Systematics of charge-pickup reactions by GeV/nucleon heavy nuclei

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(Received 11 October 1988)

We have measured cross sections for inclusive reactions in which 1.7 GeV/N ^{56}Fe, 1.46 GeV/N ^{84}Kr, 1.28 GeV/N ^{139}La, and 0.8 GeV/N ^{197}Au increased in charge by one unit. Combining these results with data on charge pickup by ^{12}C, ^{18}O, and ^{20}Ne projectiles, we find that the cross section for charge pickup by $\sim$GeV/nucleon projectiles is generally given to within a factor of 2 by the expression $\sigma_{\Delta Z=+1}=1.7\times10^{-4}\,\gamma_{PT}A_P^2$ (in mb), where $\gamma_{PT}=A_P^{1/3}+A_T^{1/3}-1.0$. This expression, with roles of projectile and target interchanged, equally well fits cross sections for (p,xn) reactions at GeV energies when summed over x. The factor γ_{PT} implies peripheral collisions; the dependence on A_P^2 is the steepest ever reported for a nuclear process.

I. INTRODUCTION

In this paper we will discuss two types of charge pickup reactions between relativistic nuclei—those in which the projectile, of charge Z_P and mass A_P, picks up one unit of charge, and those in which the target, of charge Z_T and mass A_T, picks up in one unit of charge. We ask the reader to keep clearly in mind the distinction between the two types of reactions in what follows. Until now very few measurements had been made of cross sections for charge pickup by relativistic projectile nuclei,[1–5] and no attempt had been made to look at the systematic dependence of cross section on projectile size. In experiments with a magnetic spectrometer at the Lawrence Berkeley Laboratory Bevalac, Lindstrom *et al.*[1] measured very small cross sections (<0.1 mb) for 1.05 and 2.1 GeV/N ^{12}C going to ^{12}N, for H, Be, C, Al, and Ag targets, and Olson *et al.*[2] measured larger (0.5 to 1 mb) cross sections for 1.7 GeV/N ^{18}O going to ^{18}F, for Be and Th targets. Cross sections for production of other isotopes of N (in Ref. 1) and of F (in Ref. 2) were undetectably small. Using a magnetic spectrometer and a time-of-flight (TOF) system at Saturne, Bachelier *et al.*[3] measured the energy transfer in the charge transfer reaction 0.95 GeV/N ^{20}Ne going to ^{20}Na, for C, Y, and Pb targets. They were able to detect two peaks—one at low excitation energy due to $np\rightarrow pn$ and one at $\sim$300 MeV due to excitation of a target nucleon to a delta resonance. Recently, Roy-Stephan[4,5] has reported new results by the same group in which they studied charge pickup by 900 MeV/N ^{20}Ne in H, C, and Pb (Ref. 4) and by 900 and 1100 MeV/N ^{12}C in H, C, and Pb targets. Gerbier *et al.*[6] used an array of phosphate glass dE/dx detectors to measure cross sections for 0.6 to 0.8 GeV/N ^{197}Au going to any isotope of Hg. They reported that this charge pickup reaction has a large cross section, $\sim$35 mb, and is accompanied by a surprisingly large momentum downshift. In contrast with the magnetic spectrometer measurements, the glass detectors recorded all events going to Hg ($Z=80$), regardless of isotope or energy transfer. Finally, at the Eighth High-Energy Heavy-Ion Study held at Berkeley in November, 1987, C. J. Waddington reported cross sections for charge pickup of La and Au in several targets, measured by himself and members of his collaboration, with a combination of scintillators and Cerenkov detectors.[7] They observed a large velocity decrease for projectiles that had undergone charge pickup, but because of the large thickness of their targets they were unable to distinguish an abrupt momentum downshift from gradual differential slowing in the target, which would occur for projectiles that lost many neutrons as well as picked up a unit of charge.

Charge pickup by a stationary target nucleus has been studied almost solely in proton reactions. In a study of charge exchange of 1 GeV protons with various targets, Koptev *et al.*[8] studied charge pickup by the target by measuring the emission angle and energy of the outgoing neutron. Their energy resolution of 100 MeV was sufficiently good to single out neutron production unaccompanied by meson production, $pn\rightarrow np$, but not good enough to select among final states of the target nucleus. Most of the data on charge pickup by a target nucleus have been obtained using radiochemical methods to identify an incomplete sample of radioisotopes. These data have been summarized by Silberberg and Tsao.[9]

The increase by nearly three orders of magnitude in charge pickup cross section in going from C, O, and Ne projectiles to Au projectiles motivated us to study charge pickup by relativistic projectiles of intermediate mass. We report here cross sections for charge pickup by ^{56}Fe, ^{84}Kr, and ^{139}La nuclei using Bevalac beams. An unexpected result of our study, when combined with other data, is that the charge pickup cross section for $\sim$GeV/nucleon projectiles has an extraordinarily steep dependence on projectile mass: $\sigma_{\Delta Z=+1}\approx\text{const}\,A_P^2$.

II. EXPERIMENTAL METHOD

We used an automated system to scan and measure projectile fragments in three stacks of CR-39 track-recording plastic detectors (composition $C_{12}H_{18}O_7$) that had been irradiated several years ago with 1.28 GeV/N La, 1.46 GeV/N Kr, and 1.7 GeV/N Fe nuclei for other experiments.[10,11] Each stack, comprising $\sim$60 sheets of

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dimensions 15 cm$\times$15 cm$\times$0.072 cm, was irradiated at normal incidence with a defocused beam of either La, Kr, or Fe. The sheets were etched in a stirred 6.25 normal NaOH solution for 480 h at 40 °C. Along the track of a particle with charge Z and velocity βc, etching occurs at a rate v_T that exceeds the general etch rate v_G, producing a conical etchpit at the point of entrance and exit of the particle. The ratio $s \equiv v_T/v_G$ is an increasing function of Z/β. When viewed in transmitted light through a microscope focused on a surface, the mouth of an etchpit looks like a dark, circular hole with a well-defined radius. The value of s depends on radius, r, through the relation

$$s=(1+r^2/G^2)/(1-r^2/G^2) ,$$

where $G=v_G t$ is the amount of material removed in etching time t. Since the velocity undergoes essentially no change in projectile fragmentation, measurements of the distribution of values of etchpit radii give the distribution of fragment charges. Each of the ~ 60 plastic sheets provides two independent measurements of Z/β of the particle being studied. This is analogous to having 120 independent ΔE detectors in a semiconductor detector telescope.

A unique feature of the track-etch particle identification technique, which is very advantageous in the study of projectile fragmentation, is that particles as close together as a few hundred Angstroms produce independent regions of radiation damage. This was first established by electron microscopy, which showed that chemically etched tracks of fission fragments had a diameter less than 100 Angstroms and that etched tracks a few hundred Angstroms apart could be resolved.[12] This fact, together with the rapidly rising response as a function of Z/β, means that the size of the etched track of a projectile fragment is governed solely by the broken bonds and displaced atoms in the central few tens of Angstroms of the core of the track and is immune to the presence of delta rays, mesons, nucleons, and minimum-ionizing light nuclei ($Z<6$ for CR-39; $Z<50$ for VG-13) beyond 100 Angstroms of the trajectory of the heavy particle being studied. For example, dissociation of a projectile into a number of fragments in a narrow forward cone would produce discrete, spatially resolved tracks of those fragments with high dE/dx and no tracks of fragments with low dE/dx. In contrast, the signal in a semiconductor detector is proportional to the sum of the dE/dx values of all particles passing through the detector at one time.

Our automated system locates and measures etchpits due to beam particles and relativistic fragments with $Z \geq 8$ on all surfaces of the plastic sheets, with respect to fiducial beam tracks at two opposite corners of the sheets. A VAX750 computer operates X, Y, and Z motors that provide a raster scan in the horizontal plane and maintain satisfactory focus on the top surface of a sheet. The latter is done by mapping the heights of the surface at points on a grid of spacing 1 cm$\times$1 cm before starting the scan, and then letting the computer interpolate to the height for best focus at each location in the horizontal plane. A charge-coupled-device camera views the plastic through the optics of a Leitz Metalloplan microscope at a magnification of 120$\times$. A Vicom image processor digitizes each field of view, stores the location of the centroid of each etchpit and locates the perimeter of each etchpit by a gradient operation followed by thresholding and thinning operations. The perimeter is fitted by a circle, providing the radius of the etchpit mouth and the absolute location X, Y relative to the fiducial events. Surface flaws and low-energy target fragments are rejected by requiring that a valid event show up on at least two surfaces within an angle of 20 mrad to the beam direction. Overlapping etchpits are recognized by evaluating the ratio of perimeter to area. Interactions are recognized by a sudden change in etchpit radius from one sheet surface to the next. Examples will be given in the next section.

III. RESULTS

Table I gives the number of tracks analyzed, the number of fragments with Z large enough to be detected, the measured mean free path for charge-changing interactions, the number of events with a one-unit charge increase and the cross section for this process, the number of events with a two-unit charge increase, and the number of slow particles that passed a first Z/β cut (to be discussed below). The charge standard deviation σ_Z was less than 0.18 for all projectiles and all fragments. We were able to achieve $\sigma_Z \leq 0.2$ for the high-Z fragments by averaging the signals for six successive etchpits. The mean free paths obtained in this work by determining the decrease in number of beam particles as a function of depth in the stacks agreed well with those obtained previously[10,11,24] and with the expression of Westfall *et al.*[23]

Figure 1 shows the distribution of etchpit radii for interactions of La nuclei in a thickness of 2.3 cm of CR-39. A second scale is added to the abscissa to convert from etchpit radius to nuclear charge. A peak due to interactions with $\Delta Z=+1$, as well as peaks at $\Delta Z \leq -1$, are clearly visible. Two events with $\Delta Z=+2$ were detected deeper in the stack and are thus not shown in this figure. The charge standard deviation is approximately independent of Z for the data shown. The distance between charge peaks decreases somewhat with Z, as a consequence of the nonlinear relation between etchpit radius and Z/β given above.

In studying charge pickup reactions in energy loss detectors without a magnetic spectrometer, one must be aware of a potential source of background. There is usually a finite contamination ($\sim 10^{-2}$) of the beam by particles with different charge or velocity from the beam particles, due to scraping of the beam pipe or interactions in gas or other upstream matter. With a plastic stack equivalent to 120 dE/dx detectors, eliminating such background particles is trivial. One first cuts out all particles that enter the stack with etchpit radius different from that corresponding to the value of Z/β for the beam. This step reduces the contamination level to a fraction $\sim 10^{-3}$ of particles with wrong Z and β but correct Z/β. These particles can be cut out automatically by a program that looks for events with Z/β that increases more rapidly with depth in the stack than does Z/β of the beam particles and projectile fragments of the beam. As an additional check that no slow particles were

TABLE I. Charge-pickup interactions in a CR-39 target.

Beam (GeV/N)	No. of tracks analyzed	No. of fragments	λ(cm)	No. of events with $\Delta Z=+1$	Cross section (mb)	No. of events with $\Delta Z=+2$	No. of slow particles
La(1−1.28)	15 299	7540	4.8	88	21	2	5
Kr(1.28–1.45)	12 452	4000	6.44	23	7	0	1
Fe(1.59–1.7)	18 295	4300	7.9	2	0.5	0	4

mistakenly interpreted as charge pickup events, after completing the automated analysis of each stack we used the manual control on the microscope to inspect the etch-pits downstream from each interaction identified as leading to a charge increase. By inspecting the signals in each CR-39 sheet we were able to reject any events whose apparent charge increased slowly from sheet to sheet due to slowing, and to accept only events that abruptly increased in charge in a particular sheet. Because of the small number of charge pickup events, this manual procedure does not take long to complete. The last column of Table I gives the number of slow particles that were cut out by this manual procedure.

Figure 2 shows several examples of interactions. In (a) and (b) are interactions of La with increases of charge by one and two units. In (c) is an example of a particle with initial Z/β equal to that of the La but with low Z and low β, as can be seen from the rise in its ionization rate with depth in the stack. This particle loses several units of charge by projectile fragmentation. If its ionization rate had been sampled only sparsely, the increase in ionization rate might have been attributed to charge pickup instead of to slowing. In (d) and (e) are interactions of Kr and Fe with pickup of one unit of charge. Examples of pickup and fragmentation with loss of charge, as well as of electron attachment and stripping, are shown for gold projectiles in Ref. 6.

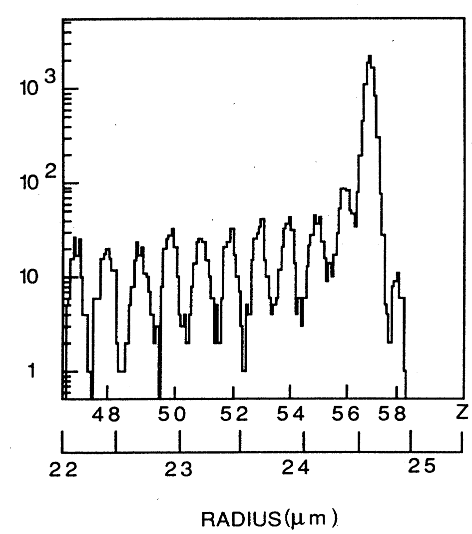

FIG. 1. Distribution of charges of 1.28 GeV/N ^{139}La nuclei and of projectile fragments with about the same rapidity and direction as the beam, produced in a CR-39 target. The absicssa is linear in etchpit radius.

As a test of the validity of the present technique, one can measure the mean free path for fragmentation of the nuclei resulting from charge loss and pickup reactions. Fragmentation mean free paths of products of charge loss at Bevalac energies, using CR-39 detectors, have been reported previously and found to be roughly consistent with expectation.[10,24] In the case of charge pickup, only for La were enough events produced to make a crude estimate of the mean free path of the product nuclei, which in that case were Ce. We found that, within the statistics, the number of Ce nuclei as a function of depth was consistent with that given by the expression

$$N_{\mathrm{Ce}}(x)=N_{\mathrm{La}}(x)x/\lambda_{\Delta Z=+1}\ , \qquad (1)$$

which is valid when the charge-changing mean free paths for La and Ce are equal. Approximate equality is about what one would expect in a geometrical model of projectile fragmentation, since the Ce product nuclei and La projectiles have comparable numbers of nucleons, and the mean free path depends on $A_T^{1/3}+A_P^{1/3}$.

Figure 3 shows the cross sections for projectile charge *increase* obtained in the present study and by other investigators. Where a group has studied charge pickup in more than one target, we have displayed only data for the target closest to C in this figure. Errors for ^{12}C, ^{18}O, ^{20}Ne, and ^{139}La are smaller than the size of the points. (Data for additional targets are shown in Fig. 4.) For comparison, Fig. 3 also shows cross sections for fragmentation with *loss* of one unit of charge measured in the present study and by others. For both charge increase and charge decrease, cross-section data for a given charge are assumed over all isotopes of that charge, with the one exception of ^{20}Ne, for which a spectrometer was set to look at ^{20}Na but not at ^{19}Na. Since the reaction $^{18}\mathrm{O}\rightarrow{}^{17}\mathrm{F}$ was found to have a negligible cross section,[2] we think it is unlikely that $^{20}\mathrm{Ne}\rightarrow{}^{19}\mathrm{Na}$ would contribute much to the Na isotopes.

For charge pickup, the number of particle-stable isotopes that could be reached by change exchange plus neutron emission increases as a function of A. For charge pickup by ^{12}C, only N^{12} is particle-stable; for ^{16}O (which was not studied) the lifetime of ^{16}F is only $\sim 10^{-19}$ s and lighter F isotopes are particle-unbound, so that the charge-pickup process could not occur unless a proton were swept up by the projectile; for ^{20}Ne both ^{20}Na and ^{19}Na are particle-stable; for ^{18}O both ^{18}F and ^{17}F are particle-stable; for ^{56}Fe at least six Co isotopes could be produced by charge exchange plus neutron removal; and in charge-pickup reactions of ^{84}Kr, ^{139}La, and ^{197}Au the number of isotopes that could be produced by charge exchange and neutron removal is larger still.

In Fig. 3 the straight lines, which are weighted least-squares fits to $\log_{10}\sigma_{\Delta Z=-1}$ and $\log_{10}\sigma_{\Delta Z=+1}$ as a function of $\log_{10} A_P$, have slopes of 0.47±0.01 and 2.29±0.28. Expressed as a power law, the exponent for charge-pickup reactions summed over all isotopes is about five times greater than the exponent for reactions with loss of one unit of charge, summed over all isotopes.

Figure 4 shows the weak dependence of projectile charge-pickup cross section on target mass. The lines through the data are consistent with power laws with exponents ~0.3±0.1. This value suggests that only the periphery of the target is participating in projectile charge pickup. For some time it has been known[1,2] that partial cross sections for relativistic nucleus-nucleus collisions resulting in loss of only a few nucleons can be expressed as the product of a factor $\gamma_{PT}=A_P^{1/3}+A_T^{1/3}-c$, which expresses the peripheral nature of these collisions, and a factor γ_{PF}, which depends on the projectile and fragment and contains the nuclear physics. We find that the target dependence for all of the data in Fig. 4 can be represented quite well by proportionality to $\gamma_{PT}=A_P^{1/3}+A_T^{1/3}-c$, with $c\sim1.0$. Our own results, presented in Table I, are for a CR-39 target of composition $H_{18}C_{12}O_7$. Since the dependence of cross section on target mass is weak, it suffices for us to approximate the mass of our target by a weighted average value 7.41 amu.

In order to include data for charge pickup in widely different targets, we assumed that $\sigma_{\Delta Z=+1}$ is proportional to γ_{PT} and did least squares fits for 18 combinations of targets and projectiles for which data were available. The best power law, with the factor γ_{PT} included, gives a charge-pickup cross section proportional to $A_P^{1.94}$, which is smaller than the dependence $A_P^{2.29}$ found earlier with A_T fixed at carbon because of the additional weak dependence of the factor γ_{PT} on A_P. The error in the exponent is ~0.2. Of course, no such simple expression can hope to account for details of nuclear structure of the

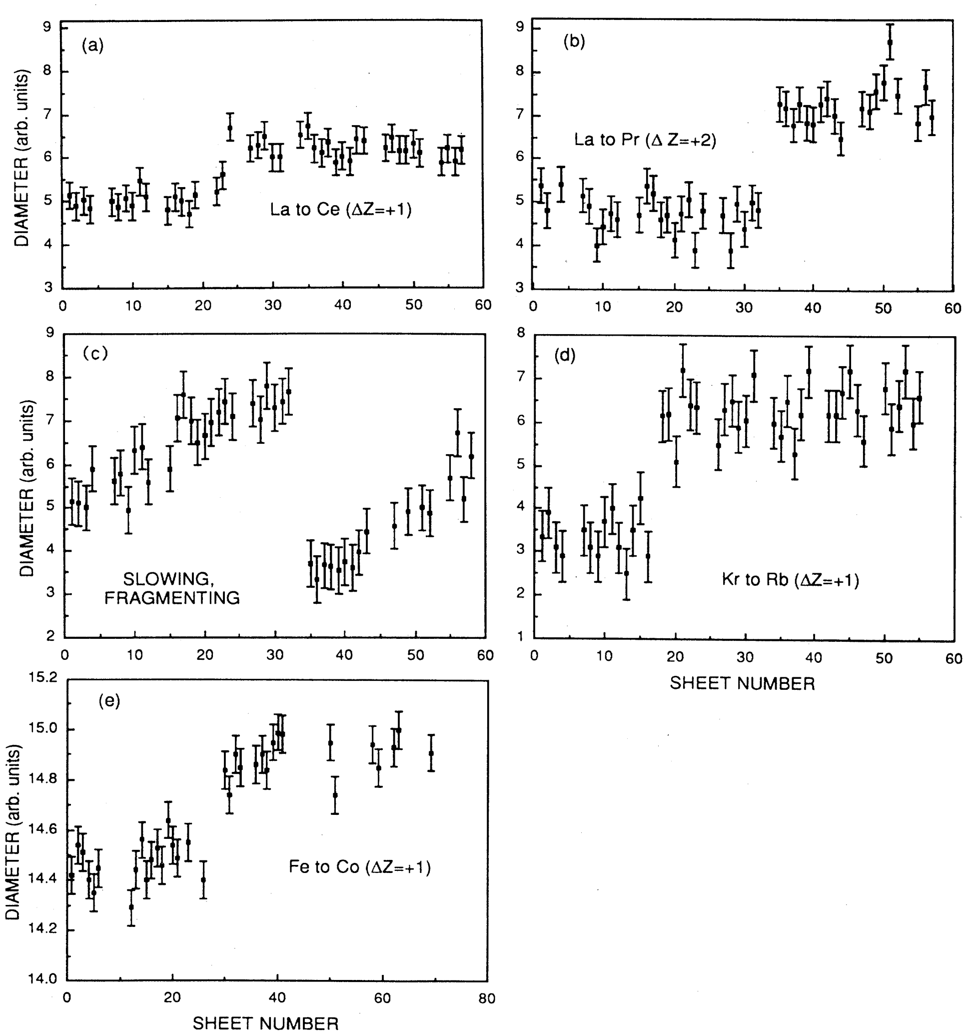

FIG. 2. Examples of charge-changing interactions; (a) 1.28 GeV/N La nucleus ($Z=57$) changes into a Ce nucleus ($Z=58$) as determined by measurements of etchpit diameter in many successive sheets of CR-39; (b) La changes into a Pr nucleus ($Z=59$); (c) a stray particle in the beam with the correct initial Z/β but with low Z and β slows and fragments into a lower charge; (d) 1.45 GeV/N Kr nucleus changes into a Rb nucleus ($Z=37$); (e) 1.7 GeV/N Fe nucleus changes into a Co nucleus ($Z=27$).

projectile and the product in the final state. The exponent is compatible with the value 2, and in fact the expression, quadratic in A_P, fits the 18 data points quite satisfactorily:

$$\sigma_{\Delta Z=+1}=1.7\times10^{-4}\gamma_{PT}A_P^2 \text{ (in mb)} , \quad (2)$$

where the coefficient is determined by a least-squares fit. This expression fits the straight line for charge pickup in Fig. 3 to within about 25% over the entire mass interval $12 \le A \le 197$.

Charge pickup data for relativistic deuterons going to ^{3}He exist but are too fragmentary[13] to enable us to test the validity of Eq. (2) at very low A_P.

The beam energy per nucleon for the Fe, Kr, La, and Au experiments decreased with A_P, and it is natural to ask if the steep dependence of charge pickup cross section on A_P might be at least partly due to a decrease of the cross section with energy. At very low energies (a few tens of MeV per nucleon), where significant mass transfer such as by fusion or compound nucleus formation can occur, one would expect large cross sections for charge pickup. However, those measurements made on the same beams at various relativistic energies indicate that there is little or no energy dependence of the cross section for charge pickup in the energy interval ~0.6 to 2 GeV/N. Lindstrom *et al.*[1] found no difference in charge pickup cross sections for ^{12}C at 1.05 and 2.1 GeV/N; Roy-Stephan[4,5] found no difference in charge-pickup cross section for ^{12}C at 0.9 and 1.1 GeV/N; Waddington[7] found no difference for charge pickup of La on CH_2, C, and Cu targets at energies 0.8 to 1.2 GeV/N. No data have been published for charge pickup at energies between ~0.01 and ~0.6 GeV/N. (While this paper was in the reviewing stage, C. J. Waddington sent us unpublished data showing a strong increase in the charge-pickup cross section for Au as the beam energy decreased below 700 MeV/N, and a weak decrease for La and Ho beams.)

IV. CHARGE PICKUP IN A STATIONARY TARGET

Silberberg and Tsao[9] developed a number of almost purely empirical equations with which to fit the roughly 700 published (p,xn) cross sections and to predict cross sections for new (p,xn) reactions. This notation signifies a reaction in which an incident proton is absorbed or suffers charge exchange with a stationary target and x neutrons are emitted. To account for the dependence on Z_T, A_T, and E over a wide range of these variables required more than 50 parameters, of which about 20 were used to fit the dependence on Z_T and A_T. We have used these empirical equations, with the roles of projectile and target interchanged, to calculate pickup cross sections for all the experiments summarized in Fig. 3. To correct the equations to reflect the fact that our targets are heavier than protons, we made the assumption, discussed earlier, of factorization of the cross section into the projectile factor $\gamma_{PT}=A_P^{1/3}+A_T^{1/3}-1.0$ and into a target factor given by the equations. Our correction to the cross section is the ratio of γ_{PT} for one of our projectiles to γ_{PT} for a proton. This correction ranges between 1.25 and 1.74. We must sum the cross sections over all possible values of x, the number of emitted neutrons. The cross sections calculated in this way are designated in Fig. 3 by the X's. The agreement between the calculated values

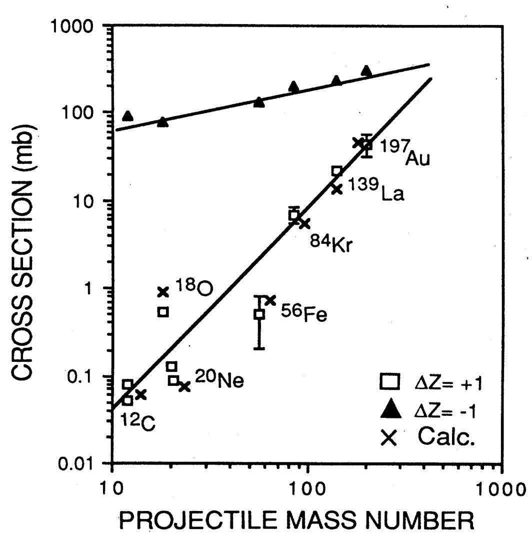

FIG. 3. Dependence of cross sections for charge pickup and single-charge-loss on projectile mass. Data are for 1.05 and 2.1 GeV/N ^{12}C in C (Ref. 1); 0.95 GeV/N ^{20}Ne in Al (Ref. 3); 0.9 GeV/N ^{12}C and ^{20}Ne in C (Refs. 4 and 5); 1.7 GeV/N ^{18}O in Be (Ref. 2); 0.8 GeV/N ^{197}Au in Al (Ref. 6); and ^{56}Fe, ^{84}Kr, and ^{139}La in CR-39 (this work; see Table I). Cross sections are summed over all isotopes of the product with nuclear charge Z_P+1. Solid lines are least-squares fits to data. Calculated values are obtained from Ref. 9 as discussed in the text.

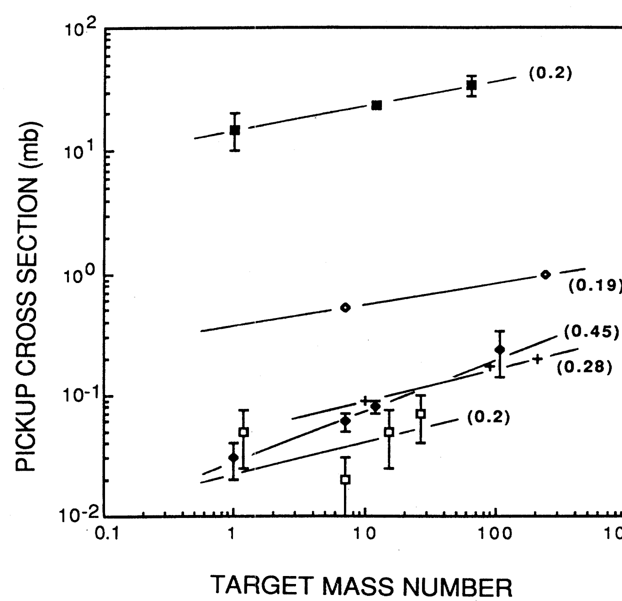

FIG. 4. Dependence of cross section for change pickup on target mass. Symbols are ■ (1.28 GeV/N La; Ref. 7); ◇ (1.7 GeV/N ^{18}O; Ref. 2); + (0.9 GeV/N ^{20}Ne; Ref. 5); ◆ (2.1 GeV/N ^{12}C; Ref. 1); □ (1.05 GeV/N ^{12}C; Ref. 1). Lines are least-squares fits to power laws; exponents are labeled.

and our data is within the uncertainty of a factor of 1.6 claimed in Ref. 9. We have thus shown that the Silberberg and Tsao expressions can easily be scaled to predict cross sections for charge pickup by relativistic heavy ions.

Conversely, the very simple expression in Eq. (2), which with one free parameter roughly fits the projectile charge-pickup data in Figs. 3 and 4, also roughly fits target charge-pickup data for GeV protons, as indicated by the proximity of the straight line in Fig. 3 to the points labeled X. The only point not predicted to within a factor 2 is the ^{18}O point, which is a factor of 4 too high. This one discrepancy suggests that the neutron/proton ratio of the nucleus picking up charge plays an important role. It is known[9] that the cross sections for (p,xn) reactions depend on the neutron/proton radio of the nucleus that picks up charge, and in fact the deviations of points with high and low N/Z from the simple power law are tracked well by the X's, which are the values calculated from (p,xn) reactions.[9]

According to data collected by Silberberg and Tsao and fitted by their semiempirical expressions, the energy dependence of the cross section for (p,xn) reactions decreases to a roughly constant value at an energy between ~ 100 and ~ 1000 MeV, consistent with our discussion of energy dependence for heavy projectiles in the previous section.

V. DISCUSSION

The strength of the dependence of the cross section for a particular type of interaction on target mass has long been used as a clue to the mechanism involved. A linear dependence of cross section on A usually indicates a long mean free path of the projectile in nuclear matter; *a* dependence on $A^{2/3}$ indicates a very short mean free path and thus an interaction at the surface; and a dependence on $A^{1/3}$ indicates an interaction at the perimeter. Our finding—that $\sigma_{\Delta Z=+1}$ depends roughly on $A_P^2\gamma_{PT}$—is intriguing. The proportionality to γ_{PT} suggests that the collision is peripheral, and this is supported by the observation that the projectile, in picking up charge, survives with little change of velocity (although its momentum may decrease substantially).

The dependence of cross section on A_P^2 is the steepest A dependence ever reported for a nuclear process, as can be confirmed by consulting recent reviews of high-energy collisions with atomic nuclei. For projectile energies greater than 5 GeV/N, see the review by Fredriksson *et al.*[14]; for projectile energies ~ 1 to 2 GeV/N, see the proceedings of the series of Lawrence Berkeley Laboratory High-Energy Heavy-Ion Studies. The large asymmetry in the dependence of $\sigma_{\Delta Z=+1}$ on A_P and A_T seems to rule out both exchange of a virtual pion between target and projectile and direct charge-exchange between a neutron in the projectile and a proton in the target as the dominant mechanism for charge pickup by the projectile. The latter process is also ruled out by the work of Koptev *et al.*,[8] which showed that the cross section for charge-exchange scattering of 1 GeV protons by targets from Li to Pb increases only as $\sim A_T^{0.4}$. As we stated earlier, this group looked at reactions leading to single neutrons unaccompanied by meson production or target fragmentation. From this result, transformed into the rest frame of the protons, we infer that charge-exchange scattering of a proton in a stationary target by a GeV/N projectile without meson production would not account for our A_P^2 dependence.

We are left with several possibilities, each of which may dominate in different regimes of A_P. (1) The projectile may increase its charge without change of mass number by emitting a real, negative meson, possibly through the intermediate step of a delta resonance.[3–5] Bachelier *et al.*[4,5] have observed two modes of charge pickup by ^{12}C and ^{20}Ne—one at low excitation energy involving one-pion exchange and several particle-hole states, and one at ~ 300 MeV involving one-pion exchange and excitation of a delta resonance in the target. The cross section for the low-excitation process shows no significant dependence on projectile mass. The cross section for the higher excitation process shows a strong dependence on projectile mass, although the difference in projectile mass between C and Ne is not large enough to permit one to establish accurately a power-law dependence of cross section on A_P from the published data. (2) Charge exchange leading to an increase in projectile Z could occur at still higher excitation energy, accompanied by knockout or evaporation of neutrons. Such a process has not been directly studied by spectroscopic techniques. (3) The projectile might increase its charge by absorbing a proton (at least) from the target and emitting one or more nucleons to carry out some of the momentum and internal energy. Such a process was suggested by Gerbier *et al.*[6] to account for the large momentum downshift in charge pickup by 0.8 GeV/N Au projectiles. For several reasons, the cross sections for processes (2) and (3) will increase rather rapidly with Z_P and A_P. The number of available particle-bound excited levels (taking into account their quantum numbers when necessary), the number of particle-bound isotopes with $Z=Z_P+1$, the ratio N/Z of the projectile, and the probability of evaporating neutrons without evaporating a proton are all quantities that tend to increase with projectile size. Any or all of these quantities may relate to the steep dependence of charge-pickup cross section on A_P. We are not yet in a position to develop a quantitative model of the A_P dependence. Instead, we will cite several experiments and theoretical papers that deal with trends of cross sections with A_P.

In one previous experiment a dependence on A_P steeper than linear was seen: In negative pion emission at forward angles in collisions of protons, deuterons, alpha particles and carbon nuclei with targets of H, C, Cu, and Pb, Moeller *et al.*[15] found that the dependence of pion yield on A_P^n was best fitted by a power n that increased with momentum, reaching a value $n \sim 1.7$ at a momentum well beyond the nucleon-nucleon kinematic limit. The target dependence was $\sim A_T^{0.4}$. It would be interesting to extend such measurements to heavier projectiles.

A strict A_P^2 dependence would suggest a coherent process such as nuclear bremsstrahlung, which depends on $Z_P^2\ Z_T^2$; Cerenkov radiation, which depends on Z_P^2 and the refractive index of the medium; and transition radiation, which depends on Z_P^2 and the plasma frequency in the medium. Several coherent processes involving pion emission have been proposed, mostly to explain emission at laboratory energies below the single nucleon-nucleon threshold of 290 MeV. In this context, we use the term *coherent* to mean a process by which energy is extracted from the relative motion by slowing down the projectile or target as a whole and converting it into one degree of freedom, the pion.

Vasak and co-workers[16,17] have proposed that the rapid deceleration of projectile and target during a collision gives rise to pionic bremsstrahlung much as a rapidly decelerated nucleus of charge Z radiates photons at a rate proportional to Z^2. In pionic bremsstrahlung the source term involves the spin and isospin of the colliding nuclei, which might be coherently generated in the initial phase of the reaction. Vasak *et al.* find that in pionic bremsstrahlung the probability of pion emission increases only as $\sim A_P$ and goes to zero for peripheral collisions, so that it does not fit our data.

Zaretskii and Lomonosov[18] have discussed coherent emission of pions in processes analogous to Cerenkov radiation and transition radiation. They studied the interaction of one nucleus in a second nucleus, at the surface of which or in the volume of which pions are emitted. In our case, to explain charge pickup the second nucleus, the source of the pions, would be the projectile. Their model has not been developed far enough for a comparison with our data.

Others[19,20] have investigated the coherent production of pions in peripheral collisions in which one nucleus excites the other into a delta-nucleon-hole state that subsequently decays into a free pion. This, and other models of coherent production, are discussed in a recent review.[21] None of them is fully developed, and none as yet predicts a mass dependence as steep as A_P^2.

The single-parameter expression [Eq. (2)] that accounts for most cross-section measurements to within a factor 2 applies only to reactions at $\sim$GeV per nucleon energies and to the sum of cross sections for production of all particle-bound isotopes with a one-unit increase of charge, whereas the expressions of Silberberg and Tsao, with their ~ 50 parameters, fit all energies and individual isotopes. We see two advantages in our Eq. (2) for the study of GeV per nucleon reactions. One is that it explicitly calls attention to the dependence on A_P and A_T and may point toward a theoretical understanding of the charge-pickup process. The other is that, being so simple, it can easily be used to estimate cross sections for charge pickup in reactions of interest in cosmic ray astrophysics, and in the evaluation of charge resolution of new detectors at heavy ion accelerators. We give two examples:

(1) To search for heavy antinuclei in the cosmic rays, Ahlen *et al.*[22] have built a multicomponent detector consisting of a large array of plastic scintillator, plastic Cerenkov detecting film, and CR-39 plastic track-recording film through which each particle must pass. The signal of a relativistic anti-iron is that it looks like normal iron in the CR-39 and Cerenkov detectors but looks like a nucleus one or two charges lighter in the scintillator. To assess the background signals that could fake an anti-iron, one needs to know the charge-pickup cross sections for Cr and Mn going to Fe, which had not been measured prior to our work. Using our result in Fig. 3, or using Eq. (2), one concludes that the charge pickup cross section is too low to pose a significant background problem.

(2) When one fragments a beam of GeV per nucleon Fe nuclei at the Bevalac and uses the projectile fragments to assess the charge resolution of a new detector, if the resolution is inferior one may see a broad peak that extends to both sides of the Fe peak. Knowning now that the cross section for charge pickup is less than 1 mb, one will not be misled into attributing the signals on the high side of Fe to charge pickup, but will look for another explanation (slowing particles that were not excluded before the beam hit the target; nonuniform response of the detector; and so forth).

VI. SUMMARY AND FUTURE PLANS

We have presented new measurements of charge pickup by GeV per nucleon nuclear projectiles which, taken with other data, show that the cross section for $\Delta Z = +1$ increases approximately as the square of the mass of the nucleus that picks up charge but only very weakly on the mass of the other nucleus that participates in the collision (through the factor γ_{PT}). Equation (2) is a convenient expression, probably without any simple theoretical significance, that accounts to within a factor of ~ 2 for charge-pickup cross section summed over isotopes. Because of nuclear structure effects, one should not expect the quadratic dependence to hold accurately between any two projectiles of quite different N/Z.

We have also shown that when the roles of projectile and target are reversed, the situation is symmetric (as it had better be): the cross section for charge pickup by the target increases as the square of the target mass.

We observed two interactions in which a relativistic La nucleus pickup two units of charge.

We are planning experiments to measure charge-pickup cross sections for uranium nuclei and to measure the energy dependence of charge pickup from ~ 0.1 to 2 GeV/N. It would be very interesting for the group of Bachelier *et al.* to extend its magnetic spectrometric analysis of charge pickup to projectiles much heavier than Ne, when they become available.

ACKNOWLEDGMENTS

We are indebted to H. J. Crawford and the staff of the Lawrence Berkeley Laboratory Bevalac for the heavy-ion beams. We thank G. F. Bertsch, S. Fredriksson, G. Gerbier, P. Radvanyi, J. Randrup, and R. Silberberg for helpful discussions. This work was supported in part by the U.S. Department of Energy and by National Science Foundation (NSF) Grant No. INT-8611276, as part of a U.S.-China collaborative research program.

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