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The Fragmentation of Relativistic Krypton and Silver Nuclei*

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ABSTRACT

In 1990 we exposed a wide range of targets to beams of relativistic krypton and silver nuclei at the LBL Bevalac at energies from 0.5 to 1.5 GeV/nucleon. Incoming and fragmented nuclei were detected in an array of ion chambers, Cherenkov detectors, and multiwire proportional chambers. The total and partial cross sections for charge-changing interactions have been measured, with emphasis on those of cosmic ray interest. These cross sections are compared to those from parametric fits.

1. INTRODUCTION

We have made a series of measurements of the interactions of UH-nuclei in various targets to better understand the propagation of UH cosmic ray nuclei, Z≥30, in the interstellar medium. In 1990 we exposed targets of CH_2, C, Li, Al, Cu, Sn, and Pb to beams of relativistic krypton and silver nuclei with energies ranging from 0.5 to 1.5 GeV/nucleon, extending our earlier measurements [Binns *et al.* 1989, Cummings *et al.* 1990] to lighter beams and heavier targets [Waddington *et al.* 1991]. A description of the array of Cherenkov detectors, Ion chambers, and multiwire proportional chambers used can be found in Binns *et al.* [1991]. These detectors show charge resolution of ~0.15 charge units [Waddington *et al.* 1991].

2. TOTAL CHARGE-CHANGING CROSS SECTIONS

Total charge-changing cross sections, σ_T, were determined by counting the number of beam particles entering our apparatus and the number of beam particles that did not interact. Corrections for interactions in our apparatus are made with a target-out run [Nilsen 1993]. Figures 1 and 2 show plots of σ_T, and indicate a possible energy dependence. Our results are compared to those predicted by several models. Hard sphere models are of the form:

$$\sigma_T = \pi(R - r_0\delta)^2 \tag{1}$$

where $R = r_0\left(A_B^{1/3} + A_T^{1/3}\right)$, r_0 is related to the nuclear radius, and δ is an overlap parameter. A_B and A_T are the beam and target masses respectively. Westfall [1979], for $Z_B \leq 26$, found δ=0.83 and r_0=1.35 fm and used for a hydrogen target $A_T = A_H^{eff} = 0.089$ (shown in fig. 1 and 2 as a dashed curve). Figure 1 shows that for a hydrogen target eq. 1 does not fit our data.

Based on our earlier data [Binns *et al.* 1989] on heavier UH-nuclei, we found it necessary to modify the overlap term to give:

$$\sigma_T = \pi\left(R - r_0 q (A_B + A_T)^{1/3}\right)^2 \tag{2}$$

Figure 2 shows the difference between our measured total cross sections and that predicted by eq. 2. Neither of these hard sphere models has any energy dependence. We have attempted to introduce some energy dependence into eq. 2, with a scaling factor of the form:

$$F = F_0 + F_1 \ln(E) + F_2\{\ln(E)\}^2 \tag{3}$$

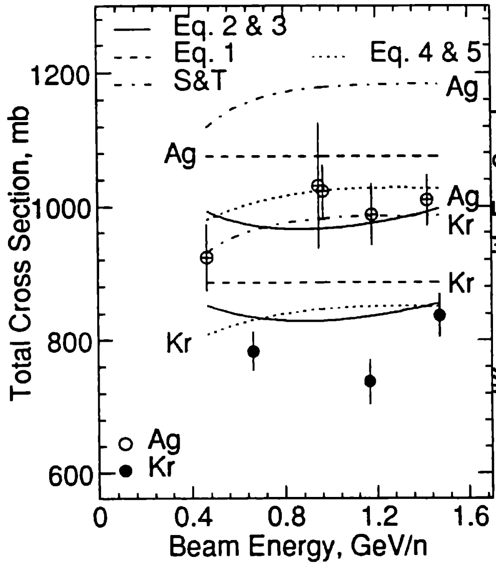

Fig. 1 Energy dependence of the deduced hydrogen σ_T's for beams of Kr and Ag.

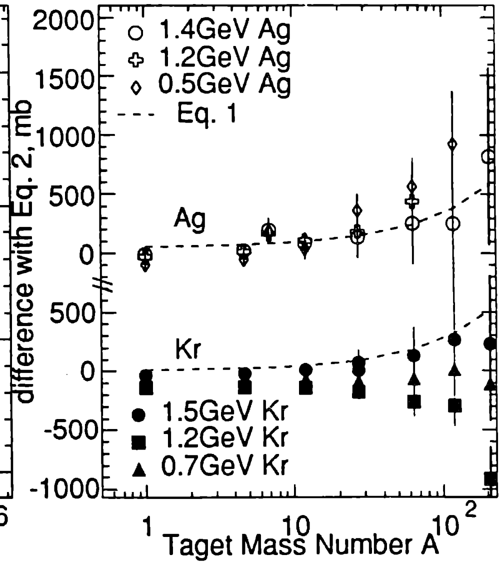

Fig. 2 Target mass dependence compared to that predicted by eq. 2 for beams of Kr and Ag

where E is the total energy in GeV/nucleon. This form is similar to that used by the Particle Data Group [1990] to fit p-p and p-n cross sections. Fitting for F_0, F_1, F_2, and q in eq. 2 to our values of σ_T (including those from our earlier measurements [Binns *et al.* 1989]) gives, F_0=1.29±0.09, F_1=−0.55±0.26, F_2=0.46±0.22 and q=0.283±0.021, giving F(1.5GeV/n)=1.19 with a reduced X^2, χ^2=3.45 (solid curve in fig. 1).

There is a semi-empirical model for charge-changing in a hydrogen target [Silberberg and Tsao 1990] (S&T), which has an energy dependence but does not fit our data well unless we make an arbitrary renormalization. (dash dotted curve in fig. 1)

An optical model by Hoang *et al.* [1985] has the form:

$$\sigma_T(A_1,A_2) = \pi\left(R^2 - 4\lambda^2 + \frac{8\lambda^4}{R^2}\left\{3 - \left[3 + \frac{3R}{\lambda} + \frac{R^2}{\lambda^2}\right]e^{-R/2\lambda}\right\}\right) \tag{4}$$

This form for the total cross sections can include an energy dependence by varying either r_0 or λ. We have scaled the mean free path parameter λ by the average total nucleon cross section:

$$\lambda = \lambda_0 / \overline{\sigma_n(E)} \tag{5}$$

where $\overline{\sigma_n(E)}$ is the average n-p and p-p total cross section as defined by Karol [1975]. Fitting for r_0, λ_0 and A_H^{eff} in the optical model gives r_0=1.233±0.014 fm, λ_0=80.1±7.9 fm-mb and A_H^{eff}=0.045±0.011, giving λ(1.5GeV/n Kr on Pb)=1.80 fm with a χ^2=3.10 for all of our data (dotted curve in fig. 1) .

3. PARTIAL CHARGE-CHANGING CROSS SECTIONS

The partial charge-changing cross sections, $d\sigma/dZ$, were determined by counting the number of beam particles entering our apparatus and the number of particles of a given charge as determined in our detectors. Corrections are then made for interactions in the detectors and the target [Nilsen 1993]. The earlier parametric equations [Cummings *et al.* 1990] for $d\sigma/dZ$ do not fit these new values very well. The hydrogen data are fitted particularly poorly with a χ^2=14.68 while the non-hydrogen data have χ^2=6.12, compared to the previous values of χ^2=2.07 and

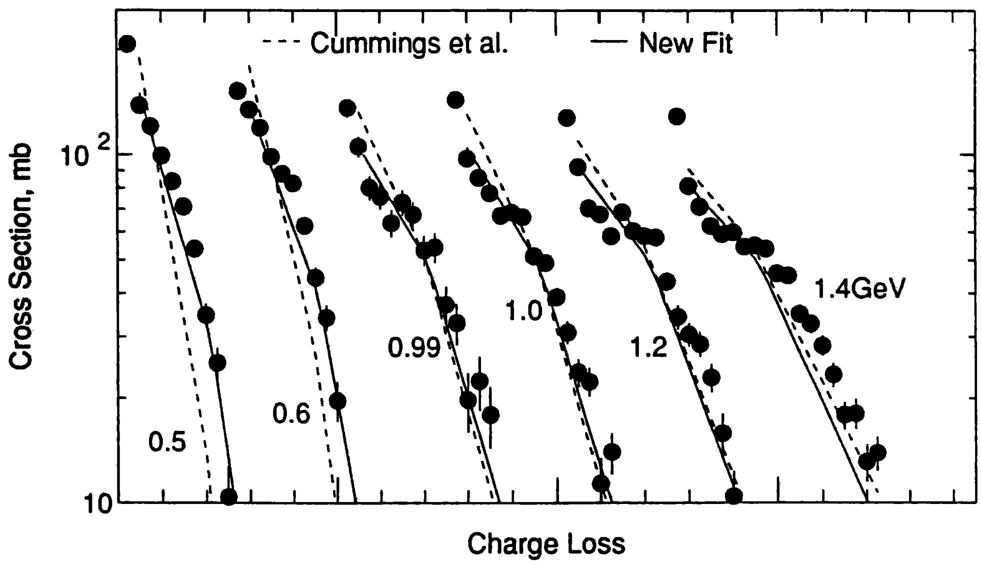

Fig. 3 Energy dependence of the hydrogen deduced partial cross sections for Ag beams of 1.4, 1.2, 1.0, 0.99, 0.6, and 0.5GeV/n. Solid line is the new fit and dashed line is from Cummings *et al.* [1990].

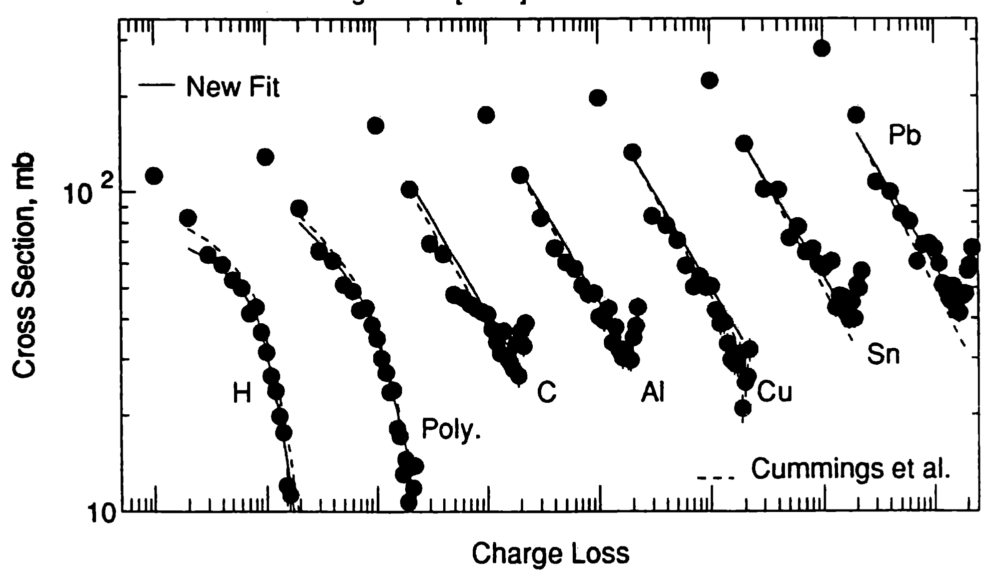

Fig. 4 Target mass dependence of the partial cross sections for 1.5GeV/n Kr beams. Solid line is the new fit and dashed line is from Cummings *et al.* [1990].

χ^2=1.81 respectively [Cummings *et al.* 1990]. After re-evaluating the parameters by combining these new data with those from Cummings *et al.* [1990] and Binns *et al.* [1989] the fits are somewhat improved, χ^2=4.93 for the hydrogen data and χ^2=4.91 for the non-hydrogen data (fig. 3, 4). However, it seems clear that it will be necessary to modify the form of these parametric functions to better model the energy dependence.

Silberberg and Tsao [1990] have developed a semi-empirical model of the charge and mass changing cross sections. These dσ/dA's can be combined to give dσ/dZ values. When compared with our derived hydrogen cross sections they do not agree well. The model by Silberberg and Tsao also introduces, at higher energies, peaks in dσ/dZ that are not seen in our data. The fit is improved at lower energies.

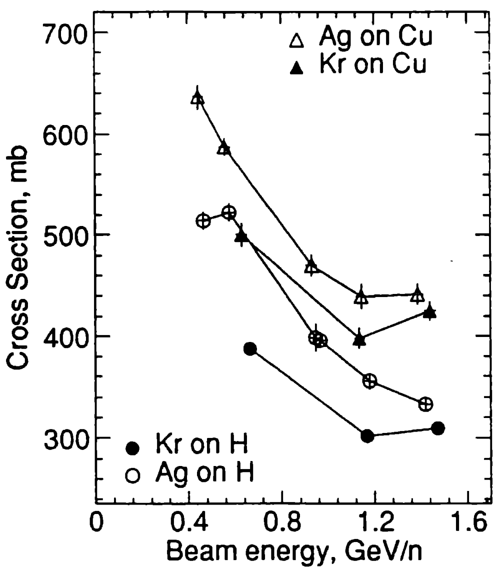

Fig. 5 Energy dependence of the sum of partial cross sections of ΔZ from -2 to -6. For target of Cu and H and beams of Kr and Ag. This shows the flattening out of the partial cross section at higher energies.

This suggests that the energy dependence, especially at energies as high as ours, in their semi-empirical model needs some adjustment.

The dσ/dZ values show a noticeable energy dependence. The most extreme peripheral interactions are expected, at high energies, to become energy independent. Evidence for "limiting fragmentation" has been found in some studies of light projectiles on heavy target ([Cummings *et al.* 1990] and references therein). Following our previous analysis [Cummings *et al.* 1990], we studied the energy dependence of the cross sections for small charge-changes defined as $-6 \geq \Delta Z \geq -2$. This Z range is chosen to ensure that the interactions are peripheral. $\Delta Z=-1$ events are excluded because they are a special case. Figure 5 shows the energy dependence of the sum of all small dσ/dZ for hydrogen and copper targets.

It appears that at the highest energies these cross sections are becoming energy independent particularly for krypton. If this is indeed the case, then it appears that for these projectiles we are approaching "limiting fragmentation" at or above 1.2 GeV/nucleon and that the threshold is not strongly dependent on the total kinetic energy or the target mass.

4. CONCLUSION

The energy dependence of the total charge-changing cross section above 1.2 GeV/nucleon may still be significant and need to be included in any future parameterization. The prediction by Silberberg and Tsao and our earlier parameterizations of the partial cross sections needs improvement at these higher energies and heavier targets. Our latest partial cross section data suggest that "limiting fragmentation" may start to come into effect at the highest of these energies but further investigations at still higher energies are needed to verify this.

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