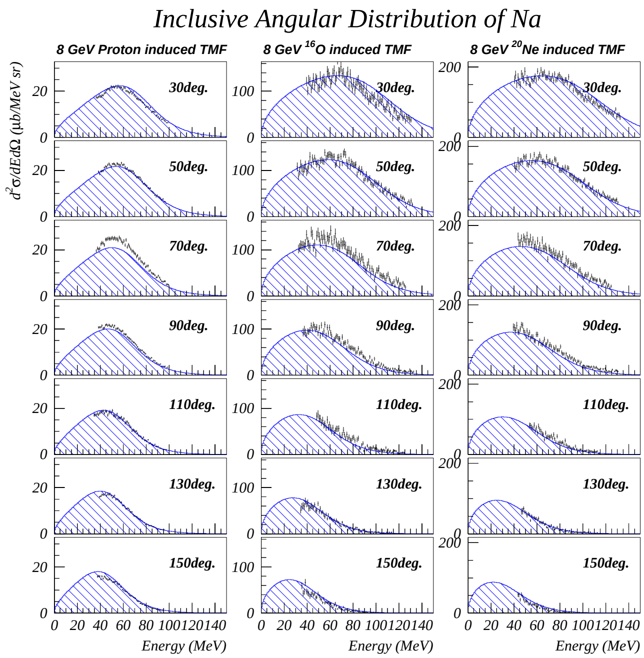

Figure 3: Inclusive angular distribution of Na for 8 GeV proton, 8 GeV ^{16}O and 8 GeV ^{20}Ne induced TMFs.

certain dynamic range in the laboratory system, took a ratio to the integrated fittings and then obtained angular distributions of relative yield to the moving source model for various IMFs of Z$\leq$16. As can be seen in the Fig. 4, 5, and 6 the resultant ratios show clear peaks at around 110° in the laboratory system for the 8 GeV ^{20}Ne and 8 GeV ^{16}O induced TMFs, which is slightly backward compared to the 70° for the proton induced TMFs at the same energy. The maximum value in the ratio evidently increases as a function of a mass of IMF and seems to decrease as a function of a projectile mass for very light IMFs (lighter than F nucleus). This trend is also visible and slightly stronger in the 12 GeV data. These facts probably indicate that though there might be some effect arising from the nuclear density prior to the target multifragmentation, a total beam energy plays a decisive role to govern a reaction dynamics for the IMF emission.

4. Summary and Future Plan

We have studied similarities and differences among the IMF formation processes in various light-projectile induced reactions in the GeV-energy domain. we found there is significant difference in the IMF spectrum shapes and magnitudes but all of their angular distributions show the existence of sideward-peaked components. This fact probably suggests that the IMF formations are mainly dictated by a total energy of the projectile (i.e. the total energy scaling exists).

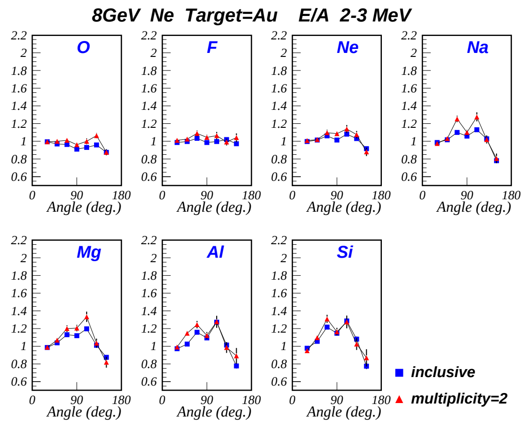

Figure 4: Angular distributions of relative yield to moving source fit for 8 GeV ^{20}Ne induced TMF on gold target.

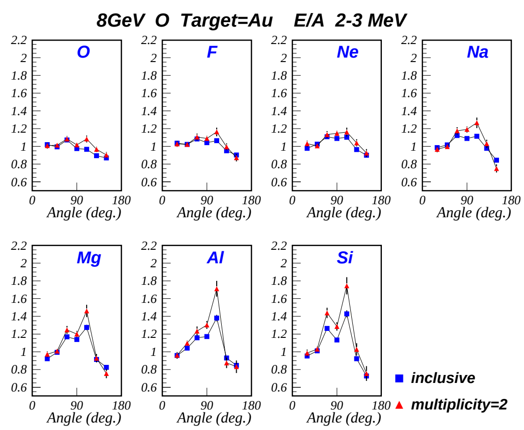

Figure 5: Angular distributions of relative yield to moving source fit for 8 GeV ^{16}O induced TMF on gold target.

As for a near future plan, we would like to finalize our analysis on ^{28}Si induced multifragmentation at 8.12 GeV and 22.4 GeV, and to compare their results with those from light-ion induced multifragmentation in details. We also want to extract "isotope temperatures" for all light heavy-ion induced TMFs in order to investigate a possible density effect in an early stage of the nuclear collision.

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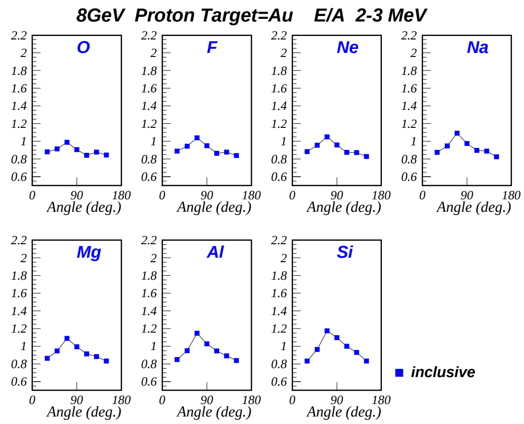

Figure 6: Angular distributions of relative yield to moving source fit for 8 GeV proton induced TMF on gold target.

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