Abnormally Large Momentum Loss in Charge Pickup by 900-MeV/Nucleon Au Nuclei

G. Gerbier,[a] Ren Guoxiao,[b] and P. B. Price
Physics Department, University of California, Berkeley, California 94720
(Received 21 December 1987)

Using a thin stack of glass detectors to measure Z/β of forward-projected fast fragments from interactions of 900-MeV/nucleon ^{197}Au nuclei, we measure a cross section of 35 ± 8 mb for charge pickup ($\Delta Z = +1$) from Au to Hg, and we infer a mean velocity downshift $\delta\beta \approx -0.004$ and a mean momentum downshift $\delta p_{\parallel} \approx -6$ GeV/c for Au to Hg, 2 orders of magnitude larger than observed for charge pickup by light nuclei. Implications of this result are discussed.

PACS numbers: 25.70.Np

In a study of collisions of relativistic ^{197}Au nuclei at the Lawrence Berkeley Laboratory Bevalac, we have used thin VG-13 phosphate-glass track detectors[1] to look for exotic processes such as production of fractionally charged[2] or high-$P_{\perp}$ projectile fragments and mass pickup by the projectile that might signal the production of a metastable, abnormally dense object.[3] Herein we report the surprising result that in charge-pickup reactions of Au projectiles ($Z=79$) the resulting Hg nuclei ($Z=80$) suffer extremely large momentum loss, $\simeq 6$ GeV/c, without destruction.

Our equipment was extremely simple and compact, consisting of a 1-cm-thick Al target of 25 cm^2 area in contact with a stack of five 1.8-mm-thick plates of VG-13 glass. This assembly was irradiated at normal incidence with 6200 ^{197}Au nuclei of energy 960 MeV/nucleon. The Al and the glass were each about 0.2 interaction length thick. The surviving Au nuclei had energies of $\simeq 800$ and 650 MeV/nucleon at the top and bottom of the glass stack.

The VG-13 can be regarded as a fine-grained Z/β detector with unprecedented resolution. Each plate was etched in a solution of hydrofluoric acid, producing conical etch pits at the points of entrance and exit of nuclei with Z/β above the threshold of $\simeq 70$. With five plates, this yields ten independent measurements of Z/β for each event with $Z/\beta > 70$. The following properties of VG-13 are relevant to this study: (1) If we denote the response by $s \equiv v_T/v_G$, where v_T and v_G are the etch rate along the track and the general surface removal rate, calibrations with relativistic U, Au, and La nuclei and their projectile fragments[1] show that s increases roughly as $(Z/\beta)^n$, with $n \approx 10$. (2) The sampling thickness, which is the portion of trajectory over which the deposited energy contributes to s, is given by $y_s = hs/(s+1)$, where h is the thickness of material removed by the etchant. For the Au beam and etching in HF, $s \approx 2.5$, $h = 44$ μm, and so $y_s = 30$ μm. (3) The standard deviation in determination of Z/β is very small.[1] In the present experiment we determined that σ_Z (at given β) for a single etch pit varies from $\simeq 0.18$ for $Z=79$ to $\simeq 0.22$ for $Z=74$. Using all ten etch pits, we achieved a resolution of $\sigma_Z = 0.056$ for the Au beam.

We used an automated system to locate and measure events on all ten surfaces of glass, with respect to fiducial Au tracks at two opposite corners of the glass. A VAX 750 computer operates two motors that provide a raster scan in the horizontal plane. A charge-coupled-device camera views the glass in transmitted light through the optics of a Leitz Metalloplan microscope. With this illumination each etch pit is a dark circular disk on a light background. Scanning is done at 120×. A Vicom image processor digitizes each field of view and stores the location of the centroid of each etch pit. At the end of the scan, the magnification is changed to 600×, the computer centers each etch pit, the image is focused by an autofocus device and digitized, and the image processor locates the perimeter of the etch pit by a gradient operation followed by thresholding and thinning operations. The perimeter is fitted by a circle, providing the radius R of the etch-pit mouth and the absolute location X, Y relative to the fiducial events. The standard deviation of the measurement of R expressed in terms of charge is < 0.05, negligible compared with the inherent resolution of the glass ($\sigma_Z = 0.18$). The standard deviation in the coordinates is 2 μm; for a particle penetrating all five glass plates, the resulting standard deviation in zenith angle is $\sigma_\theta \lesssim 0.2$ mrad, which makes feasible the measurement of small transverse momenta of projectile fragments. Background flaws and tracks of slow particles are rejected by the requirement that a valid event show up at all ten surfaces within an angle of ~ 20 mrad to the beam direction.

For a given surface the distribution of etch-pit radii exhibits peaks corresponding to charges of fragments, as shown in Fig. 1. The peaks are well defined because (a) the resolution in Z/β is excellent; (b) projectile fragmentation almost always removes nucleons from the projectile without appreciably changing the velocity of the fragment; and (c) the Al and glass stack are too thin for differential slowing of the Au and fragments to broaden the Z/β distributions appreciably. Gaussian fits to the peaks in Fig. 1(a) enable us to map etch-pit radius into Z, for charges from 79 (Au) down to $\simeq 73$, giving the Z distribution shown in Fig. 1(b). For each of the ten surfaces such a mapping was done.

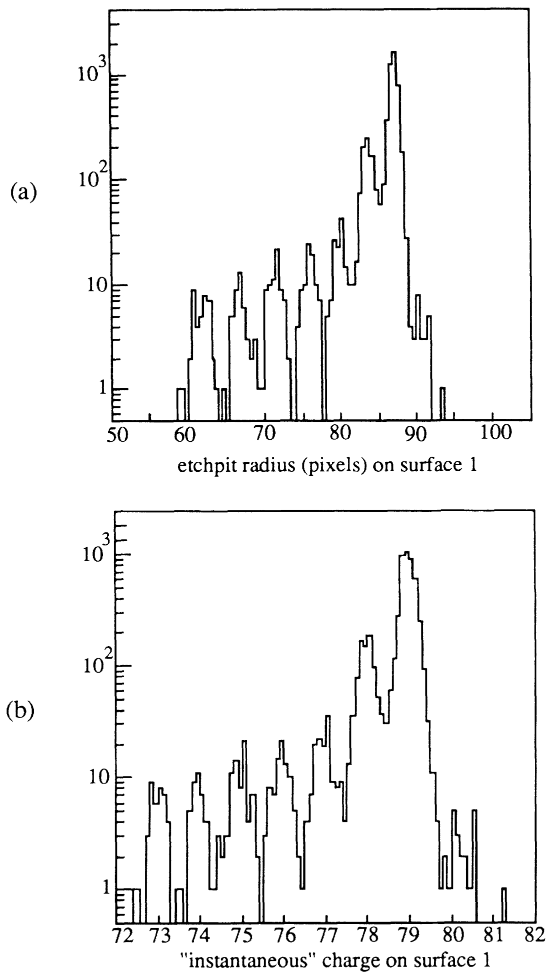

FIG. 1. (a) Distribution of radii of conical etch pits at surface 1 (first glass plate); (b) distribution of electrical charges of nuclei inferred from (a).

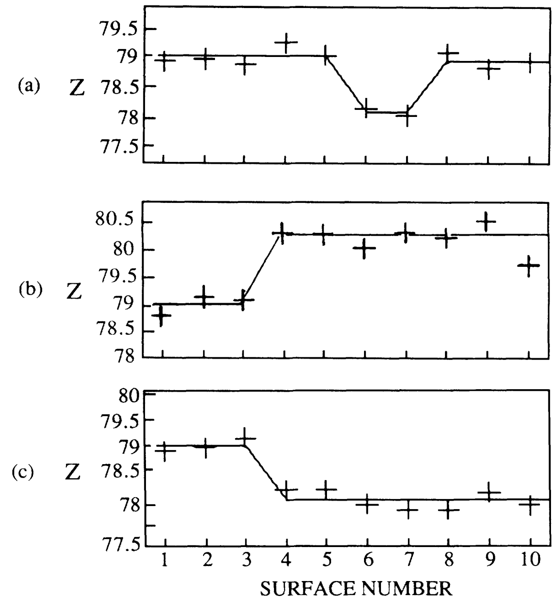

FIG. 2. Examples of measurements of ionic charge states at all ten surfaces for a Au nucleus (a) with one electron attached at adjacent surfaces 6 and 7, (b) that converts to a Hg nucleus with velocity downshift between surfaces 3 and 4, and (c) that fragments into a Pt nucleus between surfaces 3 and 4.

As a result of the capture and stripping of atomic electrons, with mean free paths λ_c and λ_s that depend on energy and charge, the atomic charge state fluctuates along the trajectory. For a mean energy of 730 MeV/nucleon for Au in VG-13, one expects[4] $\lambda_c \approx 460$ μm and $\lambda_s \approx 80$ μm. If we denote the thickness of the glass stack by H ($=9$ mm) and the fragmentation mean free path by λ_{frag} ($=4$ cm), the following inequalities hold: $y_s < \lambda_s \ll \lambda_c \ll H \ll \lambda_{frag}$. Thus a single etch pit usually samples a single charge state, and few nuclei fragment in the glass stack. By the sampling of the charge state of each particle at all ten surfaces, it is possible to distinguish atomic from nuclear charge. Figure 2 gives examples of sequences of ten measurements in which one can detect (a) single-electron pickup and stripping; (b) charge-exchange interaction with gain of one unit of nuclear charge; and (c) fragmentation with loss of one unit of nuclear charge. Our analysis of events includes algorithms for unbiased determination of true nuclear charge and detection of fragmentation with loss of as little as one charge. Often the occurrence of a single-electron charge state at one surface is accompanied by a single-electron charge state at the adjacent surface. The frequency of occurrence of a correlated pair is related to the relative sizes of y_s and λ_s and offers us a direct way of measuring λ_s. We then get λ_c by measuring the ratio $n(+78)/n(+79)$ for Au nuclei. The results, $\lambda_s \approx 90$ μm and $\lambda_c \approx 560$ μm, agree well with the calculated values.

Our algorithm determines which etch pits are due to one-electron and two-electron nuclei, excludes them from the analysis, and averages the measurements of charge obtained from etch pits due to fully stripped nuclei. Figure 3(a) shows the resulting distribution of nuclei that interacted in the Al target and upstream matter and did not interact in the glass stack. Figure 3(b) shows the distribution of nuclei that emerged from the Al target as Au nuclei (defined by $Z=79\pm0.3$) and interacted in the glass, with $|\Delta Z| \geq 0.7$. As Table I shows, the cross sections for Au fragmenting to $Z=78$, 77, 76, 75, and 74, obtained from interactions in the glass, agree within statistics with those measured for Au on Al by Binns *et al.*,[5] who used a combination of two ion chambers and a Cherenkov detector. Cross sections calculated for the distribution of nuclei exiting from the Al target [Fig. 3(a)] are consistent with the values in Table I when we take into account passage through two scintillator paddles upstream from the target.

We now focus on the events in which Au interacts to

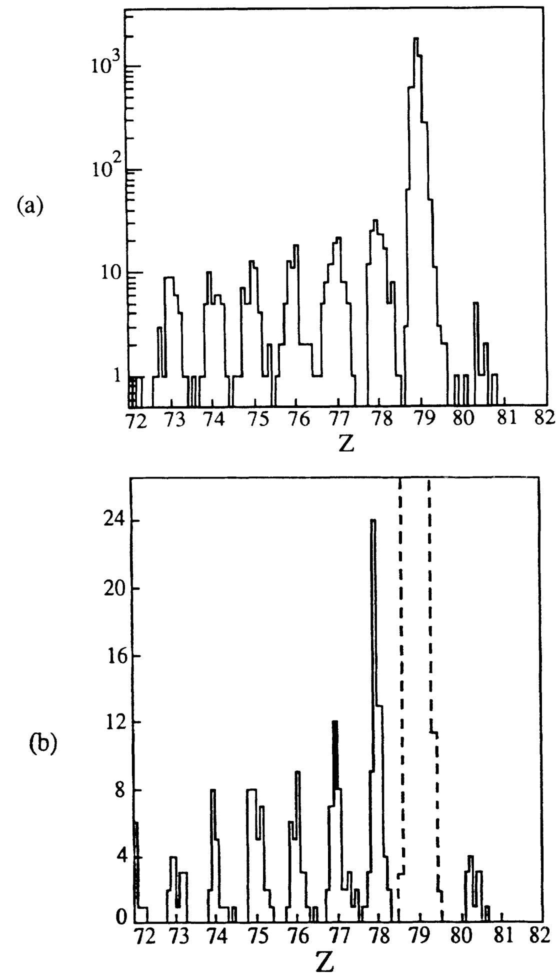

FIG. 3. (a) Distribution of nuclear charges for particles emerging from the Al target and not interacting in the glass stack; (b) distribution of nuclear charges for Au nuclei that interacted in the glass (dashed line indicates Au nuclei that did not interact).

produce nuclei with $Z \geq 80$. In both Figs. 3(a) and 3(b) we see that the Z inferred *assuming no change of* β is an integer for $Z \leq 79$ but is displaced for $Z \geq 80$. For the interactions in Al and upstream matter, there are ten events with a mean apparent charge $\langle Z \rangle \equiv Z(\beta_i/\beta_f) = 80.41$, with a standard deviation of 0.05 for the mean. For the interactions in glass, there are twelve events with $\langle Z \rangle = 80.32$, with a standard deviation of 0.04 for the mean. The function that we use to convert from etch-pit radius R to Z/β is based on calibrations of VG-13 with beams of U, Au, and La at several energies, which establish that $R \approx f(Z/\beta)$ for relativistic particles with $\beta \gtrsim 0.7$. Over a limited velocity interval, use of a restricted-energy-loss model, $R = f(\mathrm{REL})$, or a total-energy-loss model, $R = f(dE/dx)$, leads to the same value for $\langle Z \rangle$ as does a model with $R = f(Z/\beta)$. We conclude that the systematic error in $\langle Z \rangle$ arising in the

TABLE I. Interactions of Au inside the VG-13.

Z of fragment	σ (This work)	σ (Binns *et al.*)[a]
78	320 ± 34	314 ± 31
77	138 ± 22	162 ± 16
76	97 ± 19	112 ± 5
75	117 ± 21	86 ± 4
74	66 ± 16	83 ± 4
"80"	44 ± 13[b]	...

[a]Reference 5.
[b]$\sigma = 25 \pm 8$ mb for Au → Hg based on particles leaving Al target. Combining the data for interactions in Al and in VG-13 gives 22 events and $\sigma = 35 \pm 8$ mb.

conversion from R to Z is, at most, 0.1. Chemical nonuniformities in the glass might, in principle, cause a large deviation in etch-pit radii in a local region at top and bottom of one sheet but should not propagate to another sheet. We might, in principle, attribute the nonintegral charge of the ten events with $\langle Z \rangle = 80.41$ to slowing due to scraping of the beam pipe, since we did not measure their charge before they exited from the Al target, but we could not explain in this way the result $\langle Z \rangle = 80.32$ for the twelve events that interacted in the glass.

With only five glass plates, there is insufficient slowing to determine Z and β separately. Rejecting the possibility that Z increased to a fractional charge $\simeq 80.33$, we attribute the increase in Z/β to a decrease in β. The simplest hypothesis, and the one that requires the smallest decrease in β, is that the collision results in charge pickup from 79 to 80. With $R = f(Z/\beta)$, we infer that $\delta\beta/\beta_i = (80 - \langle Z \rangle)/80 = -0.4/80$ for $\langle Z \rangle = 80.4$, and that $\delta\beta = -0.0044$, for $\beta_i = 0.86$. This result is the major experimental finding of this Letter.

We have learned that Waddington and co-workers, in a followup to the work in Ref. 5, have measured a cross section of 32 mb for charge pickup with $\Delta Z = +1$ by 900-MeV/nucleon Au nuclei in a carbon target.[6] This agrees, within statistics, with our results of 44 ± 13 mb for charge pickup in interactions in the glass and of 25 ± 8 mb for charge pickup in interactions in the Al, and supports our interpretation that $Z = 80$. (The Cherenkov detector of Binns *et al.*[5] is insensitive to a downshift of β such as we observed at 900 MeV/nucleon.)

In other studies of charge increase by relativistic ions, Greiner *et al.*[7] saw very small momentum downshifts, $\langle \delta p_{\parallel} \rangle \approx -50$ to -100 MeV/c, in charge exchange by 1-GeV/nucleon ^{12}C and 2-GeV/nucleon ^{12}C going to ^{12}N, and Olson *et al.*[8] observed very small momentum downshifts in charge exchange by 1.7-GeV/nucleon ^{18}O going to ^{18}F. In charge-exchange reactions of 950-MeV/nucleon ^{20}Ne going to ^{20}Na and ^{20}F, Bachelier *et al.*[9] observed a strong peak at a momentum loss of ~ 350 MeV/c, which they interpreted as charge exchange with excitation of the delta resonance.

The cross section for charge pickup of Au with large momentum loss is a factor of more than 30 greater than for charge pickup of light ions[7,8] with small momentum loss. Our low statistics do not exclude the possibility that Au can pick up charge with either a small or a large momentum loss. Possibly the process with small momentum loss has a cross section that increases only slowly with projectile charge whereas the cross section for the process with large momentum loss increases rapidly at large projectile charge.

The large velocity decrease we observed corresponds to a momentum downshift $\langle \delta p_{\parallel} \rangle \approx -6$ GeV/c. On only one previous occasion[10] has such an enormous downshift in momentum of a relativistic projectile fragment been reported, and that was for a single event. Our result poses an interesting problem: how to add charge and downshift the momentum of all 200 nucleons by the same amount, $\simeq 30$ MeV/c, without disintegration of the nucleus. We discuss two possible mechanisms.

(1) The sweeping up of two nucleons (a proton and a neutron) from an Al nucleus or from a nucleus in the glass (containing mainly O, P, Ba, and Na) would account quantitatively for a $\delta\beta$ of -0.004 but would leave the Hg nucleus with ~ 1.8 GeV of excitation energy to dispose of as well as an angular momentum $\simeq 10^2 \hbar$ is the attachment were at large impact parameter. The sweeping up of a single proton would account for $\delta\beta = -0.002$ and is not completely excluded by our results.

(2) A quasielastic scatter of a Au nucleus (mass M) off a proton (mass m) in a target nucleus would project the proton at an angle to the beam given in a nonrelativistic approximation by $\phi \approx \arccos(w/w_{\max})$, where the energy at $\phi = 0$ is

$$w_{\max} = \frac{2mc^2\beta^2\gamma^2}{1 + 2m\gamma/M + (m/M)^2}.$$

For $\phi \lesssim 30°$, such a scatter would result in a momentum downshift of the desired magnitude. Charge exchange of the proton with a neutron in the Au would lead to a neutron projected into the beam direction and a conversion of the Au into Hg. Thus, either a neutron or a proton with high energy, up to ~ 5 GeV, would recoil in the beam direction. Madey *et al.*[11] have detected neutrons emitted in the forward direction with energies greater than 2.5 GeV in 800-MeV/nucleon Au+Au interactions.

The presence of a shoulder on the high-charge side of the Au peak in Fig. 3(a) suggests that a large momentum downshift, without charge change, might occur in inelastic collisions of Au nuclei, with a cross section comparable to that for momentum downshift with charge increase. Our statistics for production of Hg with large momentum downshift are extremely limited—ten events supposedly produced in the Al target and twelve events definitely produced in the glass. To improve the statistics and to explore further the mechanism of nondestructive high momentum transfer, we plan to use thick stacks of VG-13 plates in the HISS magnetic spectrometer to measure $\delta\beta$, magnetic rigidity, and range (and thus mass) of Hg and other nuclear fragments, as well as their interaction cross section (or lifetime).

We are indebted to H. J. Crawford and the staff of the Lawrence Berkeley Laboratory Bevalac for the Au beam and to R. Madey, M. H. Salamon, and C. J. Waddington for useful discussions. This work was supported in part by National Science Foundation Grant No. INT-8611276 and by the U.S. Department of Energy .

[(a)]Permanent address: Département de Physique de Particles et Section d'Etude Physique, Centre d'Etudes Nucléaires de Saclay, BP No. 2, 91191 Gif-sur-Yvette, France.

[(b)]Permanent address: Institute of High-Energy Physics, Academia Sinica, Beijing, China.

[1]P. B. Price, H.-S. Park, G. Gerbier, J. Drach, and M. H. Salamon, Nucl. Instrum. Methods Phys. Res., Sect. B **21**, 60 (1987).

[2]A. De Rújula, R. C. Giles, and R. L. Jaffe, Phys. Rev. D **17**, 285 (1978); G. F. Chapline, Phys. Rev. D **25**, 911 (1982); B. A. Arbuzov, Sov. J. Nucl. Phys. **42**, 342 (1985); G. L. Shaw and R. Slansky, Phys. Rev. Lett. **47**, 887 (1981); M. Gyulassy, in *Short-Distance Phenomena in Nuclear Physics,* edited by D. H. Boal and R. M. Woloshin (Plenum, New York, 1983), p. 237.

[3]T. D. Lee and G. C. Wick, Phys. Rev. D **9**, 2291 (1974); J. D. Bjorken and L. McLerran, Phys. Rev. D **20**, 2353 (1979); A. Kerman and S. Chin, Phys. Rev. Lett. **43**, 1292 (1979).

[4]M. H. Salamon *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **224**, 217 (1984).

[5]W. R. Binns *et al.*, Phys. Rev. C **36**, 1870 (1987).

[6]C. J. Waddington, private communication.

[7]D. E. Greiner *et al.*, Phys. Rev. Lett. **35**, 152 (1975).

[8]D. L. Olson *et al.*, Phys. Rev. C **24**, 1529 (1981).

[9]D. Bachelier *et al.*, Phys. Lett. B **172**, 23 (1986).

[10]P. B. Price *et al.*, Phys. Rev. Lett. **50**, 566 (1983).

[11]R. Madey *et al.*, in Proceedings of the Eighth High Energy Heavy Ion Study, Berkeley, California, 1987 (to be published).