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Dr. James Ling
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Dear Jim,

This is a final report for NASA grant NAGW-1526 "The Systematic Interpretation of Cosmic Ray Data (The Transport Project)". I am sending two copies of this report also to the NASA Center for AeroSpace Information. However, since this grant originated from headquarters but the Grant and Contracts office has now moved elsewhere, it is not clear to me where additional copies of this report should be sent. I would appreciate it if you could forward the report as appropriate.

The Transport project's primary goals were to 1) Provide measurements of critical fragmentation cross sections, 2) Study the cross section systematics, 3) Improve the galactic cosmic ray propagation methodology, and 4) Use the new cross section measurements to improve the interpretation of cosmic ray data. To accomplish these goals a collaboration was formed consisting of researchers in the US at Louisiana State University (LSU), Lawrence Berkeley Laboratory (LBL), Goddard Space Flight Center (GSFC), the University of Minnesota (UM), New Mexico State University (NMSU), in France at the Centre d'Etudes de Saclay and in Italy at the Universita di Catania. The US institutions, lead by LSU, were responsible for measuring new cross sections using the LBL HISS facility, analysis of these measurements and their application to interpreting cosmic ray data. France developed a liquid hydrogen target that was used in the HISS experiment and participated in the data interpretation. Italy developed a Multifunctional Neutron Spectrometer (MUFFINS) for the HISS runs to measure the energy spectra, angular distributions and multiplicity's of neutrons emitted during the high energy interactions. The Transport Project was originally proposed to NASA during Summer, 1988 and funding began January, 1989. Transport was renewed twice (1991, 1994) and finally concluded at LSU on September, 30, 1997. During the more than 8 years of effort we had two major experiment runs at LBL, obtained data on the interaction of twenty different beams with a liquid hydrogen target, completed the analysis of fifteen of these datasets obtaining 590 new cross section measurements, published nine journal articles as well as eighteen conference proceedings papers, and presented more than thirty conference talks. A complete bibliography is attached here along with reprints of major publications.

The two major experimental runs took place in April 1990 and April 1991 where we used the LBL Bevalac HISS facility and detectors. The experiment apparatus is fully discussed in Albergo et al. (1997) which has been accepted by Radiation Measurements and should appear in press shortly. The experiment setup and analysis techniques are also discussed in Chen et al. (1994) and Knott et al. (1996). Briefly the HISS facility was a large acceptance, magnetic rigidity spectrometer which identified the fragment isotope by measuring the particle charge immediately downstream of the target, the particle rigidity as it passed through the HISS magnetic field and the fragment velocity using a long pathlength Time-of-Flight (ToF) system. The Transport collaborators augmented the available Drift

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Chamber (DC) fragment trajectory detector and ToF system with the MUFFINS neutron detector, a liquid hydrogen (LH_2) target, upstream beam trajectory detectors and a post-target solid state detector (SSD). As MUFFINS and the LH_2 target were contributions from foreign collaborators, only a few of the detectors upstream of the HISS magnet had to be supplied by the US resulting in a very cost effective experiment. With the demise of the LBL Bevalac and disassembly of HISS facility, experiments similar to those performed by Transport would need to be done in Europe at considerably higher expense.
During the two LBL runs we collected data on the interaction of beams from ^{4}He to ^{58}Ni with hydrogen at multiple energies over the range ~400 - 900 MeV/nucleon. Guzik et al. (1994) provides a complete list of the beams measured. Due to the placement of the SSD charge detector immediately downstream of the target (and before the HISS magnet) we were able to identify the fragment charge without needing to determine fragment rigidity or velocity. This had the advantage of allowing us to obtain charge-changing (ΔZ) total and partial cross sections for all beams relatively quickly. The details of the total charge-changing cross section analysis and results can be found in Chen et al. (1994) which reported seventeen new total cross section values. One of our conclusions in this paper is that the total cross sections have an energy dependence which is generally modeled by the formulations of Letaw et al. (1983) or Garcia-Munoz et al. (1987) which provides further evidence that cosmic ray propagation models need to include energy dependent total cross sections in their calculations. Further, it was found that while simple optical model formulae appear to describe the general characteristics of the total charge-changing mass dependence (i.e. cross section increases in proportion to $A^{2/3}$) there are deviations which can be better organized if the beam neutron / proton ratio (or isospin) is taken into account. The result could potentially lead to more accurate total cross section prediction formulae.

We obtained further evidence that beam and fragment isospin are important cross section organizing parameters when we studied the elemental production cross sections as shown in Knott et al. (1996). This paper also includes details on the detectors upstream of the HISS magnet used to define the beam characteristics and identify the fragment charge, as well as on the data analysis techniques, uncertainties, "thick target" corrections and instrument acceptance. Understanding these details was a necessary precursor to the isotope analysis. Charge-changing elemental production cross sections were reported for all beams from ^{22}Ne to ^{58}Ni resulting in 140 new cross section values. One of the surprising conclusions from these results is that even at relatively high energy (400 - 800 MeV/nucleon) the nuclear structure of the fragment appears to affect the cross section value. This was clearly seen in the "odd-even" behavior for particular beams and in enhanced cross sections for fragments which have closed subshells. Further, we found that the general trend of the elemental cross sections for a specific projectile depends most significantly on the isospin ($T_z = 2Z - A$) of the beam. For projectiles with T_z=0, all show a dramatic odd-even variation of the cross sections, while T_z=-2 projectiles, show no odd-even effect and a rapid exponential decrease in cross section with increasing charge-change. The T_z=-1 projectiles show intermediate behavior between the two extremes. Finally, we also determined that for large charge-changes the cross section increases with increasing energy. This paper also included a comparison between the Transport measurements and the predictions of the Silberberg & Tsao (S&T) code and the Webber, Kish and Schrier (WKS) formula, two of the most popular cross section prediction programs used in cosmic ray propagation calculations. Both cross section prediction techniques do reasonably well, but neither consistently meets the 10% accuracy that is desired for use in propagation calculations.

The need for accurate cross section predictions is illustrated in our first publication which discussed isotopic cross section results (Chen et al., 1997). This Astrophysical Journal article reported 160 new mass changing isotopic cross sections from the interaction of ^{22}Ne and ^{26}Mg beams with hydrogen. This paper also documents the technique we developed for identifying the fragment isotopes without requiring detailed tracing of the fragment trajectory through the HISS magnetic field. In essence, this technique uses a uniform field approximation where, to first order, the fragment rigidity and bending angle as measured in the downstream drift chamber trajectory detector are related. Using this technique we can resolve the ^{22}Ne and ^{26}Mg fragment isotopes to about 0.15 - 0.25 u mass resolution. The technique is practical for beams up to ^{40}Ca, but the Cr, Fe and Ni data will require a full rigidity analysis.

The measured ^{22}Ne and ^{26}Mg fragmentation cross sections were applied to the problem of determining source abundances for galactic cosmic ray CNO with a particular emphasis on the ^{18}O / ^{16}O ratio. In models that attempt to explain the established enhancement of ^{22}Ne at the cosmic ray source, the relative abundance of CNO isotopes is also model dependent. In 1992 Gibner et al. published new CNO isotope measurements from a balloon flight payload which, according to their analysis that was based upon WKS cross section predictions, indicated that ^{18}O/^{16}O at the cosmic ray source was enhanced by almost a factor of five above the solar system value. We had observed in our cross section dataset that neutron-rich beams (such as ^{22}Ne and ^{26}Mg) have larger cross sections for the production of neutron-rich fragments (such as ^{18}O) relative to their production from beams such as ^{20}Ne and this might explain the Gibner et al. result. In Chen et al. we compiled the best ^{18}O / ^{16}O measurements available from satellite (ISEE, Voyager, CRRES, Ulysses) and balloon (Gibner et al., Webber et al., 1985) observations and derived the ^{18}O / ^{16}O source ratio for each observation using the WKS and S&T cross section predictions as well as excitation functions derived from the new Transport cross section measurements. When the WKS cross sections were used in the cosmic ray propagation calculations we were able to reproduce the Gibner et al. factor of five enhancement, but with the S&T cross sections a source ratio lower by more that two sigma is obtained. When the measured cross sections were used an intermediate value is derived, and all observations were then consistent with the solar system value. This conclusion illustrates the importance of measured cross section values even for species which do not dominate the measured GCR composition. With the new cosmic ray measurements from the ACE mission becoming available within the next several months, there will very likely be several astrophysical problems which will not be limited by instrument mass resolution or statistics, but rather from interaction cross section uncertainty.

During the last few months we also published final cross section values for the ^{36}Ar and ^{40}Ar beams (Knott et al., 1997) as well as for the ^{40}Ca beams (Chen et al., 1997). In these two papers about 310 new isotopic cross section values were reported. These two papers expanded upon the conclusions in the elemental cross section paper and showed that both the beam and fragment isospin are important parameters in organizing the systematics found in our dataset. For example, fragments with integral isospin (i.e. 0, 1) usually show a odd-even behavior in the cross section magnitude as a function of mass-change that may indicate alpha clustering, while half-integral isospin fragments show a significantly less pronounced odd-even effect or, usually, a steady decrease in cross section with increasing mass change. Further, for beams with $T_Z > 0$ the cross sections for neutron-rich fragments are significantly enhanced relative to those for beams with $T_Z = 0$. These conclusions are surprisingly universal across our dataset. In a recent publication presented at the 25th International Cosmic Ray Conference (Guzik et al., 1997), 387 cross sections from all of our $T_Z = 0$ beams (^{40}Ca, ^{36}Ar, ^{32}S) were plotted as a function of the change in proton number versus the change in neutron number and shown to have consistent cross section magnitudes. This is particularly remarkable since the beams compared cover a wide range of change, mass and energy. However, one should note that it still remains to be determined whether similar systematics can be applied across the full range of cosmic ray species and energies.

Both the Ar and Ca papers compared our cross section measurements with the WKS and S&T predictions and obtained conclusions similar to those in the Ne, Mg and elemental cross section publications. Namely, that both prediction formulations do a reasonable job in predicting the gross features of the cross section systematics, neither formulation appears to be "better" than the other, and that neither is able to predict the cross section details very to the level of accuracy needed. One of the problems with the WKS and S&T codes is that they both use analytic expressions with adjustable parameters to mimic the systematics perceived in a data set of cross section measurements. The assumption is, then, that these analytic expressions reflect the cross section systematics globally and can be used to predict unmeasured values. A better approach may be to use current nuclear physics to provide a new basis for predicting cross sections. To determine if this is a viable alternative we obtained the ISAPACE code and used it to predict the ^{32}S cross sections. ISAPACE is a full nuclear physics model with no adjustable parameters that generates excited prefragments through an intranuclear-cascade calculation and then follows the decay of these prefragments to their final state. While WKS and S&T did a slightly better job in predicting the ^{32}S cross sections, the ISAPACE results were a very close third. Thus, it may be possible to use a code like ISAPACE to develop a more robust cross section prediction method.

Finally, we have also published some initial results from the MUFFINS neutron detector. These results are documented in Tuve' et al. (1997). The MUFFINS detector was able to determine the neutron energy spectra, angular distribution, rapidity and transverse momentum distribution in reactions of ^{40}Ca with H at ~400 MeV/nucleon and ~600 MeV/nucleon. These measurements are useful for understanding the details of the nuclear interaction process and our Italian collaborators will continue to analyze the Transport data for neutron emission results.

Currently, we are in the final stages of preparing the ^{32}S results for publication. We expect to submit this paper to Physical Review C within the next several months. We were, however, not able to fully complete the analysis of all of the Transport measurements. As mentioned above isotopic resolution of fragments from the Cr, Fe and Ni beams is not possible without developing a code to transport particles through the real HISS magnetic field and thus derive an accurate rigidity for each fragment. Developing this code would have been a major undertaking and given the limited resources available, we chose to concentrate on doing the best job possible for the lighter beams. The Helium beam data also needs further analysis. In this case, mass resolution is not a problem, rather with the very light fragment the instrument acceptance downstream of the HISS magnet needs to be carefully modeled. This is not as bad a problem as attempting to develop the trajectory tracing algorithm, but would still require several man-months of effort.

During the last several months of the project we undertook a major effort to archive as much of the documentation and datasets as possible. This archive includes written notes by the principal post-doctoral students working on the project on the analysis techniques and work left to be done. In this way, we hope to preserve much of the "knowledge" of the experiment so that if at some time in the future further funding can be obtained we can attempt to complete the analysis.

Sincerely,

T. Gregory Guzik
Associate Professor - Research

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