RELEASE OF NUCLEI FROM RELATIVISTIC NUCLEUS-NUCLEUS INTERACTIONS

C.J.Waddington[1], W.R.Binns[2], T.L.Garrard[3], M.H.Israel[2], M.P.Kertzman[1], J.Klarmann[2], and E.C.Stone[3]
1 School of Physics and Astronomy, University of Minnesota, USA
2 Department of Physics and the McDonnell Center for the Space Sciences, Washington University, USA
3 George W.Downs Laboratory, California Institute of Technology, USA

Abstract. We have examined relativistic nuclei of iron, krypton, xenon, holmium and gold, accelerated to maximum rigidity at the LBL Bevalac, interacting with targets of aluminum, carbon and polyethylene. For each projectile and target combination we determined the total and partial charge changing cross-sections. From these measurements we have developed a new representation of the dependence of the total charge changing cross-sections on beam and target charge. We have also identified simple representations of the variation of the partial cross-sections with the charge of the produced fragments and shown that they are dependent on the charge and energy of the beam.

1. Introduction. Our measured cross-sections differ appreciably from those predicted from the semi-empirical fits to cross-section data[1]. Hence calculations of cosmic ray propagation can be improved if we replace those predicted cross-sections with values based more directly on experimental data. It is, therefore, desirable to identify a systematic description of the variation in the cross-sections with projectile type so that values of the cross-sections can be calculated for all projectiles. In this work we have identified suitable descriptions for the elemental cross-sections, but have found that we have an inadequate number of independent experimental variables to allow us, as yet, to apply these descriptions with confidence to the problem of cosmic ray propagation. In particular we cannot make a clear distinction between the dependence of the partial cross-sections on charge and on energy. More recent measurements, described in the following paper, may help us to resolve this ambiguity in the near future.

2. Experimental. The detectors used for the Bevalac exposure consisted of an external MWPC and an array of parallel plate ionisation chambers (IC), with a Cherenkov detector (C) and a target placed between them. The beams of nuclei and the targets used are listed in the Table. The thickness of each target used in each run is also listed . These thicknesses were adjusted for the various beams so that in each case they were between 20 and 24% of the interaction mean free path.The data from the various detectors were corrected for spatial and temporal variations. The front IC's were used to select the primary nuclei., while the IC's and the C-detector behind the target were used to examine the fragments produced. The table lists the charge resolution, in charge units, c.u., achieved.

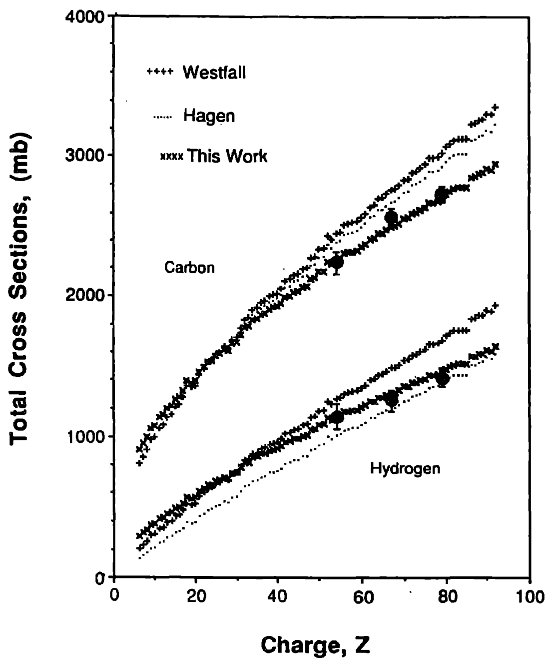
Table. Beams, targets, total cross-sections and parameters

Beam	Energy MeV/amu	Target	Thick g/cm^2	mfp	Charge resolution	σ_{tot} mb	σ_0 or Σ_0 mb	Δ_0 or α	χ^2
Kr	1419±55	Al	4.25	0.22	0.19	2330±102	163.0±7.2	0.530±0.021	0.82
Xe	1155±62	Al	3.29	0.20	0.23	2890±120	187.5±10.2	0.587±0.026	0.98
Xe	1175±41	C	1.94	0.22	0.19	2240±82	198.9±7.7	0.654±0.018	1.15
Xe	1190±27	CH_2	1.08	0.21	0.19	1511±86	159.0±2.9	7.63±0.11	2.15
Xe		H				1146±89	192.3±5.7	6.29±0.15	2.26
Ho	1022±78	Al	3.29	0.22	0.23	3120±100	226.0±10.4	0.660±0.021	0.87
Ho	1048±52	C	1.94	0.24	0.26	2564±70	229.6±8.6	0.702±0.017	0.79
Ho	1067±34	CH_2	1.08	0.24	0.25	1693±72	174.8±3.0	7.46±0.11	1.46
Ho		H				1258±75	206.0±5.8	6.29±0.15	2.71
Au	932±83	Al	2.95	0.22	0.28	3240±82	244.6±12.1	0.721±0.022	0.82
Au	961±55	C	1.73	0.23	0.30	2731±58	221.0±9.2	0.703±0.019	1.16
Au	982±34	CH_2	0.92	0.22	0.26	1861±63	202.7±3.7	6.54±0.08	2.91
Au		H				1426±65	282.9±8.3	5.10±0.10	2.40

3. Total Charge Changing Cross-Sections. The values determined for the total charge changing cross-section, σ_{tot}, are given in the Table. Earlier measurements with lighter beam nuclei ($Z \leq 26$) by Westfall et al.[2] led them and Hagen[3] to derive expressions for σ_{tot} as a function of beam and target nuclei mass numbers (A_B, A_T). Neither of these relations extrapolates well to fit the data in the mass region covered in this work. Instead we fit our data to a relation of the form:

$$\sigma_K = 10\,\pi\,(1.35)^2\,\{A_T{}^{1/3} + A_B{}^{1/3} - p[A_T + A_B]^q\}^2 \text{ mb},$$

where p and q are constants determined from the data to be 0.209 and 0.332 respectively. This relation also gives a good fit to the data of Westfall et al.[2] on Fe nuclei for our light targets where $A_T << A_B$, but does not match their data for still lower beam charges.Fig. 1 shows our measured cross-sections compared with those predicted.



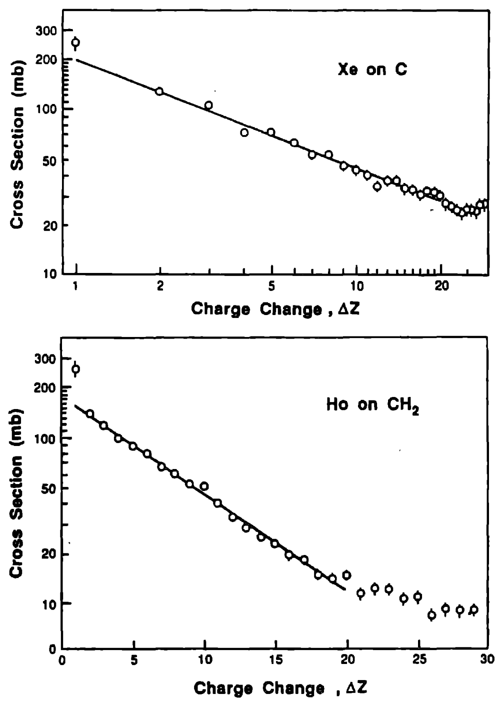


Fig. 1. The total cross-sections predicted by various expressions in carbon and hydrogen. Our values are shown as the black points

Fig.2 and 3. Fits to partial cross-sections plotted as a function of the charge change, for Xe on carbon and Ho on polyethylene

4. Partial Cross-sections Systematics. In every case the majority of the values of the partial cross-sections, $\sigma(\Delta Z)$, are found to decrease regularly with increasing charge change (ΔZ). For the heavy targets, Al and C, the data can be fitted, for $2 \leq \Delta Z \leq 20$, with acceptable values of reduced χ^2, by simple power law expressions of the form: $\sigma(\Delta Z) = \Sigma_0\,(\Delta Z)^{-\alpha}$ mb; where $\Sigma_0(Z_B, Z_T)$ and $\alpha(Z_B, Z_T)$ are constants for each beam and target. For the targets which contain hydrogen, the data are not well fitted by this power law form, but instead can be represented by exponential expressions of the form: $\sigma(\Delta Z) = \sigma_0 \exp(-(\Delta Z)/\Delta_0)$ mb; where $\sigma_0(Z_B, Z_T)$ and $\Delta_0(Z_B, Z_T)$ are constants for each beam and target. Examples are given in Figs. 2 and 3. The only exception to this behavior is for the gold beam at large charge changes, where the occurrence of fission causes a peak to appear in the $\sigma(\Delta Z)$ distributions, In addition, the values of $\sigma(\Delta Z)$ for $\Delta Z = 1$ nearly always appear to be anomalously high, presumably due to the additional process of electromagnetic dissociation causing proton stripping.

Values of these fitting parameters, Σ_0, α, σ_0 and Δ_0, determined over the range $2 \le \Delta Z \le 20$, are given in the Table, together with values of reduced χ^2. It can be seen that these simple fits are remarkably good representations of the data over a wide range of ΔZ. However, it is clear that they cannot cover the entire range of ΔZ since $\sigma(\Delta Z)$ summed over all ΔZ must equal σ_{tot}. Summation of the individual values show that quite appreciable fractions of σ_{tot} are reached even when only summing up to $\Delta Z = 20$, Fig.4.

5. Charge and Energy Dependence. It is known from work with lighter beams by Webber[4] that there are significant energy dependences in the individual partial cross-sections below about 1 GeV/amu. Similarly, studies by Kaufman and Steinberg[5] of the partial cross-sections of isotopes produced by the proton bombardment of heavy targets have shown an energy dependence that extends higher. Clearly we expect to observe energy dependent changes in our data, although they are unlikely to be large due to the rather small range of energy.

For the Al target data we find a linear dependence on Z_B for both $\Sigma_0(Z_B, Z_T)$ and $\alpha(Z_B, Z_T)$. Unfortunately, since Z_B was also correlated with the beam energy (E_B), there is a similar linear dependence on E_B. Thus in the case of the aluminum targets we cannot distinguish between the charge and energy dependence.

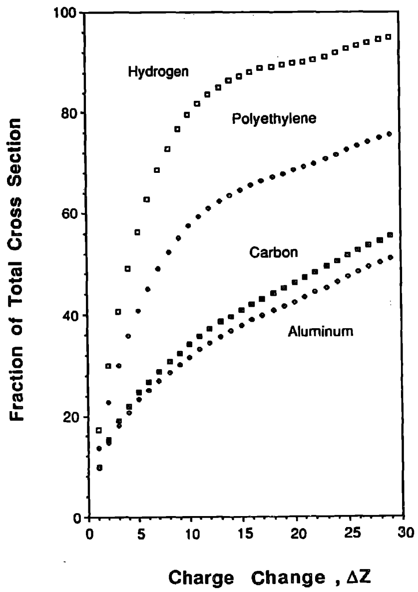
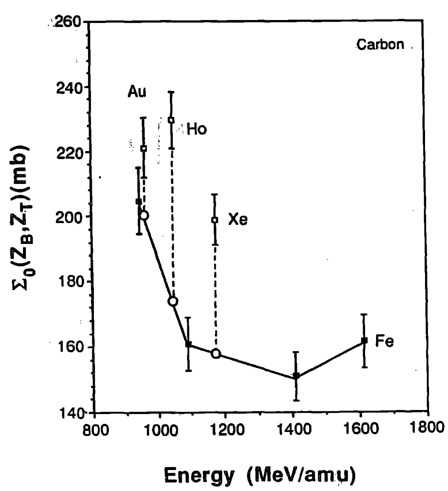


Fig.4. Incremental sums of the partial cross-sections as a function of ΔZ for gold nuclei

However, for the other targets we also have available data for iron nuclei over a range of energies[4]. Fig 5 shows $\Sigma_0(Z_B, Z_T)$ as a function of energy for the C targets, both for our results at each energy and for iron nuclei at several energies directly comparable with ours. The differences in $\Sigma_0(Z_B, Z_T)$ for two projectiles at the same energy, shown by the vertical displacements to the circle points (Fig.5), then represent the charge



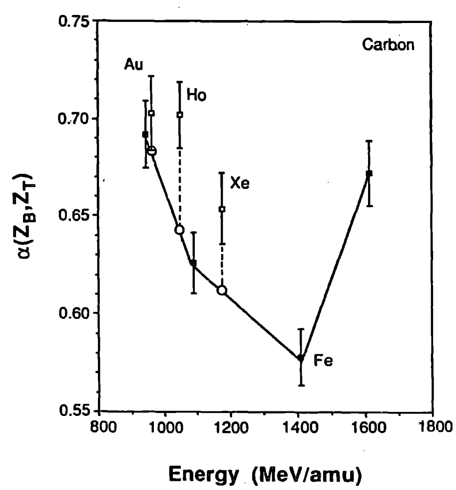


Fig.5. $\Sigma_0(Z_B,Z_T)$ as a function of E_B for carbon. Fe points are from Webber's data[4]

Fig.6. $\alpha(Z_B,Z_T)$ as a function of E_B for carbon Fe points are from Webber's data[4]

dependence of $\Sigma_0(Z_B, Z_T)$ at that energy. A similar figure can be constructed for $\alpha(Z_B,Z_T)$, and is shown as Fig 6, illustrating the charge dependence of $\alpha(Z_B,Z_T)$.

The fitting parameters for the H and CH_2 targets, can be examined in the same manner as for the C targets, Fig 7. It is found that although the parameters are not as well organized as those for the carbon targets, there is clear evidence for a charge dependence in each case, and also evidence for some energy dependence, even over the small range of energy covered by our results. We cannot distinguish between these charge and energy dependences of the cross-sections, and hence we cannot reliably predict the behavior of the cross-sections at other charges and other energies, particularly when we also consider the evidence from the p - A data[5] for energy dependence over a wide range of energy. At best, from our own data, we could assume that the entire variation observed is due to a dependence on only the charge, and use this assumption to derive "asymptopic" values.

Previously this is the assumption that has been made in our cosmic ray propagation studies and applied to the HEAO data by Binns et al.[6] and Brewster et al.[7], where we assumed that the cross-sections were energy independent. From our discussion here, and from the p -A data, we have to conclude that this assumption can probably not be justified at present, although it should not significantly affect our major conclusions, since the majority of the nuclei in the HEAO data set are of quite high energy where the cross-sections should have reached asymptopic values, which, although not necessarily the ones we assumed, should not show major systematic differences.

More details on this work are available elsewhere, Kertzman[8], Binns et al.[9]

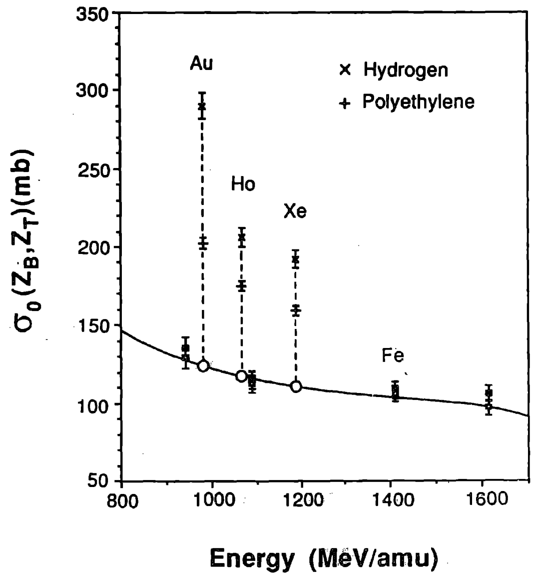


Fig.7. $\sigma_0(Z_B,Z_T)$ as a function of energy in H and CH_2. Fe points are from Webber's data[4].

*Supported in part by NASA grants NAG-8-498, 500, 502 and NGR 05-002-160, 24-005-050 and 26-008-001

[1] R.Silberberg and C.H.Tsao (1973), Ap.J. Suppl., **25**, 315 and (1973) Ibid **25**, 335 (see also R.Silberberg, C.H.Tsao and J.R.Letaw, *Composition and Origin of Cosmic Rays*, ed. M.M.Shapiro, Riedel, p.321 (1983).

[2] G.D.Westfall, L.W.Wilson, P.J.Lindstrom, H.J.Crawford, D.E.Greiner, and H.H.Heckman (1979), Phys.Rev. C **19**, 1309.

[3] F. Hagen(1976), Ph.D. Thesis, University of Maryland.

[4] W.R.Webber (1985), Proc. Baton Rouge Conf, *Cosmic Ray and High Energy Gamma Ray Experiments for the Space Station Era*, ed.W.V.Jones and J.P.Wefel, p.283; and private communication.

[5] S.B.Kaufman and E.P.Steinberg (1980), Phys.Rev. C **22**, 167.

[6] W.R.Binns, N.R.Brewster, D.J.Fixsen, T.L.Garrard, M.H.Israel, J.Klarmann, B.J.Newport, E.C.Stone, and C.J.Waddington (1985), Ap.J., **297**, 111.

[7] N.R.Brewster, P.S.Freier, and C.J.Waddington (1985), Ap J., **294**, 419.

[8] M.P.Kertzman (1987), PhD Thesis, University of Minnesota; CR 198.

[9] W.R.Binns T.L.Garrard, M.P.Kertzman, M.H.Israel, J.Klarmann, E.C.Stone, and C.J.Waddington (1987), submitted to Phys.Rev. for publication.