Measurement of Fragmentation Products including Angular Distributions for 3, 5, and 10 GeV/A C and Si on several nuclear targets at the AGS

L. Pinsky[*][1], *G. Battistoni*[5], *F. Broggi*[5], *M. Brugger*[2], *M. Campanella*[5], *M. Carboni*[6], *F. Cerutti*[2], *P. Colleoni*[5], *M. Crystl*[15], *C. D'Ambrosio*[6], *N. Elkhayari*[1], *A. Empl*[1], *A. Fassó*[3], *A. Ferrari*[2], *A. Ferrari*[6], *E. Gadioli*[5], *M. V. Garzelli*[5], *S. Geutersloh*[14], *L. Heilbronn*[14], *M. Lantz*[13], *M. Lebourgeois*[1], *K. T. Lee*[11], *G. Lukasik*[2], *A. Mairani*[5], *A. Margiotta*[9], *B. Mayes*[1], *J. Miller*[14], *M. C. Morone*[8], *A. Mostacci*[6], *S. Muraro*[5], *K. Parodi*[10], *V. Patera*[6], *M. Pelliccioni*[6], *J. Ranft*[4], *B. Reddell*[1], *S. Roesler*[2], *S. Rollet*[12], *P. R. Sala*[5], *L. Sarchiapone*[7], *M. Sioli*[1], *G. Smirnov*[2], *F. Sommerer*[1], *C. Theis*[2], *S. Trovati*[2], *R. Villari*[6], *H. Vinke*[2], *V. Vlachoudis*[2], *J. Vollaire*[3], *T. Wilson*[11], *N. Zapp*[11], *C. Zeitlin*[14]

[1]University of Houston, Houston, Texas USA
[2]CERN, Geneva, Switzerland
[3]SLAC, Palo Alto, California, USA
[4]Universität Siegen, Germany
[5]INFN & Univ. Milano, Italy
[6]INFN Lab. Naz. Frascati, Italy
[7]INFN, Lab. Naz. Legnaro, Italy
[8]Univ. Roma II, Italy
[9]INFN & Univ. Bologna, Italy
[10]HIT, Heidelberg, Germany
[11]NASA, Johnson Space Center, Houston, Texas, USA
[12]ARC Seibersdorf Research, Austria
[13]Chalmers Univ., Sweden
[14]Space Science Laboratory, LBNL, Berkeley, California, USA
[15]NASA Marshall Space Flight Center, Huntsville, Alabama, USA

Abstract

Motivated by differences in the predicted fragmentation of heavy ions at energies around 5 GeV/A as employed in the event generators used by the FLUKA Monte Carlo Code [1], a set of measurements were carried out at the AGS facility at the Brookhaven National Laboratory to determine as much information as possible about the cross sections to allow harmonization of those event generators for these incident lab energies. The FLUKA Code employs the RQMD event generator of Sorge [2] for heavy ion interactions starting at 100 MeV/A and extending into the region around 5 GeV/A. Above those energies the DPMJET code of Ranft and Roesler [3] is typically employed to simulate such interactions. The detailed predictions of these event generators had some disagreement in the vicinity of this crossover energy and in order to tune these codes to be in closer harmony at the transition, and of course to be simulating nature as closely as possible, data were taken at 3, 5 and 10 GeV/A with beams of Fe, Si and C on a variety of targets including C, Al. Fe and Cu. The Fe data have not been fully analyzed, but results from the C and Si beams are available and the forward fragment spectrum along with a measurement

*pinsky@uh.edu

of the charged particle angular distribution in a set of Si strip detectors out to about 45 degrees in the lab are available. These include sufficient statistics to provide the charged particle distributions as a function of the major projectile fragment. The detectors used in this measurement were based on what were reasonably available to us, and as such were limited in capability, and required separate data acquisition systems. Nevertheless, spectra were obtained that should be sufficient to enable the harmonization of the event generator codes at the crossover energy. This paper discusses only the experimental results and not the impact of those results on the FLUKA code.

1 Introduction

The need to incorporate heavy ion nuclear interactions over a very wide range of lab energies from threshold to ultra relativistic cosmic ray energies necessitates employing a number of different event generators, each of which are tuned for the energy range of their most accurate applicability. The FLUKA Monte Carlo code [1] employs 3 such event generators and necessarily faces the issue of transitioning from one to the other seamlessly as a function of incident lab energy. The measurements reported here were motivated by the need to harmonize the outputs of the two event generators, RQMD [2] and DPMJET [3] in the vicinity of incident lab energies of 5 GeV/A. This harmonization, of course, needs to occur not only between the codes, but at as close a reproduction of nature as possible. Because of the interest of NASA in simulating the space radiation environment for the assessment of radiation risks to astronauts and electronics as well as to other potentially radio-sensitive components of spacecraft, NASA funded the beam time and related analysis effort with respect to these measurement. However, due to budget constraints, only modest funds were available to provide for instrumentation. As such, the collaboration that was formed between groups at the University of Houston (UH), the Space Science Laboratory at the Lawrence Berkeley National Laboratory (LBNL), and the NASA Marshall Space Flight Center (MSFC) had to base the detectors and supporting data acquisition electronics on mostly existing equipment. That lead to a number of compromises, some of which have impacted the length of the analysis effort.

Data were taken in the summer of 2005 at the Alternating Gradient Synchrotron (AGS) fixed target facility at the Brookhaven National Laboratory (BNL) with three incident particle types, ^{56}Fe, ^{14}Si and ^{12}C, and for each of these particle types three incident lab energies were taken at approximately 3, 5 and 10 GeV/A. Unfortunately the Fe beams were heavily contaminated due to material inadvertently being left in the upstream beam line, a condition which has complicated the analysis to the extent that results for only the Si and C beams will be reported here. Separate reports including the results from the forward silicon detectors of the major forward fragments have been reported elsewhere. [4]

2 Experimental Setup

Figure 1 shows the experimental setup. The detectors were separated into three basic units, which were provided by separate groups and each of which was read out with separate data acquisition (DAQ) systems. The first group of detectors were those deployed along the beam line by the LBNL group. They consisted of small monolithic Si detectors and scintillators as shown. The LBNL group also deployed a number of neutron detectors, but the analysis of the data from those detectors will not be reported here. The Si detectors were all centered on the nominal beam line both vertically and horizontally, and were located as follows. 1) The primary trigger, TP, which was a 1 cm plastic scintillator with a thickness of 3 mm located 78 cm from the downstream 1 mm thick Al exit window from the beam transport vacuum pipe, and several cm in front of the targets. 2) A 3 mm thin, 3 cm by 3 cm plastic scintillator, Paddle 2, placed immediately after the target, and read out by a single 1 inch photo-multiplier tube to measure the integrated pulse height of the particles exiting the target. 3) A fully depleted 300 micron ORTEC T mount silicon detector, referred to as Si1, with an active area of 450 mm^2 (radius of 12 mm), placed immediately behind S2 . It was used to give a precise measure the energy loss, dE, of the particles ex-

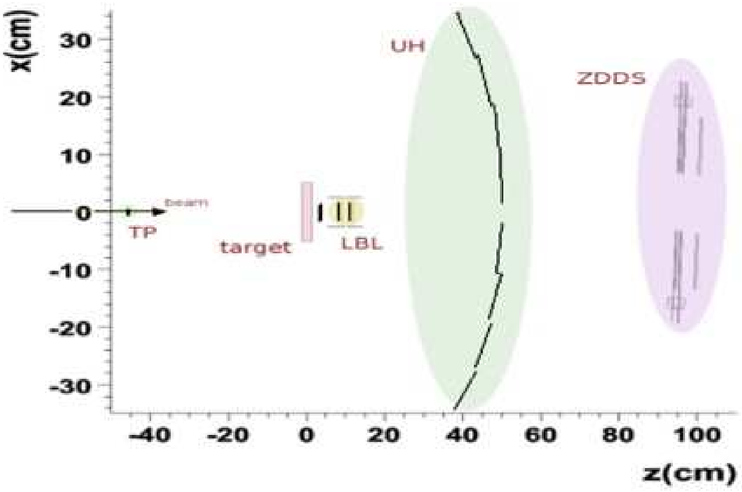

Fig. 1: A vertical projection of the general detector layout with respect to the beam line.

iting the target, principally to identify fragment charges. The dynamic range of the associated readout electronics was chosen to give a good resolution down to roughly half the charge of the beam particle. 4) A second silicon detector identical to Si1 and referred to as Si2, was sometimes placed a few cm downstream of Si1. 5) Finally, Paddle 3 was another 3 mm thick 3 cm by 3 cm scintillator placed behind the ZDDS.

The UH group supplied an array of Si-strip detectors (SSD's), which were deployed in cards of 144 channel 0.5 mm wide 50 mm high strips. Four of these 72 mm wide SSD cards were placed in an arc to both beam right and beam left roughly 50 cm downstream of the target subtending lab scattering angles from about 3 degrees out to around 45 degrees. The supporting readout electronics were designed only to record hits above an externally supplied constant threshold and provided no other information about detected particles such as the amount of charge collected.

No attempt was made to trigger on only interacting events, rather, the detector responses were recorded for all events that satisfied the input beam trigger of an incident particle within the simple discriminator cuts used to identify beam-like particles. Such a beam trigger caused a readout of the LBL beam line counters as well as the UH SSDs. Combinations of clock counters and beam spill counters were employed to provide the information needed to synchronize the different DAQ streams. The target thicknesses were all selected to be essentially half an interaction-length.

The MSFC group provided the Zero-Degree Detector System (ZDDS) instrument, which was originally designed as part of the ATIC Balloon-borne Cosmic Ray experiment. [5] It consisted of eight arrays of dual layer 8 cm by 8 cm square modules, each of which had 64 square 1 cm by 1 cm Si detector pads. The arrays were arranged in a square configuration with, contrary to its name, an open 8 cm by 8 cm hole in the center to allow beam particles to pass. [6] The ZDDS was setup 100 cm downstream of the target, giving it a minimum scattering angle acceptance of about 2.3 degrees, or a fraction of a degree less than the minimum coverage of the UH SSDs . The ZDDS readout allowed for the digitization of the charge collected by each 1 cm by 1 cm pad. The ZDDS also included its own trigger scintillator, which was located behind the Si arrays and masked their active areas. Because the ZDDS had been designed for very low balloon experiment cosmic ray data rates, it was only able to sustain a much smaller data rate than the other 2 systems. As such, the ZDDS was triggered whenever it was not busy and had a coincidence between the LBL-generated beam trigger and its internal scintillator trigger. This yielded a participation rate between 1 and 10used to measure the efficiency for the inner cards of the UH SSDs, which overlapped their acceptance as viewed from the target.

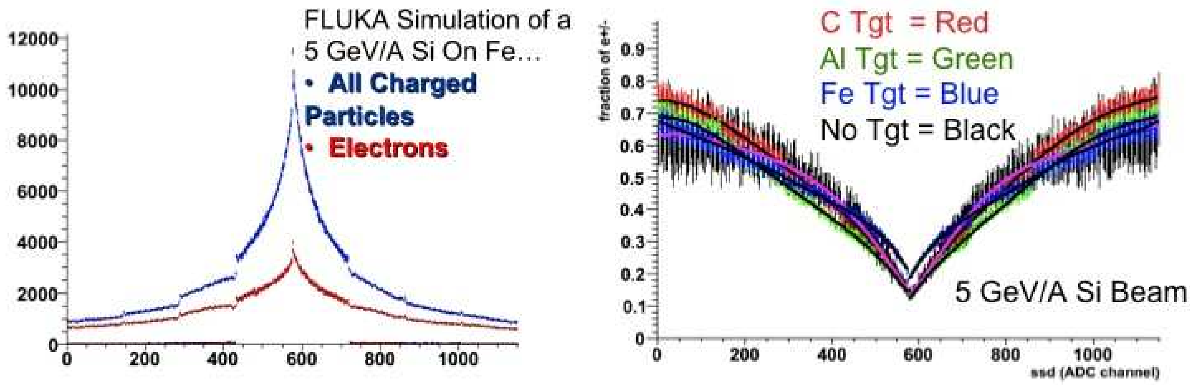

Fig. 2: (Left) The fully reconstructed FLUKA simulation of the UH SSDs for a 5 GeV/A Si beam incident on an Fe target. (Right) The fraction of the total events seen in the UH SSDs that are due to delta-ray electrons for each of the 3 targets as well as for the no-target run as a function of channel number. Note that the majority of the contamination is coming from the delta-rays produced in the air.

3 Analysis Details

Considerable effort was expended during the initial portion of the analysis effort to correlate the events in each of the 3 separate DAQs. However, were were able finally to make the correlations and proceed to deal with the finer issues within the analysis. The greatest challenge we faced was dealing with the background from the very energetic delta-ray electrons produced by the primary ions and fragments to the very high energies encountered. The lack of any particle ID information in the SSDs and the modest coverage coupled with the very low data rate in the ZDDS forced us to rely on FLUKA simulations to estimate the magnitudes and distribution of the delta-rays within the data. Fortunately, the physics of the delta-ray production is very reliable in the FLUKA code, a fact that we were able to verify from analysis of our no-target runs. Figure 2 shows the FLUKA predictions for the delta-ray contributions with respect to the total charged Particles detected distribution in the UH SSDs.

Figure 3 shows the correlations between the sum of Si1 and Si2 detectors with respect to the paddle 2 scintillator for the Si beam at 5 GeV/A with a C target. The separation of the primary fragments is reasonable down to a charge of roughly half of that of the Si primary. Tables of cross sections for production of these major fragments have been published elsewhere. [4]

4 Results

The ultimate goal of this measurement is to provide guidance in the tuning of the outputs from the two event generators in the general crossover region around 5 GeV/A. Figure 4 shows the current FLUKA simulation of the Si beam (at a beam energy of 5.4 GeV/A) incident on an Fe target for each of the two event generators, RQMD and DPMJET, separately. Note that there is general agreement at the greater angles between the event generators, but RQMD shows a clear enhancement at forward angles with respect to DPMJET. This enhancement also translates into a general overall multiplicity difference between the two event generators.

Future efforts will be undertaken to try and harmonize these two event generators with the actual measurements, examples of which are given in the following figures.

Figures 5 and 6 show examples of the results of the measurements themselves. Figure 5 shows the overall angular distribution for a 5.4 GeV/A Si beam incident on Fe, Al and C targets. The plot is normalized to particles per scattering angle degree per reaction within the acceptance of the UH SSDs.

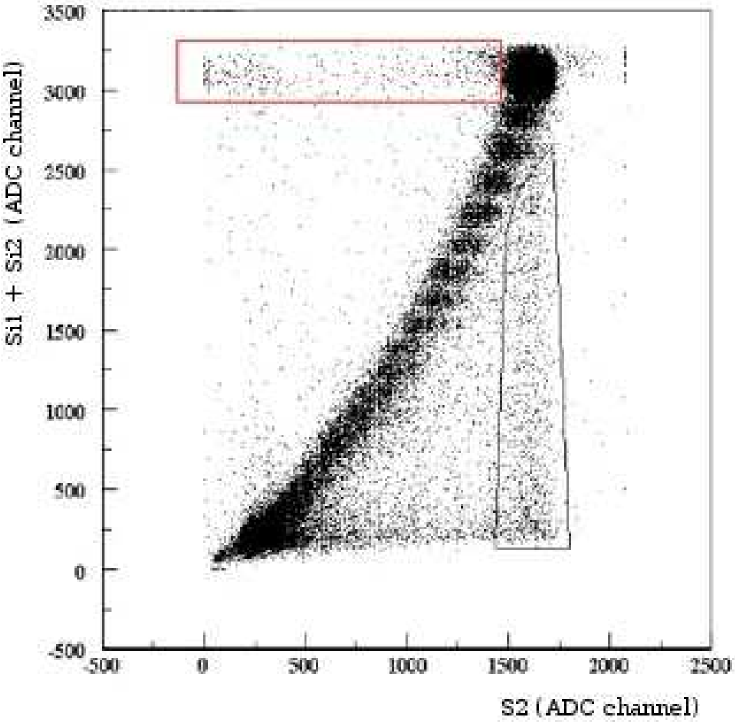

Fig. 3: This figure is a plot of the sum of the Si1 and Si2 detectors with respect to the paddle 2 scintillator yield for the Si beam at 5 GeV/A with a C target. The boxes enclose regions cut out of the analysis and reflect relative inefficiencies and include non-overlapping acceptances.

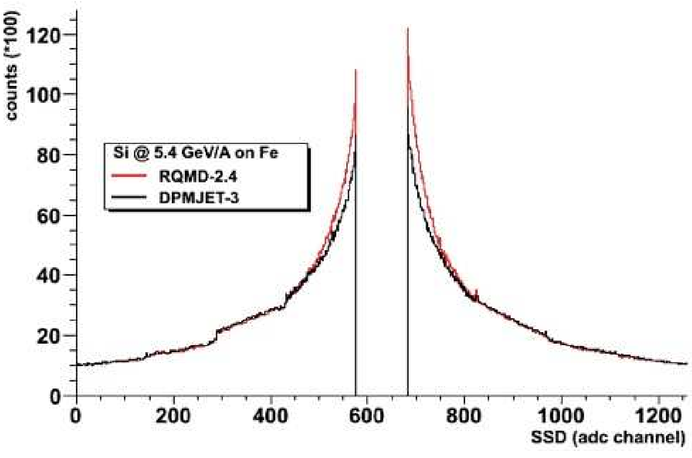

Fig. 4: This figure shows the predictions for hits in the UH SSDs from FLUKA where FLUKA has been constrained in each case to use only one or the other of the two event generators, RQMD or DPMJET. RQMD shows a clear enhancement at the forward angles with respect to DPMJET as well as goo agreement at the larger angles. The overall effect is for RQMD to predict a greater net total multiplicity in the overall angular distribution.

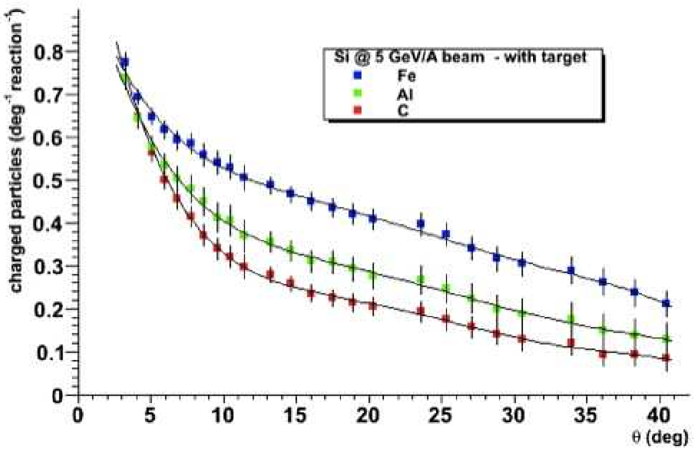

Fig. 5: This figure shows the overall angular distribution for a 5.4 GeV/A Si beam incident on Fe, Al and C targets. The data are given per interacting beam particle per scattering angle degree into the UH SSD acceptance.

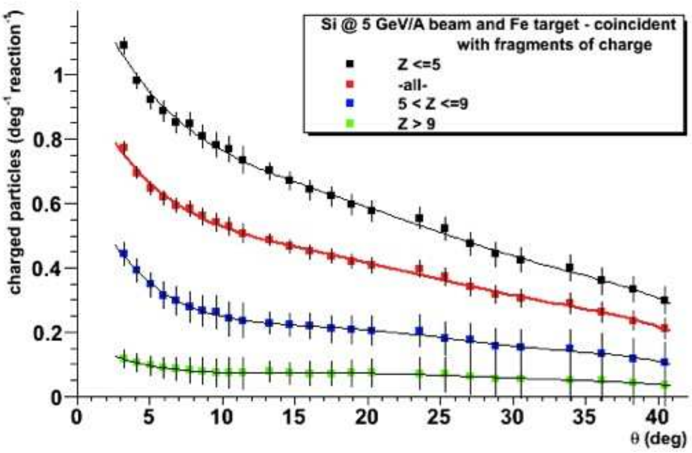

Fig. 6: This figure shows the breakdown of angular distributions for the 5.4 GeV/A Si beam incident on an Fe target where the individual curves correspond to different ranges of primary fragment size.

Because we do not measure anything outside of the acceptance of these detectors, it is not possible to generate total correlated charged particle angular production rates. However, these data should be sufficient to allow for the harmonization of the event generators.

Figure 6 presents a breakdown of the 5.4 GeV/A Si beam on the Fe target angular distributions for subsets of the events that correlate with different primary fragment ranges. These data will provide an even greater demand on the event generators during he harmonization process.

5 Conclusions

The data taken at the AGS was constrained by the available detector systems to the extent that the final data have relatively limited general use. However, they do satisfy the primary goal of the experiment, namely to provide sufficient information to allow the harmonization of the two event generators, RQMD and DPMJET as they are deployed in the FLUKA code in the general crossover region around 5 GeV/A. Efforts to accomplish that task are currently underway.

6 Acknowledgements

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References

[1] A. Fasso, A. Ferrari, J. Ranft, and P.R. Sala, *New Developments in FLUKA Modeling of Hadronic and EM Interactions*, proceedings of SARE-3, KEK-Tsukuba, H. Hirayama ed., May 7 (1997); A. Fasso, A. Ferrari, J. Ranft, and P.R. Sala, in FLUKA: *Status and Prospective for Hadronic Applications*, Proceedings of the Monte Carlo 2000 Conference (Lisbon, October 2000); A. Ferrari and P.R. Sala, *The Physics of High Energy Reactions*, Proceedings of Workshop on Nuclear Reaction Data and Nuclear Reactors Physics, Design and Safety (Trieste, Italy,1996). .

[2] H. Sorge et al., Ann. Phys **192** (1989) 266; H. Sorge *et al.*, Nuclear Physics **A 498** (1989) 567; H. Sorge, Phys. Rev. **C 52** (1995) 3291.

[3] J. Ranft, hep-ph/9911232, (1999); J. Ranft, Phys. Rev. **D 37** (1988) 1842; R. Engel *et al.*, Phys. Rev. **D 55** (1997) 6957; S. Roesler *et al.*, Phys. Rev. **D 57** (1998) 2889; R. Engel *et al.*., Phys. Rev. **D 52** (1995) 1459; R. Engel *et al.*, Phys. Rev. **D 54** (1996) 4244; J. Ranft, Phys. Rev. **D 51** (1995) 64. .

[4] C. Zeitlin, S. Guetersloh, L. Heilbronn and J. Miller, Radiation Protection Dosimetry **116** (2005) 123; C. Zeitlin *et al.*, New J. Phys. **10** (2008) 075002.

[5] J. Chang *et al.*, *An excess of cosmic ray electrons at energies of 300-800 GeV*, Nature **456** (2008) 362-365.

[6] J.H. Adams Jr., M.J. Christl, L. W. Howell and E. Kuznetsov, *The Zero-Degree Detector system for fragmentation studies*, NIM A **579** 1 (2007) 443-336.