Energy Dependence of Intermediate-Mass Fragment Angular-Distribution: Probing Nuclear Liquid-Gas Phase Transition

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1 Introduction

For a last couple of decades a nuclear multifragmentation reaction has been intensively studied in order to explore its possible link to a nuclear liquid-gas phase transition and the nuclear equation of state. The study on nuclear fragmentation reactions first attracted one's attention as early as in the 1950s as a result of radiochemical measurements performed mainly with GeV-energy Hadron beams [1]. One had to wait, however, until the early 1980s, when technologies on detectors and data-acquisitions became well developed, to investigate these complex reactions more exclusively. About that time, medium energy (below 100 MeV/nucleon) heavy ion accelerator also became available. Since then nuclear multifragmentations have been mainly studied by mean of heavy-ion induced reactions [2], but a few groups around the world, including our group, realized that there are several good reasons to utilize a GeV-energy light-projectile induced reaction instead. For instance (i) not like in heavy-ion induced reactions the intermediate-mass-fragments (IMFs) can originate only from the target nucleus in light-projectile induced reactions. Therefore one can perform a kinematically clean and relatively simple-to-analyze experiment. (ii) The low center-of-mass velocity allows us to measure both angular distribution and angular correlation of IMFs with high precision. From those information we should be able to address geometrical feature of multifragmentation. (iii) Essentially there is no compression during a formation of hot nuclear system. Therefore the light-projectile induced reaction would provide information complementary to the one from heavy ion collisions.

After several attempts performed both by the IUCF group, using 5.0-14.6 GeV/c proton and π^- beams, and 8.0 GeV/c anti-proton and π^- beams together with the Indiana Silicon Sphere (ISiS) 4π array [3] at AGS, and by our group, using 8 and 12 GeV proton beams together with the Bragg Curve Counter (BCC) array [4] at KEK (KEK-PS E337/E393), it became rather clear that nuclear liquid-gas phase transition does occur in the GeV-energy light-projectile induced multifragmentation reactions [5, 6, 7]. 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. It should be noted that according to a recent theoretical calculation based on both transport model and non-equilibrium percolation model [8], sideward peaking angular distribution might arise from a "doughnut shape" of the IMF emission source.

Here we propose to continue investigations on the mechanism of the incident energy dependence of the IMF angular distribution and to construct a new generation 4π charged particle counter array suitable to use at "multi-purpose high momentum beam line" at JHF-K for such investigations.

2 Proposed Detector Array

In the KEK-PS E337/E393 experiments we used a 37 Bragg Curve Counter Array as shown in Fig. 1. The 12 BCCs were placed in the horizontal plane in order to measure mainly angular distributions of the IMFs and the other 25 were set in upper hemisphere in order to measure the IMF multiplicity. They provided an angular coverage of θ_{lab}= 30°-150° in 20° steps and a solid angle of about 20% of 4π. The technical details of our BCCs have been published in Ref. [4]. The data were taken under the minimum bias condition; i.e. a sum of 37 self-triggers from individual BCC. Owing to their insensitive to the high-rate background radiation associated with the high-intensity primary beam, i.e. the beam halo, we could have used up to a few$\times 10^9$ /sec proton primary beams from KEK-PS for E337/E393 experiments to accumulate semi-inclusive data with high statistics [9, 10].

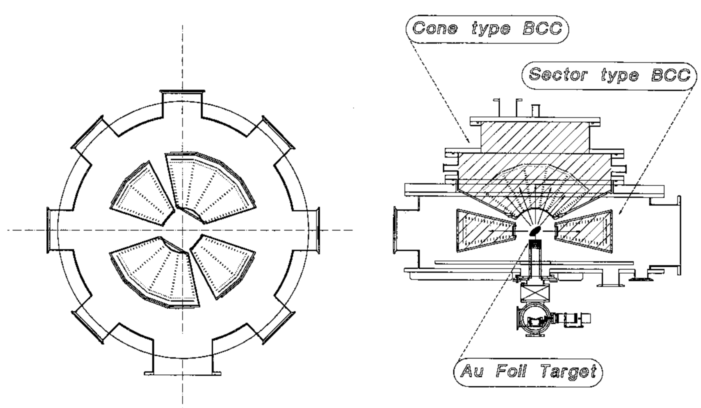

Figure 1: Experimental setup used for KEK − PS E337/E393.

We have also applied the same Bragg Curve Counter Array to measurements on target multifragmentations (TMFs) induced by relativistic light heavy-ions. In these measurements we intended to directly compare the proton and the relativistic heavy-ion induced TMFs at the same projectile energy using the same experimental apparatus. We have performed a series of experiments with ^{16}O, ^{20}Ne and ^{28}Si beams of 8 GeV, ^{20}Ne beams of 12 GeV, and ^{28}Si beams of 22.4 GeV with intensities of about several 10^8 particles/sec. accelerated by the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) [11, 12]. From this comparison we concluded that although there is some difference in their energy spectrum shapes and magnitudes for the IMFs but all of TMFs show the existence of sideward-peaked components, indicating the intermediate-mass fragment formations are mainly dictated by a total energy of the projectile (i.e. the total energy scaling exists).

From our experiences we believe it is possible to re-use the existing Bragg Curve Counter Array with minimum modification for extending the investigations on the mechanism of the incident energy dependence of the IMF angular distribution to higher energy primary proton beams, like 30 GeV, as far as a beam intensity is order of a few$\times 10^9$ /spill. In order to perform a systematic study on the incident energy dependence of TMFs without interfering with other experiments at JHF-K, however, we should consider the possibility to use variable-energy secondary proton and/or pion beams of several$\times 10^7$ /spill or less. Since the existing counter array covers only 20 % of 4π in solid angle it is not so easy to accumulate data of high IMF multiplicity events with such low intensity beams. Therefore we should construct a real 4π charged particle counter array with very low thresholds, good energy resolution, and large segmentation (fine granularity). We are still seeking for several candidates for a new counter array, but it would be more like a combination of our BCC and ISiS at the end. It should be noted that reliable IMF angular distributions can be obtained only by using the counter array which can hold on the high background environment, like our BCC. The ISiS alone is not suitable for our purpose. Nevertheless, we consider a collaboration with the ISiS group as a one of possibilities.

3 Required Beam

At a first stage we would like to use 30 GeV primary proton beam of several$\times 10^9$ /spill (assuming 1 sec of duration in 3 sec cycle) at a proposed high momentum B line. Even though our existing BCC system could have been used at the P1 and EP1B primary beam lines at KEK-PS, where about 10^6 /spill background was counted by a CsI(Tl) scintillation counter of $50\times 50\times 20$ cm^3 at the point of 100 mm apart from the beam, beam halo should be less than that of current KEK-PS primary beam line. The acceptable beam spot size is also less than 10 mm in diameter at the target position.

At a second stage we would like to place a 2 % loss production target at the "1st Split" to produce variable energy secondary proton beams of several$\times 10^7$ /spill and pion beams of several$\times 10^6$ /spill. The energy range we would like to cover is from 4 to 14 GeV. According to the estimation carried out by Yokkaichi using the Sanford-Wang formula [13] together with realistic beam-line parameters (incident energy 30 GeV, primary intensity 1×10^{14} protons/pulse, production angle 4.7°, acceptance 0.2 msr. . .%, target loss 2 %, and length of beam line 120 m) these intensities are easily accessible. Again the beam spot size should be less than 10 mm in diameter at the final focus.

Before closing this section we would like to stress that if we can use variable energy heavy-ion beams for the nuclear multifragmentation experiments in the future we certainly can explore the nature of high density nuclear matter.

4 Requirements for the beam line

Since we would like to investigate the evolution of IMF angular distribution as a function of incident beam energy, it is essential to obtain variable-energy beams of various hadrons without interfering with any other experiment. Therefore we urge that the "multi-purpose high momentum beam line" at JHF-K should be constructed so that one could place a production target of about 2 % loss at the "1st Split" for producing high momentum secondary beams.

5 Summary of Proposed Measurements

In order to investigate mainly the mechanism of the incident energy dependence of the IMF angular distribution, following experimental program would be submitted as a formal proposal in the future:

Beam	Energy	Time	Intensity
Proton	30 GeV	21 shifts	Primary –several$\times 10^9$ /spill
	4 GeV	30 shifts	Secondary –several$\times 10^7$ /spill
	6 GeV	30 shifts	Secondary
	10 GeV	30 shifts	Secondary
	14 GeV	30 shifts	Secondary
π^-	10 GeV	90 shifts	Secondary –several$\times 10^6$ /spill
	14 GeV	90 shifts	Secondary

We will use ^{197}Au target of about 1 mgcm^2. With primary beams we would use existing BCC array with minor modification, while with secondary beams we would like to use a new 4π charged particle counter array. Required beam times are estimated assuming that IMF production cross sections are as same as E337 case.

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