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Measurement of cross sections for charge pickup by relativistic holmium ions on heavy targets

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We have measured the cross section for nuclear charge pickup by relativistic holmium on several targets of larger atomic number than have been studied previously. We find that although measurements made with most of the targets are consistent with a peripheral geometric scaling, one target, silver, shows an anomalously high cross section.

Using a beam of holmium ($Z = 67$) at a kinetic energy of 981 MeV nucleon^{-1} at the Lawrence Berkeley Laboratory Bevalac, we have measured the cross sections for the process in which the beam particle increases in charge by one unit: in this case we observe the particle charge increasing from $Z = 67$ (Ho) to $Z = 68$ (Er). We used several different targets ranging in atomic number from $A = 12$ (C) to $A = 238$ (U); two targets, silver ($A = 108$) and tin ($A = 119$), have similar atomic numbers.

Our apparatus was very simple. We used thin sheets of a track-etch detector recently developed in our group [1], BP-1, a phosphate glass that exhibits unprecedented resolution in identifying relativistic heavy ions. The principle of the track-etch detector is explained elsewhere [2]; it is sufficient to say here that in this regime of particle charge Z and velocity β, the glass detector measures very accurately—with a resolution of better than 0.2%—the ratio Z/β of each particle that passes through it. The signal—the size of the etch pit in the glass—is a strongly increasing function of Z/β. The beam was essentially monoenergetic, and the detector and target thicknesses were exceedingly uniform (≤ 50 μm) so that differential slowing of the uninteracted beam was minimal ($\delta\beta \leq 7 \times 10^{-4}$). As a result, the velocity β of the uninteracted beam was approximately constant at any given downstream position. We therefore attributed a change in the detected signal to a change in the particle charge; thus, the signature of charge pickup in a target is an increase in signal consistent with an increase by one charge.

We exposed seven stacks of glass and targets, with a different target material in each stack: we had targets of graphite, copper, silver, tin, uranium and two of lead. In front of each target, we placed four pieces of glass (the first two 1.3 mm thick, the second two 0.7 mm thick) to veto beam fragments and slow ("beam-pipe scraping") holmium. After passing through the target, the beam charge was measured with a pair of thin (0.7 mm thick) pieces of BP-1; since each piece had two surfaces, each pair gave four measurements of the particle charge. With the exception of the uranium target stack, each stack consisted of at least one more target and charge-measuring pair of BP-1 sheets.

The stacks were exposed to a fluence of $\sim 10^3$ holmium ions cm^{-2}, after having passed through the exit window of the beam pipe and ~ 1 m of air. We immersed the glass in 49% hydrofluoric acid for two days, which removed $30 - 40$ μm of the surface of each piece of glass. The glass was scanned at 10× with our automated microscope system, which can measure $\sim 10\,000$ events per hour. The automated microscope measures the ellipse parameters and position of each etch pit. Positions were measured in the coordinate system defined by two fiducial etch-pits located at opposite corners of each sheet of glass. Because beam spreading was negligible and multiple coulomb scattering was slight, "constellations" of etch pits deformed little from one sheet to the next through the stack, so fiducial etch pits were easily recognized from one sheet to the next as members of those constellations.

A sample histogram of the resulting measurements of minor axis sizes is shown in Fig. 1. The smaller peaks to the left of the largest one are composed of holmium nuclei which fragmented to lower charge; the $Z = 66$ peak also includes holmium nuclei which have captured an electron. The charge resolution is easily determined by measuring the widths of the peaks and dividing by the separation between them: we found the resolution to be typically $\sim 0.16e$. The valleys between peaks are somewhat filled in due to atomic electron capture and loss within the sensitive regions of the detector. The number of such events is consistent to within a factor of 2 with calculations of mean free paths for electron capture and loss [3].

It is possible to mismeasure the sizes of real etch pits. This can be due to a bit of dust resting on the side of the etch pit, or due to the confusion of two overlapping etch pits for one real one. Such a mismeasurement of the etch pit of a beam particle etch pit distorted by either dust or overlap will result in larger measured values of both axes of the ellipse, but measurement of the major axis is more affected than that of the minor axis. Thus, the apparent eccentricity of the ellipse increases. These events were rejected by insisting that the eccentricity of the ellipse be identical to that of the beam. We washed the glass

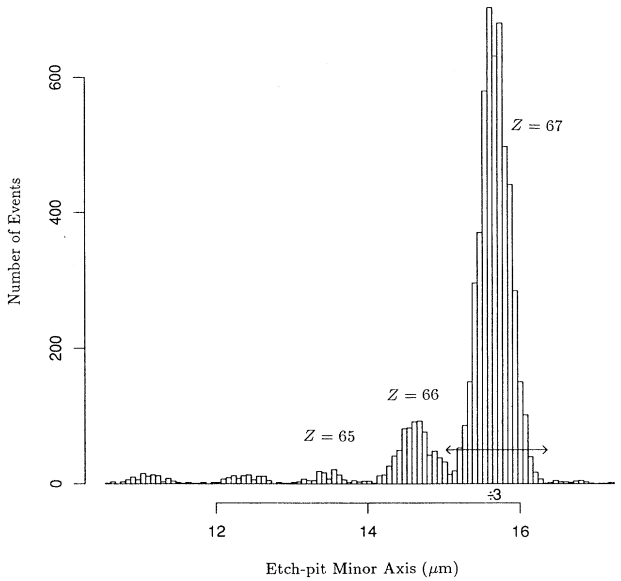

FIG. 1. Histogram of minor axes of etch pits as measured by the automated microscope system. The holmium peak is reduced by a factor of 3 for clarity.

in chromic acid before each scan, so dirt and dust were uncommon. The fraction of events overlapping in each surface was $\sim 0.4\%$. We calculate that the number of pairs of etch pits overlapping sufficiently that they could pass this cut was < 1 for any of these exposures.

We matched each etch pit found in the scan of the first surface past the target to surfaces upstream and downstream of that surface. We matched only on the basis of position, and did not attempt to match using other characteristics (such as size). In order for two etch pits to be assigned to the same particle track, they had to fall within 70 μm of each other in the fiducial coordinate system; the mean separation was ~ 350 μm. By counting the number of events—on any surface except the first—that fell within the holmium peak and that did *not* match to a surface upstream, we could measure the efficiency of the match, which we found to be always better than 97%.

After matching, we converted the measured etch-pit minor axis into apparent charge by fitting Gaussians to the observed peaks at charges 66 and 67 and doing a linear conversion. We measured the nonlinearity of the relationship between minor axis and charge for $62 \leq Z \leq 67$ (measured on the first surface of the stack to minimize differential slowing of fragments), and concluded that the error introduced in extrapolating due to this curvature is small (we underestimate the charge of the $Z = 68$ peak by $0.025e$).

In order to minimize mismatching—especially across the target—we searched the area on each piece of glass around each candidate charge pickup event for any anomalously large events. None were found, placing an upper limit on mismatching probability for *charge pickup events* of 3%. By comparing matches between three well-separated sheets—taken in pairs—we found that the number of inconsistencies *overall* in matching was about 0.8%.

The accidental confusion of dust, scratches, or flaws in the glass was a source of noise for our detector. We discarded these "etch pits" naturally by insisting that any apparent etch pit be matched by an etch pit on each of the other surfaces.

Using the matching information and the apparent charge, we assembled the apparent charge history of each track. We placed cuts on the first surface and the last surface of the veto stack in order to reject the vast majority of the fragments and rare "beam-pipe scraping" slow events. Figure 2 is a histogram of the *averaged* measurements of charge on the adjacent surfaces of the two downstream thin sheets. The charge pickup events at $Z = 68$ are well separated from the main beam. One event that picked up two charges is seen at $Z = 69$.

We counted the number of beam particles that passed these same cuts; we then inferred the cross section from

$$\sigma = \frac{N_{68}}{N_{\text{beam}}} \frac{A}{N_A \rho l},$$

where N_{68} is the number of charge-pickup events seen, N_{beam} is the number of beam particles *exiting the target*, A is the atomic number of the target, ρ is its density, l is its thickness, and N_A is Avogadro's number. These values are tabulated in Table I.

Figure 3 shows the measured cross sections divided by the usual peripheral scaling $(A_{\text{target}}^{1/3} + A_{\text{projectile}}^{1/3} - 1)$ for the various targets, plotted against the atomic mass of the target. The horizontal line is the weighted mean of

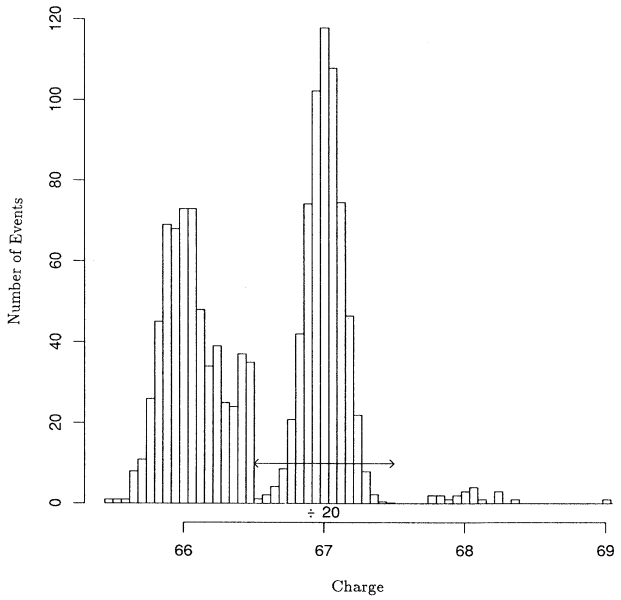

FIG. 2. A histogram of the *averaged* measurements of charge on the adjacent surfaces of the two thin sheets downstream of the first silver target. One nucleus has picked up two charges in the silver target. The holmium peak is reduced by a factor of 20 for clarity.

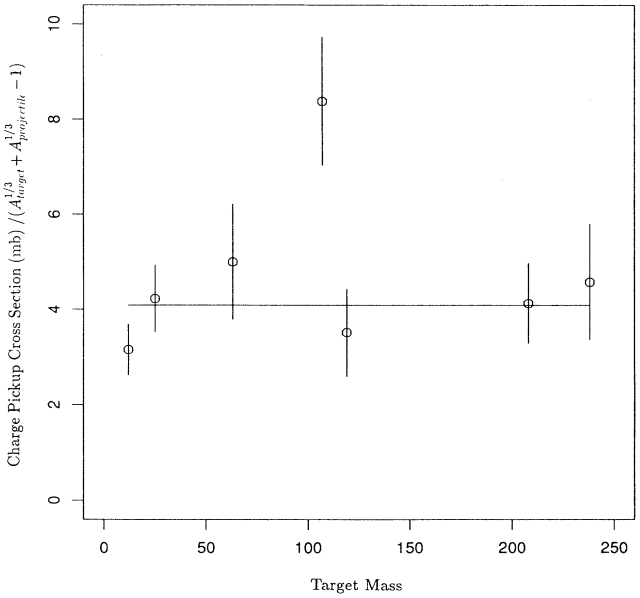

FIG. 3. Cross section for charge pickup divided by $(A_{\text{target}}^{1/3} + A_{\text{projectile}}^{1/3} - 1)$ vs A_{target}. The weighted mean for all of the data is shown as the horizontal line.

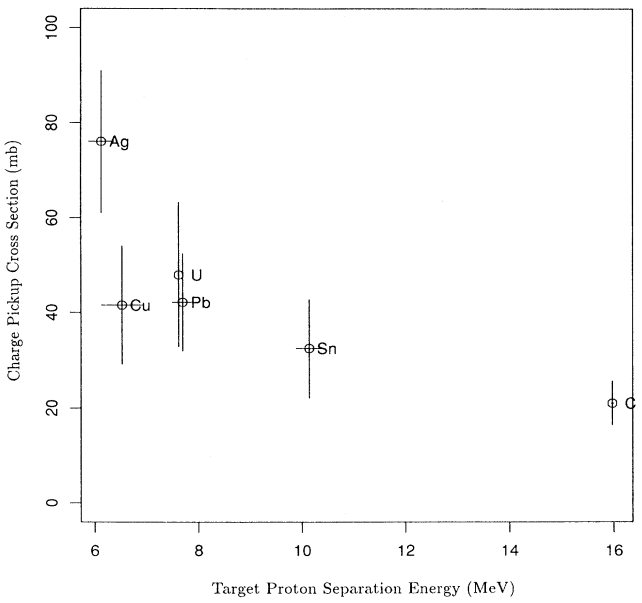

FIG. 4. Cross section for charge pickup versus proton separation energy of the target.

all of the measured cross sections. Most of the data fall within 1σ of this mean. However, the cross section for charge pickup on silver is 2.6σ above the mean line, and 2.4σ different from the cross section on tin. The large apparent difference in cross section between these similar nuclei is surprising. That the cross sections for charge pickup at Bevalac energy ($E/A \sim 1000$ MeV nucleon^{-1}) should depend so strongly on nuclear structure (with nuclear binding energies ≤ 8 MeV nucleon^{-1}) is unlikely. To be sure, the process certainly takes place in a peripheral collision, so perhaps one should not compare total kinetic energies but transverse momentum in the collision, which would be small. Nevertheless, it is difficult to construct a model that gives this kind of dependence.

A model giving this result naturally is a geometric one. If the collision is strongly peripheral and if the charge-pickup mechanism requires positive charge to be available in the interaction region of the collision, then one can imagine explaining this difference in cross section by arguing that the proton density near the surface of a silver nucleus is much larger than that near the surface of a tin nucleus. That tin nuclei have a closed-shell ("magic number") in protons makes this proposal even more attractive. No modern measurements of the charge distribution of silver isotopes have been done, but accurate measurements have been made of the charge distributions of tin and its neighbors indium and cadmium [4]. Using the best-fit profiles, we have calculated the expected proton density at the surface of each nucleus, and we find differences of less than 5%.

Perhaps the proton binding energy can play a role. Figure 4 plots the scaled cross section against proton sep-

TABLE I. Charge pickup data.

Target	Thickness (mm)	Mean energy (MeV nucleon^{-1})	$N_{\Delta Z=+1}$	$N_{Z=67}$	$\sigma_{\Delta Z=+1}$ (mb)
C no. 1	4.76	884 – 925	13	14682	23.9 ± 6.64
C no. 2	4.76	825 – 866	8	11944	18.1 ± 6.4
Cu no. 1	2.38	834 – 925	11	13076	41.6 ± 12.5
Ag no. 1	2.38	828 – 925	15	13293	81.0 ± 20.9
Ag no. 2	2.38	708 – 809	11	11094	71.1 ± 21.5
Sn no. 1	2.00	871 – 925	5	15549	43.4 ± 19.4
Sn no. 2	2.00	797 – 853	2	13434	20.1 ± 14.2
Sn no. 3	2.00	721 – 778	2	11956	22.6 ± 16.0
Pb no. 1	2.38	833 – 925	7	18405	48.2 ± 18.2
Pb no. 2	2.38	851 – 940	6	18102	35.0 ± 15.6
Pb no. 3	2.38	739 – 831	5	14567	43.4 ± 19.4
U	3.18	726 – 925	10	13572	48 ± 15.2

aration energy for each element studied. The dispersion of each point in the abcissa is the width of the proton-separation energy distribution within each element due to variations among isotopes. Except for the fact that silver has the largest cross section and the smallest proton separation energy, no convincing correlation (or anti-correlation) is evident.

It is also difficult to reconcile this result with models that have been considered previously. Price *et al.* [5] have pointed out several features in the charge-pickup data: neglecting some obvious structure, projectile charge pickup on light targets seems to increase with *projectile* mass roughly quadratically, pointing to some coherent process. However, there is asymmetry in cross section between target and projectile, implying that the nearly charge-blind strong forces do not play a role. They reviewed several possible charge-pickup mechanisms, and pointed out that none give such a strong dependence of pickup cross section on projectile mass. The mechanisms of pion exchange, pionic bremstrahlung, and delta formation, while each able to explain some features of the data qualitatively, cannot explain all features; none of them predict any dependence on nuclear structure.

By following the tracks of nuclei that picked up charge in the first silver target through the second silver target, we observe that their apparent charge increased to $Z = 68.41 \pm 0.18$. We attribute the apparent increase in charge of the pickup events to differential slowing of those nuclei due to mass loss, probably through evaporation of neutrons. We calculate that the charge-pickup events have lost 12 ± 7 neutrons in the process. This result is consistent with the observations of neutron loss by Cummings *et al.* [6].

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