Charge-changing interactions of ultrarelativistic In nuclei

U. I. Uggerhøj,[1] I. A. Pshenichnov,[2,3] C. Scheidenberger,[4] H. D. Hansen,[1] H. Knudsen,[1] E. Uggerhøj,[1] P. Sona,[5] A. Mangiarotti,[5] and S. Ballestrero[5]

[1]*Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus, Denmark*
[2]*Frankfurt Institute for Advanced Studies, J.W. Goethe Universität, D-60438 Frankfurt am Main, Germany*
[3]*Institute for Nuclear Research, Russian Academy of Sciences, 117312 Moscow, Russia*
[4]*Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany*
[5]*Department of Physics, University of Florence, I-50125 Florence, Italy*

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We present experimental results of nuclear-charge changing interactions for 158A-GeV ultrarelativistic In ions in Si, Ge, Sn, W, and Pb targets. Calculations based on the abrasion-ablation model for hadronic interaction and the RELDIS model for electromagnetic dissociation are compared to the data.

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In Ref. [1] we reported a strong suppression of nuclear-charge changing interactions for In ions channeled in a bent Si crystal. With almost the same setup, information about fragmentation of medium-size nuclei could be obtained as presented in the following. To facilitate an efficient design of a collimation system for the CERN Large Hadron Collider (LHC) operating as an ion collider, it is necessary to test nuclear fragmentation models in a wide range of masses and energies of colliding nuclei. This must be done to make the foundation for an extrapolation to higher beam energies as solid as possible and thus reduce the likelihood of, e.g., superconducting magnet quench as a result of interception of fragments. In comparison to the LHC operating with protons, collimation of heavy-ions in the LHC is a complex task [2,3]. The reason for this is the traditional division into primary and secondary collimators where the primary in the case of protons almost exclusively acts as a scatterer and the secondary intercepts the scattered particles [4,5]. In the case of ions, the primary collimator to a large extent generates fragments, the motion and distribution of which are much less well known than multiple scattering distributions. Thus, systematic experimental tests of fragmentation models over a wide range of beam energies, targets, and/or projectiles are needed to determine the accuracy of such models. Previous studies by some of us [6,7] have investigated fragmentation and nuclear-charge pick-up reactions for ultrarelativistic Pb in a variety of targets. Predictions of several fragmentation models [6–8] were already compared to these data. The present article investigates the fragmentation cross section for In ions with charge $Z_1 = 49$ in targets of charges $Z_2 = 14$, 32, 50, 74, and 82 and thus supplements the previous measurements.

The experiment was performed in the H2 beam line of the SPS accelerator at CERN, where In^{49+} ions of momentum 370 GeV/c per charge unit are available with a small divergence. The ions were incident on a range of targets, Si, Ge, Sn, W, and Pb, of which Si, Ge, and W were single crystals. The crystals in a misaligned (so-called random) direction act as an amorphous target, see, e.g., Ref. [9] about heavy-ion channeling at high energies. The target thicknesses were measured to be $\Delta t_{Si} = 60.0 \pm 0.2$ mm, $\Delta t_{Ge} = 10.0 \pm 0.1$ mm, $\Delta t_{Sn} = 6.3 \pm 0.1$ mm, $\Delta t_W = 1.63 \pm 0.05$ mm, and $\Delta t_{Pb} = 2.1 \pm 0.1$ mm with the uncertainty in most cases being dominated by thickness variations.

The experimental setup—a reduced version of that presented in Ref. [1]—is shown schematically in Fig. 1. Here, S1 denotes a scintillator that was used as an event trigger. To detect the charge state of each ion before the interaction, a MUltiple Sampling Ionization Chamber [10], MUSIC1, was used. After the passage of the target, the resulting charge state was detected in a downstream chamber, MUSIC2. The distance between MUSIC1 and MUSIC2 was 10.9 m with air at atmospheric pressure for the Si target, for the remaining targets reduced to 6.6 m. Advantage was taken of the horizontal position information of MUSIC1, by which it is possible to select events in the central region of the target. This identification can be performed on an event-by-event basis in conjunction with the charge-state identification.

In Fig. 2 is shown the high-Z part of a typical charge spectrum in the downstream MUSIC2. Here it was required by the upstream ionization chamber (MUSIC1) that the incoming particle could be identified as In^{49+}. The spectrum is fitted with Gaussians plus a constant background, and the resulting sum is shown to fit the data very well. All charge states (typically down to $Z \simeq 20$) can be identified (for clarity only the high-Z part is shown in Fig. 2). In particular the nuclear-charge pickup reaction leading to $Z = 50$ can be extracted, although with substantial uncertainty. It was carefully checked that tighter event selections in the upstream MUSIC1 did not lead to a significant change of the results, neither for position nor charge selections. Furthermore, for all data sets the expected Z^2 dependence of the signal on charge state was verified by a parabolic fit to the Gaussian centroids versus Z. For the deflected ions the Gaussian fit to extract the pick-up channel Sn^{50+} was required to be centered at the same distance from the In^{49+} peak and with the same width. The charge resolution was 0.25 charge units (RMS), similar to that in previous studies [6,7] although only one anode of each MUSIC was included in the present analysis. The numbers extracted from the Gaussian fits $N(Z)$ normalized to the number of incoming In^{49+} $N(49+)$ were used to determine the fragmentation cross section, $\sigma = (R_1 - R_0)/n\Delta t$, as a function of charge number Z with $R_1 = N(Z)/N(49+)$ being the ratio with target and subscript 0

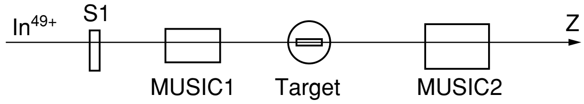

FIG. 1. A schematical drawing of the experimental setup.

denotes the empty target configuration. The total nuclear charge-changing cross sections were likewise determined from $\sigma_{cc} = \ln(R_0/R_1)/n\Delta t$, where $R_1 = N_{\text{out}}(49+)/N_{\text{in}}(49+)$ is the ratio of outgoing to ingoing In^{49+} ions with the target and subscript 0 again denotes the empty target configuration. The areal atomic density of the target is given by $n\Delta t$. In all cases is the partial charge-changing probability much smaller than unity, typically a few percentages. However, the thicknesses in units of nuclear interaction lengths were 13.2, 3.79, 2.83, 1.7, and 1.29% for Si, Ge, Sn, W, and Pb, respectively. Thus, in particular for the light targets, single interaction conditions were not fulfilled.

The experimental results for the total nuclear-charge changing cross sections $\sigma(Z_2)$ as a function of target charge Z_2 are shown in Fig. 3. The cross sections calculated within the revisited abrasion-ablation model for hadronic interaction [7] and the RELDIS model [11] for electromagnetic dissociation of nuclei in distant collisions are also presented in Fig. 3 along with the sum of these cross sections. The agreement for the inherently noncrystalline targets, Sn and Pb, is very good, whereas for the crystalline targets, Si, Ge, and W—although oriented along a "random" (noncrystallographic) direction—the experimental value falls short of the theoretical prediction, in particular for the lightest target nuclei, Si and Ge. The crystallinity is, however, unlikely to be the explanation for the discrepancy. The contribution of electromagnetic dissociation to the total fragmentation cross section is important for W and Pb targets. However, In fragmentation on Si is mostly because of hadronic interaction, and the abrasion-ablation model can be directly tested in this case.

According to the abrasion-ablation model, some nucleons in the overlap zone of nuclear densities are abraded from the colliding nuclei. As a result, excited remnants (prefragments) of the initial nuclei are created. In Ref. [7] various approaches to calculate the distribution of excitation energies of prefragments were tested by comparison to Pb fragmentation data [7]. Following Gaimard and Schmidt [12], a linear function for the density of one-hole states was used providing the Ericson formula [13] as a particular case. The mean excitation energy per removed nucleon obtained with the linear function amounts to 13.3 MeV for the first nucleon and to 8–10 MeV for others and 20 and ~40 MeV, respectively, with the Ericson formula.

The statistical multifragmentation model (SMM) [14] employed to describe the decay of excited prefragments takes into account not only a sequential evaporation mechanism but also an explosive multifragment breakup process possible at high excitations. Presently, these approaches can be tested with In fragmentation data for a medium-size projectile. For other details concerning the models and the calculational procedures, see Ref. [7].

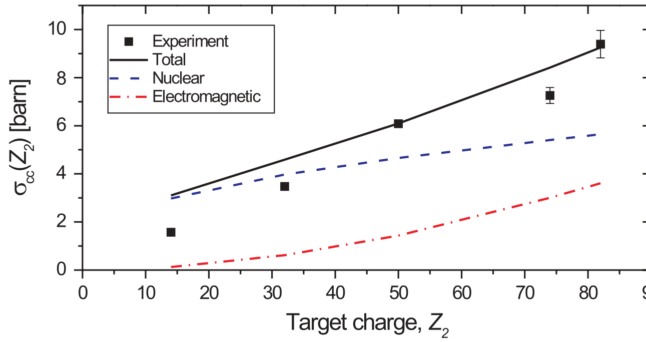

FIG. 3. (Color online) Total nuclear-charge changing cross sections $\sigma_{cc}(Z_2)$ as a function of target charge Z_2 for 158A-GeV $^{115}\text{In}^{49+}$ ions. The error bars on the experimental points shown by filled squares indicate a 1σ statistical uncertainty. The solid line represents the calculated values from the combined hadronic (abrasion-ablation, dashed) and electromagnetic (RELDIS, dash-dotted) interactions.

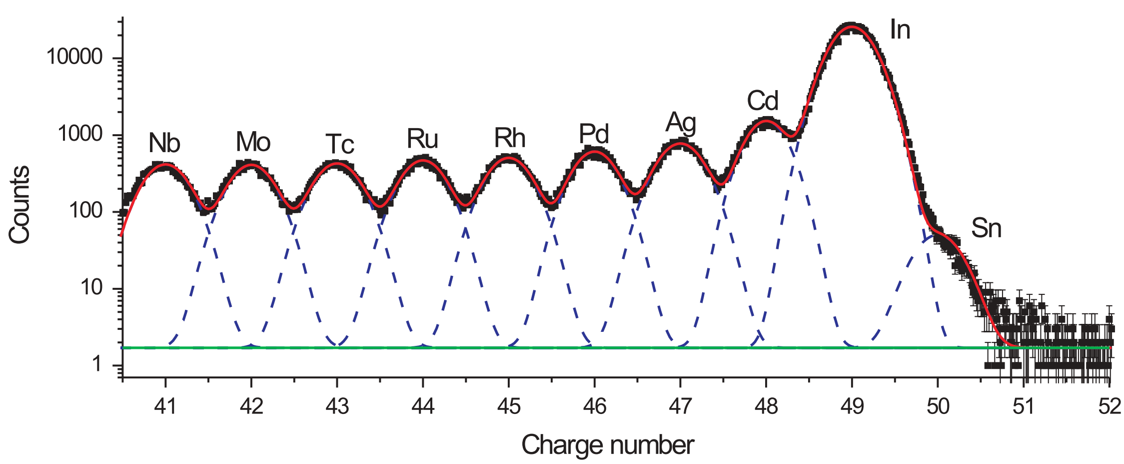

FIG. 2. (Color online) The high-Z part of a typical charge spectrum observed in the downstream MUSIC2 for In^{49+} in Si. Gaussian fits with a constant background and the resulting sum are shown. The different elements can be clearly identified (for details see text). The error bars indicate a 1σ statistical uncertainty.

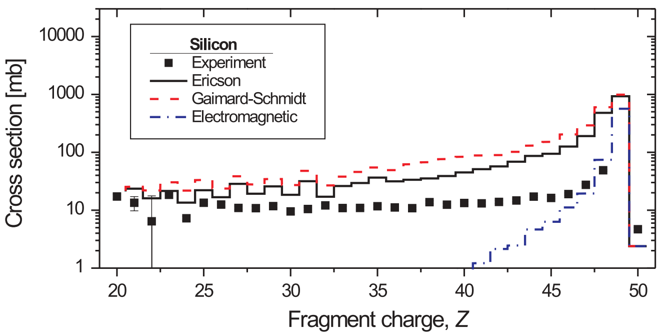

FIG. 4. (Color online) Partial nuclear-charge changing cross sections $\sigma(Z)$ as a function of fragment charge Z for 158A-GeV $^{115}In^{49+}$ ions in Si. The error bars on the experimental points shown by filled squares indicate a 1σ statistical uncertainty. The solid line is the calculated values from the combined hadronic and electromagnetic interaction code based on the Ericson approximation, the dashed line is based on the Gaimard-Schmidt approximation, and the dot-dashed line is the electromagnetic contribution.

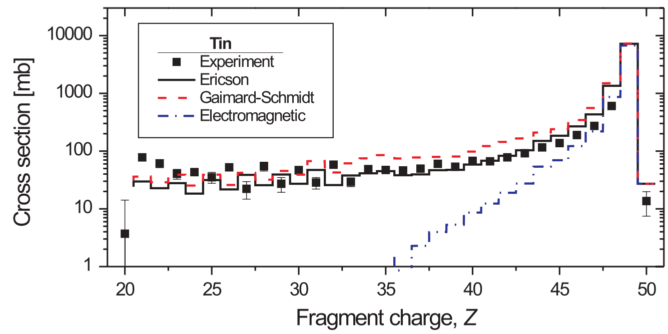

FIG. 6. (Color online) As described in the legend to Fig. 4 but for Sn.

The results for the partial nuclear-charge changing cross sections $\sigma(Z)$ as a function of fragment charge Z are shown in Figs. 4 to 8. In each case, the experimental results are compared to calculated values.

In Fig. 4 a significant discrepancy between the calculated values and experimental data is observed, in particular for high values of Z. This is not surprising given the target thickness in units of interaction lengths, as a generated fragment may interact again leading to a distortion of the spectrum compared to single interaction conditions. In particular, the yields of fragments with $Z = 45$–47 are comparable to $Z = 20$–25 yields, as opposed to the data obtained for thin targets. As a collimation scheme is likely to be based on thick targets, more sophisticated models with several generations of interactions is called for to accurately describe observations.

In Fig. 5 the overall agreement is significantly improved compared to Fig. 4, mainly by the reduction of a factor of 3.5 in effective thickness. The data point for $Z = 50$ has been discarded because of a large statistical uncertainty.

In the case of tin shown in Fig. 6 the agreement between data and theory is very good for all fragment charges examined, except a tendency for the data to be below theory for the highest values of Z.

For the indium ions traversing tungsten shown in Fig. 7 there is good agreement in shape, but about a factor ≈ 2 overestimate by the model.

The data and calculations for lead shown in Fig. 8 show a nice agreement in shape as well as for the absolute value.

For thin targets in units of nuclear interaction lengths, Sn, W, and Pb, the calculations based on the revisited abrasion-ablation model for hadronic interaction and the RELDIS model for relativistic electromagnetic dissociation describe the experimental results quite well. The electromagnetic dissociation contributes $\sim$30–40% of the total fragmentation cross section for the medium-weight and heavy target nuclei.

Not surprisingly there is some discrepancy, in particular for the heavier fragments, for thick targets, Si and Ge, as the model describes single interactions only. In a view of the agreement between measured and calculated cross sections for thin targets, one can conclude that the methods used to estimate the excitation energy and decay modes of prefragments created at the ablation step of Pb fragmentation [7] can be also extended to In projectiles. The large statistical uncertainties of measured cross sections for $Z = 20 - 35$ make difficult the choice of the best method. However, one can still note that the calculations based on the Ericson formula are generally closer to the data. This supports previous findings [7] that in fragmentation of ultrarelativistic nuclei the excitation energy of residual nuclei may be described on average as

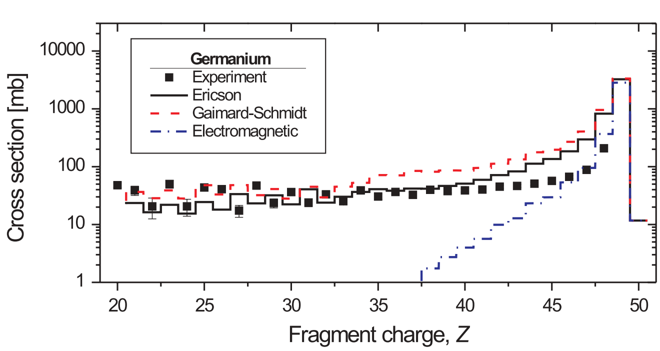

FIG. 5. (Color online) As described in the legend to Fig. 4 but for Ge.

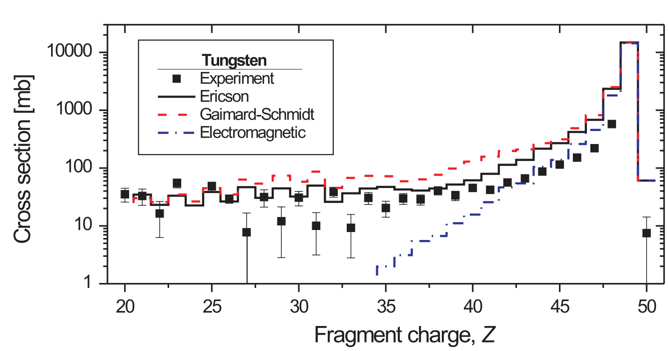

FIG. 7. (Color online) As described in the legend to Fig. 4 but for W.

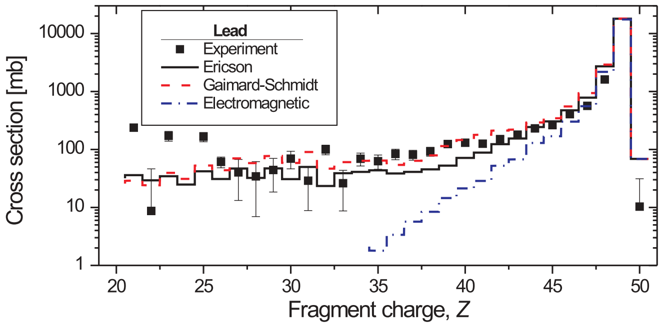

FIG. 8. (Color online) As described in the legend to Fig. 4 but for Pb.

$\sim$40 MeV per removed nucleon, with some increase in this value compared to fragmentation at $\sim 1A$ GeV.

The cross sections for nuclear-charge pickup channel forming $_{50}$Sn nuclei were also measured and calculated. This process is solely attributed to the electromagnetic production of a negative pion by an equivalent photon.

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[1] U. I. Uggerhøj *et al.*, Phys. Lett. B **619**, 240 (2005).
[2] J. M. Jowett, J.-B. Jeanneret, and K. Schindl, *Proceedings of the Particle Accelerator Conference, Portland, Oregon, IEEE 03CH37423 (2003)*, Vol. 3, p. 1682.
[3] R. W. Assmann, H. H. Braun, A. Ferrari, J. B. Jeanneret, J. M. Jowett, and I. A. Pshenichnov, EPAC-2004-MOPLT010, presented at the 9th European Particle Accelerator Conference (EPAC 2004), Lucerne, Switzerland, 5–9 July 2004.
[4] J. M. Jowett, H. H. Braun, M. I. Gresham, E. Mahner, A. N. Nicholson, E. Shaposhnikova, and I. A. Pshenichnov, EPAC-2004-MOPLT020, prepared for 9th European Particle Accelerator Conference (EPAC 2004), Lucerne, Switzerland, 5–9 July 2004.
[5] J. B. Jeanneret, Phys. Rev. ST Accel. Beams **1**, 022801 (1998).
[6] C. Scheidenberger *et al.*, Phys. Rev. Lett. **88**, 042301 (2002).
[7] C. Scheidenberger *et al.*, Phys. Rev. C **70**, 014902 (2004).
[8] F. Ballarini *et al.*, SLAC-PUB-10813, presented at International Conference on Nuclear Data for Science and Technology (ND2004), Santa Fe, New Mexico, 26 Sep–1 Oct 2004.
[9] G. Arduini *et al.*, Phys. Rev. Lett. **79**, 4182 (1997).
[10] M. Pfützner *et al.*, Nucl. Instrum. Methods B **86**, 213 (1994).
[11] I. A. Pshenichnov, J. P. Bondorf, I. N. Mishustin, A. Ventura, and S. Masetti, Phys. Rev. C **64**, 024903 (2001).
[12] J.-J. Gaimard and K. H. Schmidt, Nucl. Phys. **A531**, 709 (1991).
[13] T. Ericson, Adv. Phys. **9**, 425 (1960).
[14] J. P. Bondorf, A. S. Botvina, A. S. Iljinov, I. N. Mishustin, and K. Sneppen, Phys. Rep. **257**, 133 (1995).