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CURRENT AND FUTURE USES OF ACCELERATORS
IN PARTICLE ASTROPHYSICS

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ABSTRACT

Beams of artificially accelerated heavy ions, p , $\bar{p}$, e^- and e^+ currently available at (and planned for) numerous facilities around the world are a valuable resource to the Cosmic Ray community. Such beams have been used to test detector concepts, calibrate balloon-borne and space flight experiments and to measure fundamental nuclear physics parameters necessary for the interpretation of Cosmic Ray data. As new experiments are flown the quality and extent of Cosmic Ray measurements will continue to improve. It will be necessary to increase activity at ground based accelerators in order to test/calibrate these new instruments and to maintain (or possibly improve) our ability to interpret these data. In this area, the newly formed *Transport Collaboration*, supported by NASA, will be providing new nuclear interaction cross section measurements for beams with $Z \leq 58$ and supporting new instrument calibrations at the Lawrence Berkeley Laboratory Bevalac accelerator.

INTRODUCTION

Even before the 1950's, when the elemental composition of Galactic Cosmic Rays (GCR) was just beginning to emerge^{1,2}, it was clear that fundamental nuclear and atomic processes were critically important not only for understanding these energetic particles but also as input to simulations of new cosmic ray instrument designs and to determine corrections for instrument and atmospheric induced backgrounds. Indeed, long before ground based accelerators the "Cosmic Ray Beam" was of critical importance in the study of elementary particles^{3,4}. Today, it is still crucial to understand the nuclear and atomic processes, since this understanding has lagged behind our technical ability to measure the GCR composition. The variety of nuclear/atomic physics information required is quite broad. We need cross sections as a function of energy for the secondary production of pions (which decay into gamma rays, electrons and positrons), muons, neutrinos, anti-protons (and heavier anti-nuclei), alphas, heavy-ions and fission products. For radioactive species we need the mode of decay (beta, alpha, e^- capture, fission), the branching ratio of each mode and its lifetime. We need to know the electron capture and loss cross sections as a function of energy and to understand the ionization energy loss process in solids, liquids and gases.

Most of these processes can be measured in the laboratory and much information can be obtained from sifting through the existing literature. On the one hand, it is perhaps not surprising that researchers have used simplifying approximations to, for example, secondary production cross sections or radioactive decays rather than devoting scarce resources to the considerable effort necessary for such a literature search. On the other hand, data analysis simplifications may have contributed to several "controversies" in

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the literature (e.g. N isotope source abundances^{5,6,7,8}; Constant value for λ_e and/or PLD truncation^{9,10}). As instrumentation improves, resulting in data over an extended energy/charge range with increased precision, such simplifications will limit the reliability of astrophysical conclusions.

Over the last ten years there has been some movement to improve this situation where various members of the community have summarized some of these important data (e.g. Ahlen on ionization energy loss¹¹) or have provided new measurements (e.g. Crawford et al. with electron capture and loss cross sections¹², Binns et al., Guzik et al., Webber et al. with heavy ion fragmentation cross sections^{13,14,15}). In addition, beam time at the Lawrence Berkeley Laboratory (LBL) Bevalac accelerator has been made available for the community to perform such measurements and/or to test and calibrate new instruments.

Recently, a NASA supported collaboration has been formed involving researchers at Goddard Space Flight Center (F. Jones), Louisiana State University (T.G. Guzik), University of California (Berkeley) - Space Science Laboratory (H.J. Crawford), University of Minnesota (C.J. Waddington) and the University of New Mexico (W.R. Webber). The principal goals of this *Transport Collaboration* are to: 1) Perform measurements of important fragmentation cross sections and study cross section systematics, 2) Improve the theoretical development of the Astrophysical context of cosmic rays, 3) Apply the knowledge gained to an extensive interpretation of the available measurements, and 4) Provide supervision of the cosmic ray instrument test/calibration beam time at the LBL Bevalac.

Since the scope of this effort is quite broad, I will focus the discussion on three topics; available accelerator resources, a summary of the current fragmentation cross section database, and a brief description of the new measurements planned by the *Transport Collaboration*.

ACCELERATOR RESOURCES

The new space missions discussed during this workshop, which hopefully will be carried out over the next decade, will push our ability to measure the charged particle radiation to higher energies and charges as well as improve the precision in determining the charge state and isotopic composition. The following generation of instrumentation will presumably move these boundaries even further. Such experiments will need to fly proven technology and have available accurate calibrations. At accelerators the charged particle beam energy, composition and trajectory can be precisely controlled allowing new detector concepts to be thoroughly tested and new flight instruments to be calibrated. For the last ~14 years about 150 to 200 hours of beam time per year has been available at the LBL Bevalac for this purpose, and the cosmic ray community has grown to depend upon this service. The Bevalac, however, does have a limited lifetime and capability, such that the community should examine the possibility of establishing similar programs at other accelerators.

A number of accelerators, such as FERMILAB, BNL, SLAC, CERN and KEK, around the world can provide beams of protons, anti-protons, neutrons, pions, electrons, positrons, and muons from a few MeV or 10's of MeV up to 1 TeV.¹⁶ Some of these facilities have "Test Beam" areas where a detector can be exposed to a mixture of hadrons and

leptons. Such exposures may be ideal for experiments, such as POEMS and/or WIZARD, to test particle discrimination capability. There are also areas where relatively pure beams could be obtained for precise instrument calibrations. The principal objective of these accelerators, however, is for the study of elementary particle physics and as a result, the newest and highest energy beams are part of collider systems. Thus, fixed target facilities, necessary for the "Cosmic Ray" work, may not be available for all beam species and energies.

Figure 1: Current, planned and proposed heavy ion accelerator capabilities.

The beams possible at various heavy ion accelerators around the world are indicated in Figure 1. Machines which are currently available are shown by the diagonal hashing and the filled squares. Planned extensions or proposed machines are indicated by the speckled regions and the open triangles. For light ions ($Z_p < 8$) and low energy ($E_p < 200$ MeV/nucleon) various small cyclotrons are available. Other accelerators such as SATURNE, Dubna and BNL can provide beams up to ^{28}Si - ^{40}Ar . CERN has the highest energies currently available and can deliver precisely ^{16}O and ^{32}S at 60 and 200 GeV/nucleon. For higher charges the mainstay is still the LBL-Bevalac, though the highest energies attainable are somewhat less than that for the lower charges as the ultra-heavies are difficult to fully strip of electrons prior to acceleration. Shortly, the Bevalac will be joined by a machine with roughly the same capability located at GSI (Darmstadt). The SIS is expected to be online by next year and capable of accelerating up to Uranium with a maximum energy somewhat less than the Bevalac. By about 1992 the Booster ring at the BNL-AGS will be completed and this should allow that machine to accelerate nuclei at least up to Gold and possibly heavier. Also in the same time frame CERN should have completed its Lead beam. Beyond this is the proposed Relativistic Heavy Ion Collider (RHIC) and details about

this machine are still being developed. It is expected, however, that RHIC may be operational with light ions up to 100 GeV/nucleon by the middle 1990's and eventually move up to heavier beams. It is uncertain, however, whether RHIC will have a fixed target beam capability, without which its usefulness for measurements of fragmentation cross sections or instrument tests at high energy is questionable.

It appears that the capability of currently available and planned ground based accelerators is sufficient to enable tests/calibrations and measurements of support data for most of the cosmic ray instrumentation planned for the next decade. While the LBL-Bevalac has been reasonably tolerant of the cosmic ray community using beam time, for what some might consider secondary (or worse) science objectives, it may now be advisable to be determined whether and how similar arrangements might be established at other accelerators.

CROSS SECTION MEASUREMENTS

Being able to unfold the secondary production of cosmic ray species as a function of energy in order to reveal the underlying composition of the source or to study the propagation of GCR in interstellar space is a requirement for essentially all cosmic ray investigations. Such deconvolutions require an accurate knowledge of production cross sections over broad energy, charge and mass ranges. Available measurements, however, are sparse at best and, in many cases, conflict or have large errors. In addition, it will never be possible to measure all the cross sections that are needed, requiring continued reliance on formulae, such as have been developed in the past,^{15,17,18,19} to predict cross section values. To produce reliable predictions a sufficient understanding of the nuclear interaction process needs to be developed and new cross section measurements as a function of beam, target species and energy are necessary to improve this understanding. In this section, I will discuss the *Transport Collaboration's* effort in this area for species with $Z > 3$ and refer the reader to a number of other references for discussions of the secondary production of anti-protons,²⁰ positrons,^{21,22} and light isotopes.^{23,24}

a. The Cross Section Database

Recently a database of measured cross sections compiled from over 100 references has been established. This database, described by Crawford et al.,²⁵ contains cross sections from proton-induced as well as heavy ion nuclear interactions and can be used for investigations of cross section systematics, for checking the accuracy of any cross section prediction routines or for developing the nuclear interaction parameters needed as input to propagation calculations. Part of the *Transport Collaboration* effort is to maintain this database (e.g. correcting errors, providing public access) and to update it as new measurements become available.

Figure 2 illustrates the current contents of the database and, thus, indicates the extent of available measurements. The format of the figure is in terms of fragment charge (Z_f) versus beam energy (E_b) and the darkness of a square is proportional to the number of measurements in the database. One should note that the cross

sections are actually functions of the beam (Z_b , A_b , E_b), target (Z_t , A_t) and fragment (Z_f , A_f), so the number of values attributed to a single cell in Figure 2 may actually be for measurements involving different beams and/or targets. Figure 3 shows a restricted subset of the database where the target is ^1H (i.e. p-induced, CH_2 - C subtraction, or actual H target) and the experiment reports values for fragment isotopes with an uncertainty less than 20%.

From the figures we can see that there appear to be fragments which are well measured and, conversely, vast regions with little or no data. Before the age of heavy ion accelerators, cross section measurements were accomplished by irradiating a target with high energy protons and then analyzing that target using mass spectrographic or radioactive decay counting methods (see review by

Figure 2: Fragmentation cross sections contained within the database.

Raisbeck and Yiou²⁶ and references in Garcia-Munoz et al.¹⁰). As a result, cross sections for the production of radioactive fragments such as ^7Be , ^{10}Be , ^{22}Na , ^{26}Al , and unstable isotopes of Sc - Ni account for much of the data (including those at energies around 20 to 30 GeV/nucleon). In addition, the intense interest by the cosmic ray community in using ^{10}Be as a cosmic ray chronometer resulted in the Be isotopes being well studied during the first half of the 1970's.

By 1975 the LBL Bevalac was accelerating light ions and direct measurements of the fragmentation of ^{12}C and ^{16}O started to become available.²⁷ This technique has several advantages. First, the incident beam can be selected to be a particular isotope. Second, the resulting fragments are observed directly and include stable as

well as unstable species and, finally, the measured interaction is similar to the process occurring in interstellar space. In the intervening years, the Bevalac capability has improved such that now isotopes of Uranium can be accelerated. However, the Bevalac is devoted mainly to Nuclear Physics investigations which often do not result in cross section measurements of direct use to cosmic ray studies. As a result, there has been little improvement in the database until recently. Over the last several years Webber published values for a variety of fragment isotopes produced by beams from ^{12}C to ^{58}Ni at 600 MeV/nucleon¹⁵ and Waddington, with colleagues, have been providing charge changing measurements of the ultra-heavy ($Z > 30$) elements.^{18,19} It is mainly because of work by these and other members of the cosmic ray community that our knowledge of fragmentation cross section results have been improved.

There remains, however, significant areas where cross section measurements are needed. For example, little data is available for

Figure 3. Restricted subset of database cross section measurements.

He and heavier targets. The He cross sections are needed for GCR propagation in a realistic interstellar media and the cross sections on heavier targets are necessary for producing a reliable scaling method that could be used in correcting atmospheric or instrument induced backgrounds. Further, the fragmentation cross sections can be energy dependent below a few GeV/nucleon. The very highest energies (< 10 GeV/nucleon) also need further investigation in order to determine whether the cross sections are indeed independent of energy.²⁸ In addition, beams commonly run at heavy ion accelerators may not be the isotope of interest for cosmic ray work. For example,

Argon fragmentation cross sections are typically for ^{40}Ar , rather than for the isotopes ^{36}Ar and ^{38}Ar which may dominate the cosmic ray Argon composition. Finally, no measurements in the ultra-heavy region are yet available where the isotopic composition of the secondary fragments are identified. Such measurements are important even if the cosmic ray instrument only has elemental resolution in order to correctly predict the GCR secondary component due to radioactive species. It is expected that the new measurements to be performed by the *Transport Collaboration* over the next several years will address some of these deficiencies and lead to a significant improvement in our knowledge of heavy ion fragmentation cross sections

b. Planned Cross Section Measurements

One of the immediate goals of the *Transport Collaboration* is to provide new fragmentation cross section measurements which will aid in the interpretation of Ne to Fe GCR data. These measurements will take place at the Lawrence Berkeley Laboratory (LBL) Bevalac using the Heavy Ion Spectrometer System (HISS) facility.²⁹ In particular, we have applied for and received 300 hours of accelerator beam time (independent of the "NASA Calibration" time) which we will use to measure ^{32}S , ^{36}Ar , ^{40}Ca and ^{56}Fe fragmentation in liquid H_2 and He targets within the energy range ~ 400 MeV/nucleon to 1.6 GeV/nucleon. Our first run, currently scheduled for Nov/Dec 1989, will concentrate on the low energy ($\sim 400 - 900$ MeV/n) measurements and the high energy data ($\sim 900 - 1600$ MeV/n) will be taken during our second run planned for May/June 1990. After the successful completion of these runs it is our intention to move on to higher charges and measure cross sections for fragments of ^{90}Zr and/or ^{140}Ce beams.

The HISS facility configuration to be used during the Fall, 1989 runs is shown in Figure 4. The beam enters the facility from the left hand side and passes through a series of detectors (TOF0, V1, UDEW, DT1, FISH, V2, E) which define the incoming beam geometry and characteristics. The beam strikes the target (TGT) and the trajectory of any fragment produced is measured (DT2) prior to entering the field of the large aperture superconducting HISS magnet. The fragments are separated by the magnetic field and measured in detectors downstream of the magnet to determine the particles velocity, charge and final trajectory. From these measurements the

Figure 4: HISS facility configuration for fall 1989 runs.

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particles' rigidity (R) can be determined and the particular isotope identified using the rigidity versus velocity technique. Depending upon the charge and energy range to be studied, the detectors used downstream will be somewhat different. For the Fall, 89 runs the downstream trajectory will be measured by the HISS Multiplane Drift Chamber (DC), velocity will be determined by time-of-flight and the charge will be determined from the scintillator signals in the small TOF wall (SW). During the higher energy runs, we will replace the DC with MUSIC, a multiple sampling ionization chamber, which will provide both charge identification and particle tracking and we will use a set of total-internal-reflection Cherenkov counters as the velocity measuring device (VMD). For these configurations we expect rigidity to be determined with an accuracy of $\Delta R/R < 0.01$, the time-of-flight to have an uncertainty of $\Delta t = 50 - 90$ ps and the VMD to have a velocity resolution comparable to a 20 ps resolution in a TOF system.

With this kind of performance, we expect that the uncertainty in a majority of the cross sections measured will be dominated by statistical errors. The liquid H_2 and He targets used will be thin; resulting in only 3% to 5% of the beam interacting. While this is a low yield, the thin targets greatly simplify the data analysis as multiple-scattering, multiple-interactions and energy losses in the target are reduced and the thin-target approximation can be used to determine cross sections. Background in this experiment is dominated by interactions of the beam in the detectors and air gaps, and will be assessed with target out runs and eliminated during data analysis by accepting only those fragments with a trajectory that can be traced to a single interaction point in the target and matched to a single beam particle within the accepted geometry. We will also use a beam veto (BV) detector to identify and eliminate from the data stream most of the uninteracted beam. Using these methods the beam time allocated to us will allow measurements of 1.0 mbarn cross sections to ~10% statistical accuracy.

CONCLUSIONS

Detailed knowledge of a number of nuclear and atomic physics processes and parameters will be needed from the initial development through the data analysis phase of most cosmic ray missions planned for the next several decades. It may be most efficient to establish a "Particle Astrophysics Database", perhaps under the NSSDC, where such support data is collected, maintained and made available to the community. The new missions planned would also greatly benefit by exposing prototype detectors or completed flight instruments to controlled beams of heavy ions, protons, anti-protons, electrons and positrons available at accelerators world wide. Currently, however, only the LBL-Bevalac has an established mechanism where NASA programs can obtain such beam time and developing similar procedures at other accelerators may prove necessary. Our understanding of heavy ion fragmentation continues to improve, but further measurements as a function of beam species, target and energy are still required. The Transport Collaboration has undertaken a program of new measurements using the HISS facility and of investigations into cross section systematics which will be of great importance to the analysis of data from future cosmic ray missions.

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