Charge-changing interactions of ^{197}Au at 10 GeV/nucleon in collisions with targets from H to Pb

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(Received 10 November 1994)

Total and elemental charge-changing cross sections for reactions $\Delta Z = +1, -1, -2, -3$ were measured for 10 GeV/nucleon ^{197}Au ions colliding with CH_2, C, Al, Cu, Ag, and Pb targets. Contributions to the total cross sections by the process of electromagnetic dissociation are discussed.

PACS number(s): 25.75.+r, 25.70.De, 25.20.−x

I. INTRODUCTION

First measurements of the total charge-changing fragmentation cross sections for ^{197}Au at 10 GeV/nucleon ions available at the alternating-gradient synchroton (AGS) at the Brookhaven National Laboratory were performed by He and Price [1] and Waddington *et al.* [2]. The data of these two experiments disagree systematically, especially for heavy targets. Both groups derived from their data the contribution by electromagnetic dissociation (ED) to the total charge-changing cross section. These cross sections disagree also and appear to be surprisingly high. The excitation of the projectile nucleus by absorption of virtual photons from the electromagnetic pulse encountered in the close passage of a heavy target nucleus is dominated by the giant resonance. For a heavy nucleus like ^{197}Au with a neutron excess it is expected that the deexcitation is dominated more by neutron emission than by proton emission, due to the Coulomb barrier. Motivated by the conflicting results of the two experiments [1,2] and their interpretation, we remeasured the total charge-changing cross sections and some elemental charge-changing cross sections for $1 \leq |\Delta Z| \leq 3$ for different targets. In the second ^{197}Au run at Brookhaven we irradiated stacks containing track detectors similar to the experiments of He and Price [1].

II. EXPERIMENT

We have used CR-39 solid state nuclear track detectors in the past to investigate the electromagnetic dissociation of ^{16}O, ^{28}Si, and ^{32}S in experiments performed at CERN and Brookhaven [3–7]. In the experiment described here we additionally used BP-1 glass. BP-1 is a barium phosphate glass (the composition is given in [8]), which was developed by Wang *et al.* [8] some years ago. It has an excellent charge resolution for the Au beam particles and their fragments, especially when etched in NaOH [9].

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Our experimental technique has been published in detail in [10]. Therefore only a short overview is given here.

We used a simple experimental setup placing on both sides of the target one BP-1 glass plate of size 10 cm×10 cm×0.15 cm for charge measurement and some additional CR-39 ($C_{12}H_{18}O_7$) plastic nuclear track detectors for tracing particle trajectories. These stacks were exposed to a 10 GeV/nucleon ^{197}Au beam. The development of the latent tracks in the BP-1 was done by etching the irradiated BP-1 plates in 6N NaOH at 60 °C for 12 or 15 h, respectively. The analysis of the tracks on the detector surfaces was performed with our automatic scanning system [11]. A field of 7 cm×7 cm was scanned on all detector surfaces. From the maxima observed in measured distributions of track areas we derived a charge calibration [9]. The charge resolution for particles with $Z = 79$–76 is about $\sigma_Z = 0.1e$. The trajectories of the projectiles and fragments with $Z \geq 75$ were reconstructed and followed through the whole experimental setup.

Charge-changing cross sections for the fragmentation of ^{197}Au were obtained by following all tracks of Au ions entering the target and determining the charges of these nuclei when leaving the target. Since we used targets of a thickness which corresponds to about 20% of the interaction length, it was necessary to correct for the fragmentation of fragments within the target. For the determination of elemental fragmentation cross sections of the beam particles, we applied an iterative procedure to solve a set of one-dimensional diffusion equations as described in [10]. As an input for this procedure we need total cross sections for beam projectiles and fragments and elemental charge-changing cross sections for the fragments. The total charge-changing cross sections for beam particles ($Z = 79$) are measured directly in our experiment, whereas those of the fragments were estimated by scaling the beam cross section with the ratio of predictions by an empirical overlap formula [12].

The elemental fragmentation cross sections of the fragments were estimated assuming a constant fragmentation probability for beam particles and fragments for the same ΔZ. Based on this assumption the cross section for beam particles was scaled down with the ratio of the total cross sections.

For the C target, we took cross sections measured earlier [9] as an input for the first iteration. After several iterations the results depend only slightly on the initial input data. The fragment cross sections for the other targets were determined from the C target data by scaling them with the ratio of target factors given by the ratio of the square roots of the total cross sections.

III. EXPERIMENTAL RESULTS

The derived cross sections for the target set CH_2, C, Al, Cu, Ag, and Pb are listed in Table I. In Fig. 1 we compare our total charge-changing cross sections with the results of He and Price [1] and preliminary results of Waddington *et al* [2]. Obviously we find a very good agreement for all targets with the data of Waddington *et al.*, whereas the data of He and Price tend to be systematically higher. The curve in Fig. 1 has been derived from an overlap model of the form [13]

$$\sigma_{\rm tot} = 10\,\pi\, r_0^2 [A_P^{1/3} + A_T^{1/3} - b\,(A_P^{-1/3} + A_T^{-1/3})]^2, \quad (1)$$

with parameters $r_0 = 1.31$ fm and $b = 1.486$ fitted to our data.

The partial charge-changing cross sections for $\Delta Z \leq -1$ show a similar behavior. We find a reasonable agreement with the data of Waddington *et al.* [2] whereas the partial cross sections measured by He and Price [1] are systematically higher, although the effect is not as strong as for the total cross sections. Our measured cross sections for charge pickup ($\Delta Z = +1$) are in better agreement with the data of Waddington *et al.* [2] than with He and Price [1].

IV. DISCUSSION AND INTERPRETATION OF THE DATA

A. Electromagnetic dissociation

Electromagnetic dissociation is important for the emission of single nucleons or α particles from a projectile when interacting with the electromagnetic field of a heavy nucleus. It occurs for impact parameters which are too large for an overlap of target and projectile nuclei. In our experiment, similarly to the other two experiments, the sum of contributions by both the nuclear and the electromagnetic processes is measured. For the separation of both components different methods have been applied.

TABLE I. Measured total and partial charge-changing cross sections for ^{197}Au at 10 GeV/nucleon. All values in mb.

Target	Total	$\Delta Z=+1$	$\Delta Z=-1$	$\Delta Z=-2$	$\Delta Z=-3$
H	1502± 50	9.8 ± 3.3	168±11	81 ±7	64 ±6
CH_2	1945± 30	10.8± 2.0	180±7	89 ±4	67 ±4
C	2830± 40	12.7± 3.1	203±4	104±5	72 ±4
Al	3523± 64	20.8± 5.8	257±14	123±7	87 ±6
Cu	4603± 75	15.8± 5.7	298±32	145±10	94 ±8
Ag	5437±250	22.3± 8.7	437±57	170±21	129±15
Pb	6908±196	28.4±15.2	575±47	227±26	134±12

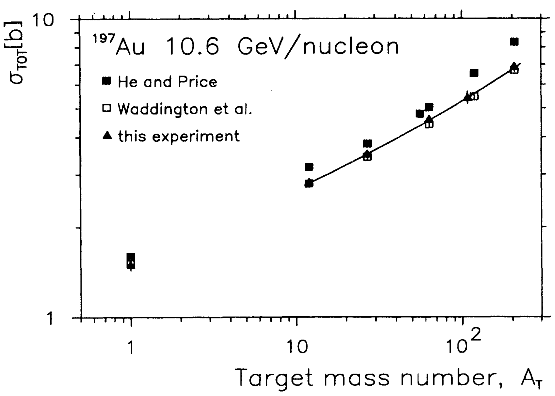

FIG. 1. Total charge-changing cross sections for ^{197}Au at 10 GeV/nucleon from this experiment (closed triangles) in comparison with the data obtained by He and Price [1] (closed squares) and Waddington *et al.* [2] (open squares). The line represents a simple overlap model fit as described in the text.

Waddington *et al.* [2] use a semiempirical formula for the nuclear cross section which was derived by Binns *et al.* [14] from experiments with heavy projectiles and light targets at Bevalac energies (around 1 GeV/nucleon). They assumed that the total nuclear cross section does not change for 10 GeV/nucleon and subtracted the predicted cross sections from the measured ones, thus determining a difference cross section (Waddington *et al.* call it the excess cross section) which they provisionally attributed to ED. Thus they found a charge-changing ED cross section for ^{197}Au interacting with Pb at 10 GeV/nucleon of about 600 mb, whereas using the He and Price data they get a value of nearly 2400 mb when applying the same method.

He and Price performed a fit to their measured data using an overlap model for the nuclear component and a power law for the electromagnetic component. In this way they derived an ED cross section of more than 1000 mb for the Pb target.

The calculation of total charge-changing electromagnetic cross sections requires photonuclear data describing the reaction of the nucleus when absorbing photons. For ^{197}Au the (γ, n) cross sections were measured by the authors of [15] and [16] in the giant resonance regime, but for the emission of charged particles no photonuclear data are available. In order to estimate electromagnetic cross sections for the emission of charged particles we thus had to make reasonable assumptions. For the emission of a proton from an Au nucleus a photon energy of at least $E_{\rm thresh} = -Q + E_{\rm Coul}$ is needed, where Q is the binding energy of a nucleon within the Au projectile and $E_{\rm coul}$ is the size of the Coulomb barrier. Using the parametrization for the Coulomb barrier of Kox *et al.* [17], we find a value of about 20.4 MeV for $E_{\rm thresh}$. This threshold energy lies well beyond the giant resonance of the Au nucleus.

The total calculated ED cross section is very sensitive to the input photonuclear data close to the threshold, since the photon spectrum is much more intense in this region compared to higher energies. We assume that the cross section for the emission of protons with energies above E_{thres} rises smoothly and follows an exponential law as

$$\sigma_\gamma = \frac{Z}{N}\sigma_{\gamma n}\left[1 - \exp\left(-\frac{E_\gamma - E_{\text{thresh}}}{E_{\text{thresh}}}\right)\right], \quad (2)$$

where $\sigma_{\gamma n}$ is the total photoneutron cross section. This behavior is similar to that observed for the emission of neutrons by ^{197}Au with energies $E > E_{\text{thres}} = Q$ [15]. The heaviest nucleus for which we found measured (γ, p) cross sections for γ energies close to E_{thresh} is ^{89}Y. These cross sections rise smoothly, too.

The total photoneutron cross section for Au in the delta resonance region can be obtained using the total photo cross section data for U compiled by Ahrens [18]. These were scaled by the ratio of mass numbers onto ^{197}Au, and then by the ratio N/A to get the photoneutron cross section. In the region between $E_\gamma = 50$ MeV and E_{thresh} no photonuclear data are available. Therefore we used an interpolation between the scaled data of Ahrens and data for Au of Berman *et al.* [16] at energies below 20 MeV. The total and charge-changing photonuclear cross sections estimated with these assumptions are shown in Fig. 2.

We use these cross sections as an input for the Weizsäcker-Williams calculation of the total ED charge-changing cross sections. The method applied is the same as described in our earlier paper [3]. In Fig. 3 we show the results of our calculation for ^{197}Au with energies between 1 and 100 GeV/nucleon. For comparison we have also calculated the ED neutron emission cross section (only single-step excitation was taken into account) which is nearly twice as high as the nuclear cross section at 10 GeV/nucleon. The charge-changing ED cross section is found to be only a small fraction of the nuclear cross section at 10 GeV/nucleon, as expected. It should be stressed again that these cross sections can only be taken as an approximation, since the exact photonuclear cross section has to be known for a precise calculation. However, there are significant differences between our

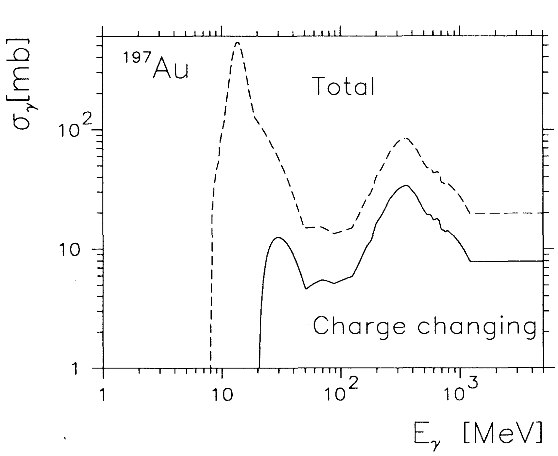

FIG. 2. Total and charge-changing photonuclear cross section data for ^{197}Au. For more details see text.

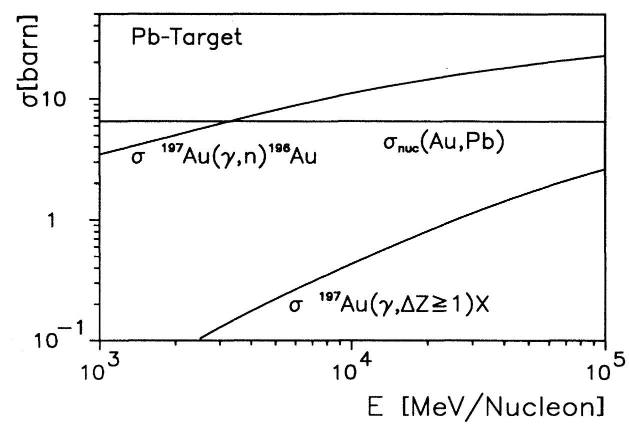

FIG. 3. Energy dependence of the electromagnetic dissociation cross sections for neutron emission and charge-changing reactions for ^{197}Au colliding with a Pb target. For comparison the total charge-changing cross section for nuclear interactions is shown (empirical relation [14]).

calculated value of $\sigma_{\text{EM}}^{\text{tot}} = 378$ mb for the Pb target and the values derived from the other experiments [1,2].

Measurements of $\Delta Z = -1$ interactions can be systematically biased by changes of electronic charge states of the projectiles in the target by pickup of electrons [electronic charge capture (ECC)]. The attachment of electrons to the projectile ion can be misinterpreted as a nuclear interaction with a loss of a proton. This effect, which is large for small energies and heavy projectiles, becomes important especially for track detectors where the dE/dx signal is measured over short ranges (typically 50 μm). It has to be corrected for in our experiment.

Anholt and Becker [19] have derived expressions to calculate cross sections for charge state changes, i.e., electron attachment and electron loss in collisions of ultrarelativistic ions with matter. Applying their expressions to ^{197}Au at 10 GeV/nucleon we find for a carbon target a mean free path for electron capture of $\lambda_{\text{cap}} = 9.77 \times 10^4$ μm and a mean free path for electron stripping of $\lambda_{\text{str}} = 369$ μm. A small fraction of 0.38% of Au ions leaving a thick target (thicker than several λ_{str} which is the case in all experiments discussed here) have one electron attached. This has a small effect on the total charge-changing cross section, where the statistical errors are much larger. For the partial cross section $\Delta Z = -1$ for carbon, however, it amounts to 14.1% (for carbon the effect is maximum). In Table II we have listed the cross sections for $\Delta Z = -1$ which were corrected for electronic charge changes. The correction decreases with increasing target charge.

To determine ED cross sections from our data we use a procedure which is different from those of [1,2]. Nuclear partial cross sections factorize in the form $\sigma_{\text{nuc}}(P,T,F) = \gamma_P^F \gamma_{PT}$, where the first factor only depends on the projectile and the fragment and the second only on the projectile and the target. For the target factor γ_{PT} it is possible to write $\gamma_{PT} = \sqrt{\sigma_{\text{tot}}(P,T)}$ [4]. The ratio of two partial cross sections for the same ΔZ but for

TABLE II. Measured partial charge-changing cross sections $\Delta Z = -1$ for ^{197}Au at 10 GeV/nucleon (second column). The same partial cross sections after correction for the effect of electronic charge capture (ECC) are given in the third column. All values in mb.

Target	$\sigma(\Delta Z = -1)$ uncorrected	$\sigma(\Delta Z = -1)$ ECC corrected
C	203	175
Al	257	225
Cu	298	284
Ag	437	404
Pb	575	553

different targets should, for pure nuclear cross sections, lead to a constant value which is equal to the square root of the total cross section quotient. To demonstrate this we have plotted in Fig. 4 the ratio of the Pb and Cu target cross sections of Waddington *et al.* (taken from [2]) to the values for a C target. The horizontal lines are calculated from the square root of the ratio of total cross sections as mentioned above. For the Pb target and $\Delta Z = -1$ we find a significant enhancement of the cross section ratio over the average value which we attribute to the ED effect. Figure 5 shows the same plot for our data and all targets. ECC corrections were applied to the $\Delta Z = -1$ channel. The contribution of the ED to a partial cross section with a charge change ΔZ can now be estimated by evaluating the difference cross section:

$$\sigma_{\mathrm{ED}}(\Delta Z, T) = \left(\frac{\sigma_{\mathrm{mea}}(\Delta Z, T)}{\sigma_{\mathrm{mea}}(\Delta Z, T = C)} - \sqrt{\frac{\sigma_{\mathrm{tot}}(T)}{\sigma_{\mathrm{tot}}(T = C)}} \right) \times \sigma_{\mathrm{mea}}(\Delta Z, C). \quad (3)$$

This relation originates from the factorization of partial nuclear and ED cross sections [5] under the assumption that ED can be neglected for the C target. ED cross sections derived by this procedure are given together with the calculated total charge-changing ED cross section in Table III. The cross sections resulting from our data

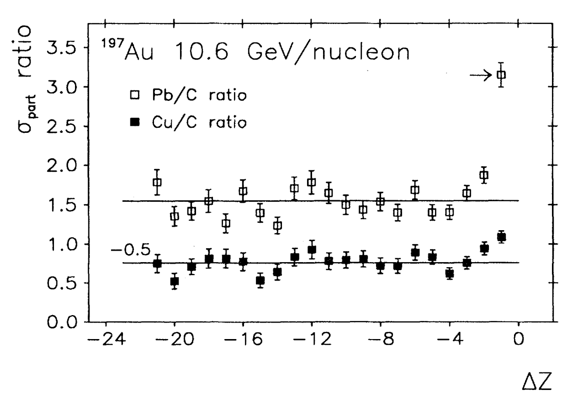

FIG. 4. ^{197}Au partial cross section ratios for targets Pb/C and Cu/C. Data are taken from Waddington *et al.* [2]. The Cu/C ratios are shifted down by 0.5 units. The horizontal lines show the square root of the ratio of the total charge-changing cross sections.

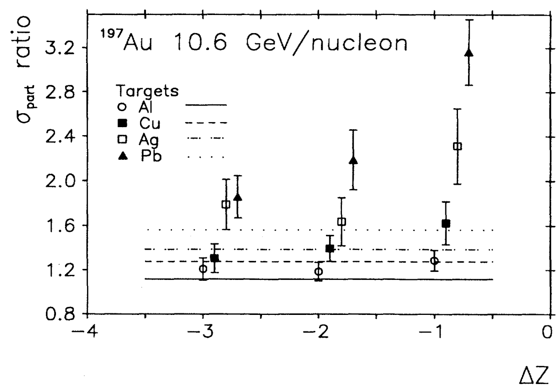

FIG. 5. Cross section ratios for targets Al/C, Cu/C, Ag/C, and Pb/C for three partial cross sections from this work. The horizontal lines show the square roots of the total charge-changing cross sections of this work.

agree fairly well within the errors with those we have determined in the same way from the data of Waddington *et al.* Furthermore, the agreement with the calculated total value (it is assumed that the ED partial cross sections $\Delta Z = -1$ and $\Delta Z = -2$ totally exhaust the total charge-changing ED cross section) is good considering the quite simple assumptions made for the input data of the calculation. This leads to the conclusion that charge-changing ED cross sections for ^{197}Au are smaller than was estimated before [1,2].

The target dependence of total ED cross sections is dominated by two effects. First, the number of virtual photons available for ED interactions scales with Z_T^2 (Z_T = target charge) [3]. Secondly, the total ED cross sections vary due to the minimum impact parameter for ED interactions with different targets. As a result, the cross section can be parametrized in the form

$$\sigma_{\mathrm{ED}} = k(E) Z_T^{\tau(E)} \quad (4)$$

with a $\tau(E)$ different from the value 2. In Fig. 6 we show the exponent τ for this power law fitted to the cal-

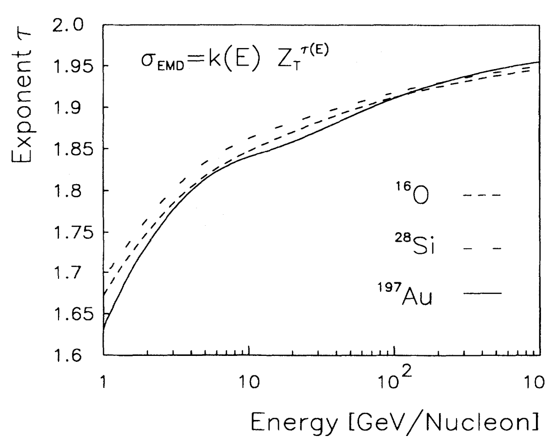

FIG. 6. Energy dependence of the exponent τ of a power law fit $\sigma_{\mathrm{ED}} = kZ_T^{\tau}$ to the calculated charge-changing ED cross section for ^{16}O, ^{28}Si, and ^{197}Au.

TABLE III. Calculated total charge-changing ED cross sections σ_{calc} and partial ED charge-changing cross sections σ_{expt} derived from experiments with ^{197}Au at 10 GeV/nucleon. All values in mb.

Target	$\sigma_{\text{calc}}(\lvert\Delta Z\rvert \geq 1)$	$\sigma_{\text{expt}}(\Delta Z = -1)$ Our data	$\sigma_{\text{expt}}(\Delta Z = -1)$ Data of [2]	$\sigma_{\text{expt}}(\Delta Z = -2)$ Our data
C	3.8			
Al	15.6	30±16		
Cu	68.0	61±33	61±23	
Ag	166.0	162±58		26±22
Pb	455.7	280±49	294±36	65±27

culated charge-changing ED cross sections for ^{16}O, ^{28}Si, and ^{197}Au ions. For 10 GeV/nucleon a value of about 1.84 can be expected for ^{197}Au.

Waddington *et al.* [2] fitted a power law of the form A^{τ} to their measured excess cross sections to investigate whether these cross sections are caused by ED. Thus they determined a value of $\tau = 0.6$. A fit of the form Z^{τ} gives a value of $\tau \approx 0.8$. This value is surprisingly small and indicates that their excess cross sections contain other contributions apart from ED.

From a fit to our experimental ED cross sections of Table IV we get $\tau = 1.41$ and $k = 0.88$ mb with a value of $\chi^2/f = 0.63$. If we fix the exponent τ to 1.84 we get $k = 0.13$ mb with a value of $\chi^2/f = 1.09$. The χ^2 values of both fits indicate that the target dependence of our measured ED cross sections is not in contradiction to the theoretical predictions.

B. Total charge-changing cross sections

In Table IV we compare our total charge-changing cross sections with those measured by Binns *et al.* for the fragmentation of ^{197}Au at 1 GeV/nucleon [14] and the nuclear cross sections calculated with an empirical overlap formula and parameters as determined by the same authors. We determined the total nuclear cross sections at 10 GeV/nucleon by the difference of our measured and ECC corrected total cross sections and total ED cross sections derived from results of Table III. Our cross sections exceed the calculated values of [14] significantly. It should be noted, though, that the difference is biggest for the targets Cu, Ag, and Pb, for which no cross sections were measured by [14].

V. SUMMARY AND CONCLUSIONS

Using simple experimental setups with nuclear track detectors we have measured the total and some elemental charge-changing cross sections for fragmentation of 10 GeV/nucleon ^{197}Au projectiles in the targets H, C, Al, Cu, Ag, and Pb. Our data, which were obtained using a similar experimental technique as that of He and Price [1], disagree with their data. However, they are in excellent agreement with the data of Waddington *et al.* [2], who used an experimental setup with ion chambers, Cherenkov counters, and multiwire proportional counters.

We have considered that $\Delta Z = -1$ cross section measurements for heavy projectiles even at energies of about 10 GeV/nucleon are affected systematically by electronic charge capture in the target. After correction of the data for this small effect our experimental ED cross sections are in good agreement with calculated values.

To determine the total nuclear cross sections at 10 GeV/nucleon we subtracted ED contributions from measured values (after ECC correction). The cross sections exceed the values predicted by an empirical formula [14]. Based on the data presently available it cannot be decided whether this formula, which was fitted to data

TABLE IV. Comparison of our measured total charge-changing cross sections of 10 GeV/nucleon ^{197}Au to calculated nuclear cross sections and cross sections measured by [14] at energies of about 1 GeV/nucleon. The values of [14] have not been ECC corrected since the correction is negligible for this experimental setup. All values in mb.

Target	σ_{tot} ECC corrected	σ_{ED}	$\sigma_{\text{tot}}^{\text{nucl}} = \sigma_{\text{tot}} - \sigma_{\text{ED}}$	$\sigma_{\text{calc}}^{\text{nucl}}$ [14]	$\sigma_{\text{expt}}^{\text{nucl}}$ [14]
C	2802±40	3.8 (calc)	2827±40	2696.1	2731±58
Al	3491±64	30±16	3494±66	3257.1	3240±82
Cu	4589±75	61±33	4542±82	4105.2	no data
Ag	5404±250	188±62	5249±258	4809.6	no data
Pb	6886±196	345±56	6564±204	5937.0	no data

for light targets, fails for heavier targets, or whether there is an unexpected energy dependence of the total nuclear charge-changing cross section. This needs further investigation. We plan to repeat our experiment for 1 GeV/nucleon Au ions and heavy targets at GSI, Darmstadt.

ACKNOWLEDGMENTS

We are grateful to the staff of Brookhaven National Laboratory for support of our experiment (E883). This work was funded by the German Ministry for Research and Technology (BMFT) under Contract No. 06 SI 356.

[1] Y. He and P. Price, Z. Phys. A **348**, 105 (1994).
[2] C. Waddington *et al.*, Nucl. Phys. **A566**, 427c (1994).
[3] C. Brechtmann and W. Heinrich, Z. Phys. A **330**, 407 (1988).
[4] C. Brechtmann and W. Heinrich, Z. Phys. A **330**, 463 (1988).
[5] C. Brechtmann, W. Heinrich, and E. Benton, Phys. Rev. C **39**, 2222 (1989).
[6] W. Heinrich and C. Brechtmann, Mod. Phys. Lett. A **19**, 1879 (1989).
[7] S. Hirzebruch *et al.*, Phys. Rev. C **46**, 1487 (1992).
[8] S. Wang *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. B **35**, 43 (1988).
[9] S. Hirzebruch, G. Rusch, E. Winkel, and W. Heinrich, Nucl. Instrum. Methods Phys. Res. Sect. B **74**, 519 (1993).
[10] C. Brechtmann and W. Heinrich, Nucl. Instrum. Methods Phys. Res. Sect. B **29**, 675 (1988).
[11] W. Trakowski *et al.*, Nucl. Instrum. Methods Phys. Res. **225**, 92 (1984).
[12] P. Lindstrom *et al.*, LBL Report No. 3650, 1975.
[13] H. Heckman *et al.*, Phys. Rev. C **17**, 1735 (1978).
[14] W. Binns *et al.*, Phys. Rev. C **36**, 1870 (1987).
[15] A. Veyssierre *et al.*, Nucl. Phys. **A159**, 561 (1970).
[16] B. Berman *et al.*, Phys. Rev. C **36**, 1286 (1987).
[17] S. Kox *et al.*, Phys. Rev. C **35**, 1678 (1987).
[18] J. Ahrens, Nucl. Phys. **A446**, 229c (1985).
[19] R. Anholt and U. Becker, Phys. Rev. A **36**, 4628 (1987).