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Nuclear Interaction Cross Sections for UltraHeavy Nuclei

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Abstract

We summarize additions to our data base of charge-changing cross sections for relativistic ultraheavy nuclei interacting in targets ranging from H to Pb. We have improved parametric fits to those cross sections as functions of energy and of projectile, target, and fragment charge. At high energies, we have determined cross sections for Au projectiles at 10.6 GeV/nucleon in targets of H, CH_2, C, Al, Cu, Sn, and Pb. Compared with cross sections at ~1 GeV/n, fragment production is substantially changed, especially for the H target. These changes have important implications for calculations of interstellar propagation of ultraheavy nuclei. At lower energies, we have added Kr and Ag to our list of projectiles. Analysis of these data has led to a better understanding of the systematics of these cross sections, hence more physically meaningful parameterizations for fragmentation at high energies and for charge pickup.

1 The Data Collection

The UHIC collaboration has measured cross sections for projectile beams of $_{26}$Fe, $_{36}$Kr, $_{47}$Ag, $_{54}$Xe, $_{57}$La, $_{67}$Ho, and $_{79}$Au. The beam energies were 10.6 GeV/nucleon at Brookhaven (BNL) and ranged from ~0.4 to 1.6 GeV/n at the LBL Bevalac. Target materials have included $_3$Li, $_6$C, polyethylene (CH_2), $_{13}$Al, $_{29}$Cu, $_{50}$Sn, and $_{82}$Pb. Cross sections for $_1$H are derived from C and CH_2. The most complete descriptions of these new data are in the theses of Nilsen [1] and Geer [2]. The data are also described in [3,4], with references to the earlier measurements in those papers.

1.1 Total Charge-changing Cross Sections

Since the earlier runs did not always include absolute normalizations, the new data represent a substantial addition to our collection of total cross sections. The data are consistent with a treatment of the total cross section as being composed of two major components, nuclear interaction and electromagnetic dissociation (EMD). The EMD component is undetectable in charge changes at Bevalac energies, ~1 GeV/n, but is easily measured at 10.6 GeV/n.

The EMD component and the nuclear component can be separated by assuming factorization [3]. Nuclear cross sections have been fit by hard sphere models with overlap. The EMD component at 10.6 GeV/nucleon ranges from 0.7% in C to 4.5% in Pb.

1.2 Partial Charge-changing Cross Sections

Partial cross sections for production of fragments of a given charge have been measured for charge changes (ΔZ) from +1 (charge pickup, [5]) down to roughly -25 to -30. For most fragments, targets, and energies the cross sections have a power law dependence on ΔZ with an exponent typically between -0.5 and -0.9. For low energy (Bevalac energies) particles incident on H targets, the dependence is instead roughly exponential. For $|\Delta Z| >\sim 25$ our technique does not necessarily unambiguously measure the charge of the largest fragment due to additional physical phenomena such as multifragmentation and fission.

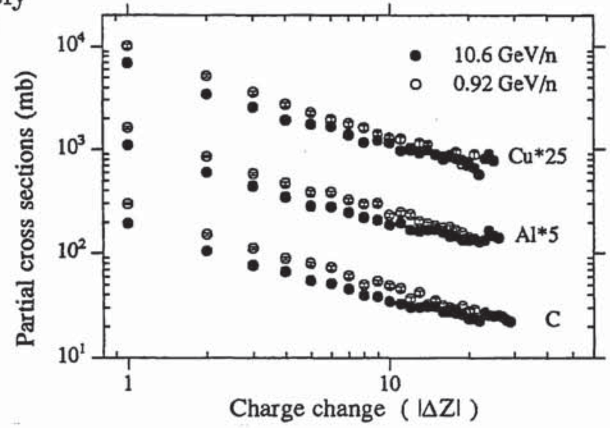

Fig. 1: Partial cross sections for production of fragments of charge change $|\Delta Z|$ for Au projectiles on three indicated targets and at two indicated energies versus $|\Delta Z|$. Data for Cu and Al are scaled up as indicated.

Fig. 1 shows a sample of the partial cross sections for producing fragments from Au at a given ΔZ. There are hundreds of such data points which are tabulated in the theses referenced and references therein. The data may also be available from the Space Physics Data System by the time of the conference.

The charge pickup (+1) cross sections, reported in [5], show a good correlation with the neutron excess of the projectile nuclei. The ΔZ = -1 cross sections tend to differ from the extrapolation of the fits to fragments with greater changes in Z described below, especially at 10.6 GeV/nucleon where EMD contributes. We have not yet done any extensive parametric fits of these particular (-1) cross sections.

As seen in Fig. 1 and 2, the partial cross sections with ΔZ between -2 and -20 are generally well organized and they have been fit with power law or exponential dependences on ΔZ. Fig. 2 also illustrates the qualitative change in the Au on H cross sections from high energy to low energy. Similar changes have been reported for Fe on H by Webber *et al.* [6]. These observations invalidate those cosmic ray propagation calculations which are based on the assumption that fragmentation cross sections do not change substantially at high energies. The strong (and essentially unmeasured) energy dependence between 1 to 2 and 10 GeV/n should be kept in mind for such calculations, and needs additional study.

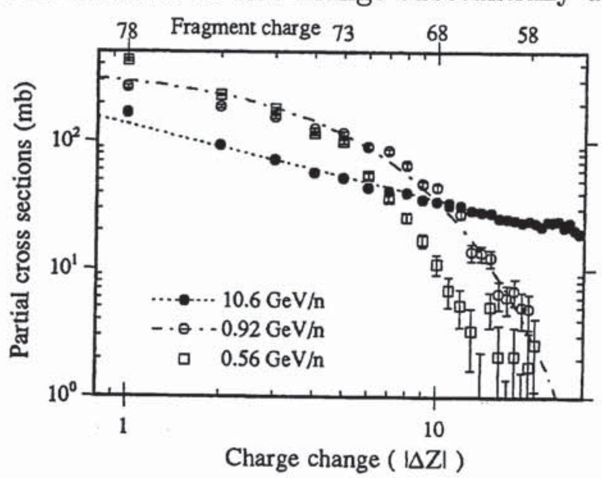

Fig. 2: Like Figure 1 but for H target at three indicated energies, with simple curves drawn to guide the eye.

2 The Parametric Fits

Cross sections for H targets have been collected, extensively studied and (semi-empirically) fit by Silberberg and Tsao and co-workers ([7] and references therein). For non-H targets, in some cases, it may be more convenient to use interpolation on the collection of measured data points. Often, however, a simple parametric fit with a limited number of parameters and special cases can be very useful, and these are presented below.

2.1 Total Charge-changing Cross Sections

Ignoring the small energy dependence, a very good parametric fit to the total cross section data shown in Fig. 3 is given by a hard sphere/overlap model: $\sigma = \pi(R_P + R_T - \Delta R)^2$ [4]. The fit has $\Delta R = 2.94$ fm with target and projectile radii (R_T and R_P) given by 1.24 times R_e, the tabulated nuclear radii measured using electron scattering. Space limitations preclude showing these tables, but they will be published (with references) in [4], with discussions of uncertainties and goodness of fit. The poster presentation and handout will have these additional details also, and a discussion of simpler, non-table based algorithms. Adding energy dependence to the parameterization improves the fits somewhat, at the cost of increased complexity. In addition to having smaller χ^2 than the fits based on $A^{1/3}$ scaling, these fits based on R_e reproduce H target cross sections without the non-intuitive special treatment (effective mass of H = 0.089) otherwise required.

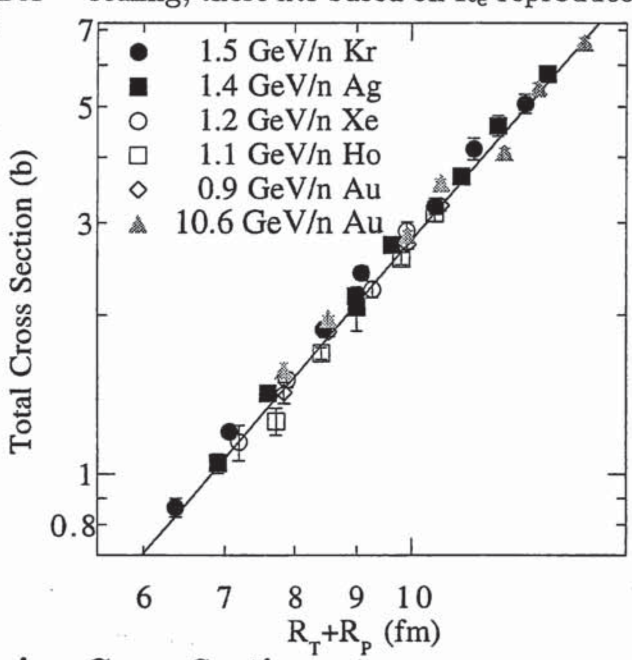

Fig. 3: The total charge-changing cross sections for the highest energy beams of Kr, Ag, Xe, Ho, and Au on all targets is plotted as a function of $R_T + R_P$. The line is a power law of the form $5.7(R_T + R_P)^{2.7}$. The actual best fit to the data includes an overlap term and has a smaller χ^2.

2.2 Partial Charge-changing Cross Sections

As noted above, these cross sections are fit over a limited range of ΔZ, $-20 \leq \Delta Z \leq -2$. They also represent measurements taken with a rather non-uniform sampling of targets and projectile energies. Caution must be used in deciding if they represent reasonable interpolations or unjustified extrapolations for any particular calculation. Scaling with R_e (mentioned above) did not improve the fit to these measurements. The best fits we have attained to date are patterned after the earlier fits of [7], but are a slight improvement in terms of χ^2 and do not diverge at high energies the way those fits did. The non-H fit is also compatible with the high energy (BNL) data. The fits (and uncertainties and goodness of fit) are given in detail in [4] and the poster presentation, and a preliminary paraphrase is given here for low-energy H targets:

$$\sigma_{\Delta Z}(A_P, H, K, \Delta Z) = 18A_P^{0.48}K^{-1.09}\exp - \left[\frac{|\Delta Z|}{6.89K^{1.25}}\right] \quad \text{if } |\Delta Z| \leq 8.27$$

$$= 18A_P^{0.48}K^{-1.09}\exp - \left[\frac{8.27 + 1.56(|\Delta Z| - 8.27)}{6.89K^{1.25}}\right] \quad \text{if } |\Delta Z| \geq 8.27$$

and for non-H targets:

$$\sigma_{\Delta Z}(A_P, A_T, K, \Delta Z) = 24(A_P^{1/3} + A_T^{1/3} - 1.62)(1 + 0.42/K)\times |\Delta Z|^{-0.06(1+\frac{A_P^{1/3}}{0.66}+\frac{A_T^{1/3}}{4.2}+\frac{1.1}{K})}$$

where K is the kinetic energy (GeV/n) of the projectile in the target system and the cross section is in mb.

3 Conclusions

The new measurements have contributed substantially to our understanding of the systematics of these interactions – the Kr and Ag results have inspired the correlation of charge pickup interactions with neutron excess which appear to give an adequate fit to all of our data and they have confirmed and improved our understanding of the systematics of fragmentation for ΔZ in the range -2 to -20. The measurements at higher energies have shown an unexpectedly strong energy dependence for cross sections with H targets, the primary element of interest for astrophysical applications. The importance of this latter result to calculations of propagation must be stressed, and indicates clear need for additional studies of energy dependence that will be conducted shortly.

4 Acknowledgements

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