GLOBAL REPRESENTATION OF THE CROSS SECTIONS FOR THE PRODUCTION OF FRAGMENTS OF UH NUCLEI

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Abstract

We have examined the fragmentation of relativistic iron, lanthanum, holmium and gold nuclei with energies between 500 and 1200 MeV/n incident on targets of polyethylene, carbon, aluminum, copper and lead. We have determined 1,256 elemental partial cross sections for the production of fragments from interactions in pure target materials. Deduced values have been found for another 417 cross sections in a hydrogen medium. The dependencies of these cross sections on energy, mass and charge have been studied. We have generated a seven parameter global fit to the cross sections for the heavy targets which fits a significant range of the data with a standard deviation of 7%. We have also generated a similar global fit to the cross sections for the hydrogen target which fits a slightly smaller range of the data with a standard deviation of 10%. These representations show that weak factorization can apply, but slightly better fits can be obtained without it. The mean mass losses observed for fragments that have lost a few protons, show that typically three or more neutrons are lost with each proton, producing fragment nuclei that must be highly proton rich, and consequently very unstable.

Introduction: We have reported experimental results from our initial analysis of heavy nuclei fragments produced by interactions in various target materials using the Lawrence Berkeley Laboratories Bevalac particle accelerator, Waddington *et al.* (1987), Binns *et al.* (1989). Here we describe some of the conclusions we can draw from these data after a complete analysis. These data are fully described elsewhere, Cummings *et al.* (1989), Cummings (1989).

We have used the systematics of the partial cross sections for the production of heavy fragments to produce a global fit that allows the prediction of those cross sections that are not measured directly. The main objective of this analysis is to provide a procedure to calculate the cross sections for the production of heavy fragments from charge changing interactions between heavy beam nuclei with energies of at least several hundred MeV/nucleon and various target nuclei.

Experimental: The detector was similar to that described earlier, consisting of an array of 4 multiple parallel plate gas ionization counters and 2 diffusion box Cherenkov counters with Pilot 425 radiators. A multi-wire proportional counter was mounted directly in front of the Cherenkov counters and was used for position determination. For a lanthanum beam at an energy of 1161 MeV/nucleon in the center of the target, the ion chambers and Cherenkov counters had resolutions of 0.31 and 0.12 charge units respectively. We used runs with no target to correct for those interactions produced in the material of the detector.

Determination of Cross Sections: The signals from the Cherenkov and ion chambers were combined to yield an energy independent charge scale. The resulting histograms had distinct peaks, nearly Gaussian in shape, corresponding to each charge from that of the beam nuclei, Z_{beam}, down to $|\Delta Z| \approx Z_{beam}/2$.

Corrections were made to the raw data in order to find the true cross sections. By applying the same selections and corrections to the target-out runs as the target-in runs, we corrected for particles interacting in the material of the detector and other background particles which pass the selection criteria. The corrections, when applied to the numbers of selected events, give the numbers of particles of each charge which were produced in the target and did not interact in the material of the detector. However, the proportion of particles that do interact in the detector is different for each charge and we also had to correct for this. Finally, the targets we used in this experiment were not thin, in the sense that particles which interacted early in their passage through the target had an appreciable chance of suffering a second interaction. Thus the numbers in each charge peak reflect a smaller population of small charge changes and a larger population of large charge changes than would occur in a thin target. Therefore, we also applied a thick target correction.

The complete set of cross sections found in this work, and also the slightly modified cross sections found in the 1984 run, Binns *et al.* (1987), are listed in the thesis by Cummings (1989), and are available on request. These cover a range of values for $\Delta Z = +1$ to -36.

Global fit for negative ΔZ: We have found global equations that will provide acceptable fits to all the measured cross sections but do not depend on an excessively large number of parameters. Earlier, we found that for heavy beam nuclei interacting with heavy targets, the fragments with relatively small ΔZ have cross sections which are very nicely described by power laws in ΔZ, eq. 1. Also, heavy nuclei on hydrogen targets have cross sections which show a somewhat less regular exponential dependence on ΔZ, eq. 2.

$$\sigma_t(\Delta Z) = \sigma_\beta \cdot |\Delta Z|^{-\beta} \quad \ldots\ldots \; (1) \qquad \sigma_H(\Delta Z) = \sigma_\delta \cdot \exp -(|\Delta Z| / \delta) \quad \ldots\ldots\; (2)$$

where the fitting parameters, σ_β, β, σ_δ, and δ, are all functions of energy and the masses of the beam and target nuclei. There are several possible ways to attempt to characterize these dependences. In particular, it has been shown by Olson et al. (1983), that for beams of iron and lighter nuclei the beam and target dependences can be separated by "factorization", and it is reasonable to attempt to apply the same principle to these heavier beams. Here the cross section for the production of a fragment F from a beam nucleus, B, interacting with a target nucleus ,T, can be written:

$$\sigma(F,B,T) = \gamma(F,B)\ \eta(B,T) \quad \ldots\ldots\ldots \; (3)$$

where $\gamma(F,B)$ is a factor which depends only on the species of beam and fragment but not the target, and $\eta(B,T)$ is a factor which depends only on the species of beam and target but not on the fragment.

Fits to the heavy target data: We fit the cross sections for charge changing interactions over a limited range of values of ΔZ for each beam, target, energy combination with the form of eq. 1. The range $2 \le |\Delta Z| \le 20$ was chosen since experimental cross sections were measured over this range for almost all the runs; $|\Delta Z| = 20$ is still safely above the location in signal of the gold fission peak; and the processes leading to $\Delta Z = -1$ fragments appear to include an additional component, probably attributable to electromagnetic dissociation, yielding a larger than expected cross section. The reduced χ^2 for these fits is in almost all cases close to 1.0. The next step to determining a global fit was to find the beam, target, and energy dependences of the σ_β and β parameters. By using the principle of factorization as a guide, we investigated a number of possible parametric representations of the entire data set. This led to the global fit we chose as the most general equation incorporating these principles to the data. With 9 variable parameters, this equation, when applied to the entire data set, gave a reduced χ^2 of 1.78. Modifications and simplifications resulted in an equation with only 7 free parameters, see the Table, which we take as our best fit:

$$\sigma_t = p_1 \cdot (A_B^{1/3} + A_T^{1/3} - p_2)\,(1+\frac{E}{p_3})\,|\Delta Z|^{-\{p_4\,(1+\frac{A_B}{p_5})\,(1+\frac{A_T}{p_6})\,(1+\frac{E}{p_7})\}} \quad \ldots\ldots \; (4)$$

and which had an insignificantly greater χ^2 of 1.81. This fits all 796 cross sections in our $2 \le |\Delta Z| \le 20$ data set to within a factor of 1.28. Fig. 1 shows the distribution of the normalized residuals between the fits and the measured cross sections. This distribution is characterized by a nearly Gaussian peak with a standard deviation of 0.075; and a 95th percentile of 0.146.

Fits to the hydrogen target data: The first step in a global fit to the hydrogen target data is finding a fit for each run to eq. 2, an exponential in ΔZ. The results of the least square fit to the cross sections of $2 \le |\Delta Z| \le 20$ interactions for the 16 available runs give reduced χ^2's for these runs which varied widely with an average of about 3. A better fit comes from a modified form of eq. 2 with a double slope exponential;

$$\sigma_H = \sigma_\delta \cdot e^{-[\,|\Delta Z| / \delta]} \qquad \text{for } |\Delta Z| \leq |\Delta Z_C|$$

$$\sigma_H = \sigma_\delta \cdot e^{-[\,|\Delta Z_C| / \delta]} \cdot e^{-[\,(\,|\Delta Z| - |\Delta Z_C|\,) / \delta']} \qquad \text{for } |\Delta Z| > |\Delta Z_C| \quad ....$$

(5)

Here the χ^2's are on the average about 1.5. The σ_δ, δ, and δ' parameters show dependence on beam mass and energy and led to our choice for a most general global fit equation with 9 variable parameters and a χ^2 for the entire data set of 2.00. Simplifying gives the resulting eq. 6 with only 7 free parameters:

$$\sigma_H = q_1 A_B^{q_2} E^{q_3} e^{-[\,|\Delta Z| / \{q_4 E^{q_5}\}]} \qquad ....\text{for } |\Delta Z| \leq q_6$$

$$\sigma_H = q_1 A_B^{q_2} E^{q_3} e^{-[\,q_6 / \{q_4 E^{q_5}\}]} e^{-[\,(|\Delta Z| - q_6) / \{q_7 E^{q_5}\}]} \qquad ....\text{for } |\Delta Z| > q_6 \quad ....$$

(6)

with a χ^2 of 2.07. Fig. 2 shows the distribution of the normalized residuals between the fits and the data points. This distribution is characterized by a peak with a standard deviation of 0.10, but has appreciable tails on both sides, so that the 95th percentile is 6.84. On inspection these examples of poor fits turn out to be predominantly a consequence of the large uncertainties on the small cross sections for large $|\Delta Z|$. Thus, for a more limited range of ΔZ, i.e. $2 \leq |\Delta Z| \leq 10$, the 95th percentile is 0.198, while even for $2 \leq |\Delta Z| \leq 15$, it is still only 0.522.

Mass Losses in Interactions: Nuclear interactions will normally result in changes in the neutron number, (Δn), as well as in the proton number, ΔZ. There is also a non-negligible cross section for interactions with finite Δn but zero ΔZ. A knowledge of the cross sections for production of all the isotopes is important for application to the problem of cosmic ray propagation and to understanding the nuclear physics that is occurring. The semi-empirical cross section formulae, Silberberg *et al.* (1987), predict larger than proportional neutron losses in small charge loss interactions and also large neutron losses for charge pickup interactions. The differing rates of velocity change of nuclei of the same charge but different mass as they experience ionization energy losses allows a degree of mass discrimination, Binns *et al.* (1989),. The mean numbers of neutrons lost per proton in a couple of representative cases are shown in Fig. 3. The large mass losses found indicate that for $|\Delta Z|$ as large as 10 - 15 the fragments formed are very proton rich and will decay in time to stable isotopes with Z as much as 5 - 8 charge units less than that of the initially produced fragments. Since these mass losses also have a wide range of values the composition of a decayed beam of fragments will be significantly different from the observed beam, and thus affect any calculation of cosmic ray propagation.

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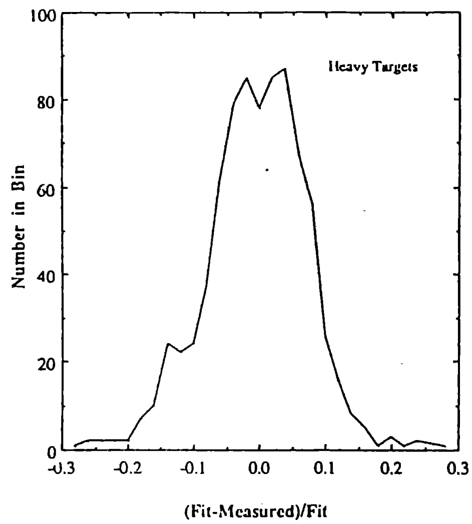

Fig. 1 Normalized residuals between the fits from eq. 4 and the measured cross sections.

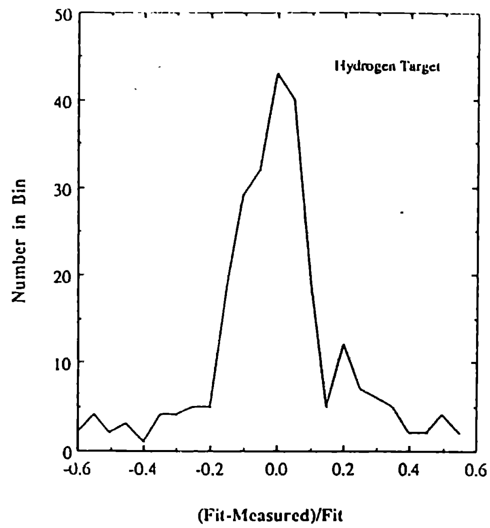

Fig. 2 Normalized residuals between the fits from eq. 6 and the measured cross sections. (Notice change in scale from Fig.1)

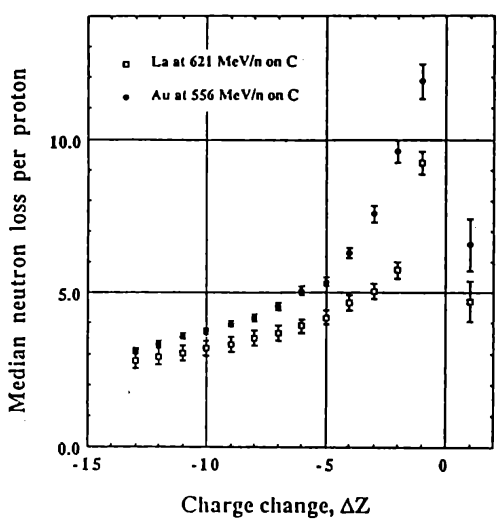

Fig.3 Median neutron loss per proton as a function of ΔZ for La and Au on carbon. For ΔZ=+1 the values shown are for the median mass loss.

Cross sections in mb, energies in GeV/n

#	Eq. 4 (p)	Eq. 6 (q)
1	45.2 ± 2.2	15.5 ± 1.9
2	0.81 ± 0.36	0.51 ± 0.02
3	-3.48 ± 0.16	-1.28 ± 0.03
4	6.14 ± 0.01	6.87 ± 0.11
5	789 ± 60	1.43 ± 0.03
6	1173 ± 204	7.91 ± 0.16
7	-11.13 ± 1.72	-4.15 ± 0.07
Red. χ**2	1.81	2.07

Table of fit parameters to eq. 4 and 6