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Strong suppression of nuclear-charge changing interactions for 18 TeV/c In ions channeled through a bent Si crystal

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Abstract

We present experimental results giving evidence for the strong reduction—a factor of more than 20—of nuclear-charge changing interactions for 18 TeV In^{49+} ions channeled through a silicon crystal bent to 7.5, 11.9 and 19.8 mrad. A very small fraction of the deflected ions suffer electromagnetic or nuclear interactions leading to proton loss while traversing the 60 mm long crystal, even though its thickness corresponds to about 0.13 nuclear interaction lengths for an amorphous material. By considering the deflected ions only, we show experimentally that the nuclear-charge pickup reaction believed to be induced by virtual photons is a short-range phenomenon.

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1. Introduction

In this Letter we report the observation of: (1) a strong suppression of the proton-loss mechanism for heavy ions channeled and deflected in a bent crystal and (2) a nearly complete elimination under channeling conditions of the nuclear-charge pickup believed to be a result of a $\gamma n \to p\pi^-$ reaction by virtual photons [1,2].

Since its prediction [3] and the first experiments in the late 1970s [4], the use of and knowledge about pro-

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ton channeling in bent crystals has increased steadily and is now at a well-established stage where almost all aspects of the phenomenon have been explored.

However, the investigation of effects pertaining to the use of high energy heavy ions in bent crystals is still evolving, with the first extensive studies appearing at the turn of the millennium [5–7], following early experiments [8]. It turns out that, regarding deflection efficiencies and critical angles, heavy ions behave in bent crystals as protons of the same energy per charge, as expected. Nevertheless, since heavy, fully stripped ions are composite particles of high charge a number of additional effects may appear, such as electromagnetic dissociation and/or nuclear interactions. In the restframe of the incident ion with the Lorentz factor $\gamma \simeq 160$ the extremely strong, crystal electric fields $\mathcal{E} \lesssim 10^{11}$ V/cm are boosted to very high values. It is thus not a priori excluded that electromagnetic dissociation for example through a giant dipole resonance is significant [9–11]. The fundamental frequency in the ion restframe for interaction with the lattice is $\omega_0 = 2\pi\gamma\beta c/d$ which is of the order 1 MeV for a characteristic lattice spacing $d \simeq 2$ Å.

This Letter discusses the specific aspects of heavy ion channeling in bent crystals and in particular the strong suppression of nuclear charge pick-up and loss reactions under channeling conditions. The main motivation is to demonstrate experimentally what can be the expected composition of a crystal-extracted heavy ion beam in a scheme like the seemingly feasible one proposed for the LHC [12].

2. Ion channeling in bent crystals

In the so-called continuum approximation [13], charged particles incident on a single crystal with small angles to crystallographic directions, experience the collective atomic fields as if smeared along the string or plane. If, further, a particle has sufficiently low transverse momentum with respect to the axis or plane of the crystal it can be restricted to areas away from the nuclei (positively charged particles) or close to the nuclei (negatively charged particles). In this case the particle is channeled and is guided by the lattice such that a separation of the longitudinal and transverse motions is present. The result is a conserved 'transverse energy' and therefore a transverse potential in which the particle moves [13]. The particles to be channeled must be incident on the crystal within a critical angle to the plane, ψ_p, which is of the order 10 µrad at $(370\ \mathrm{GeV}/c)/Z$.

The guidance of channeled particles persists even if the crystal is slightly bent, such that the particle may be deviated from its original direction of motion as in a dipole magnet. Since the fields that are responsible for this deviation are the extremely strong (screened) fields present near the lattice nuclei, the corresponding bending power can reach a magnitude equivalent to a magnetic field of several thousand Tesla.

In an earlier experiment [14] we investigated the restricted energy loss of fully stripped Pb ions in silicon and showed that the well-channeled particles suffer an energy loss of about 70% of the random value when channeled in a plane.

For a recent review of the deflection in bent crystals as well as of its applications at high energy accelerators, see Ref. [15].

3. Experiment

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 silicon crystal, 60 mm long in the beam direction, bent horizontally over 56 mm in a 'three-point bender'. The crystal was mounted on a 2 µrad stepsize goniometer and alignment of the crystalline planes to the beam direction was performed by observation of the deflected beam in a scintillator counter.

The experimental setup is shown schematically in Fig. 1. Here, S1 denotes a scintillator that was used as an event trigger in conjunction with $\overline{\mathrm{SL1}}$ which is a scintillator with a 0.2 mm wide slit used as a veto. To detect the charge state of each ion before the interaction, a MUltiple Sampling Ionization Chamber [16], MUSIC1, was used. After the passage of the crystal, the resulting charge state was detected in a downstream chamber, MUSIC2. At the downstream end, two scintillators, S2 and S3 (with a $\simeq 5$ mm overlap) that can be used in coincidence, S2·S3, were mounted on a movable table. These scintillators were used during alignment of the crystal which was performed by detection of the deflected particles (denoted as D in Fig. 1) as a function of the turn angle of the goniome-

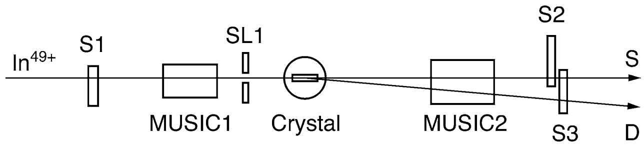

Fig. 1. A schematical drawing of the experimental setup.

Table 1
Deflection angles, measured beam divergence of the incoming beam and deflection efficiency

θ [mrad]	$\sigma(\vartheta)$ [µrad]	ε [%]
7.5 ± 0.3	34 ± 1	3.0 ± 0.2
11.9 ± 0.2	35 ± 1	2.0 ± 0.1
19.8 ± 0.2	26 ± 7	0.4 ± 0.1

ter. The distance between MUSIC1 and MUSIC2 was 10.9 m with air at atmospheric pressure, for the 19.8 mrad data reduced to 6.6 m. Advantage was taken of the horizontal position information of MUSIC2, by which it is possible to sort the deflected particles (D) and those that go straight through the crystal (S). This identification can be performed on an event-by-event basis in conjunction with the charge-state identification. Once the crystal was aligned, overlap between the slit of $\overline{\text{SL1}}$ and the 1.5 mm wide endface of the crystal was confirmed by a comparison of (1) the beam profile in MUSIC1 with $\overline{\text{SL1}}$ in the trigger, looking at all particles and (2) the beam profile in MUSIC1 using only deflected particles. The area thus corresponding to the crystal endface was used as a condition in the data analysis. Furthermore, the beam divergence over the 1.5 mm frontface was derived from angular scans with goniometer step-size 7 µrad and Gaussian fits to the number of deflected particles as a function of angle. The resulting RMS values for the angular divergence, $\sigma(\vartheta)$, after deconvolution of the (110) planar critical angle, 6 µrad, are given in Table 1. The errors stated are statistical only and the comparatively large uncertainty for the angular divergence of the 19.8 mrad data set reflects the low deflection efficiency.

4. Results

In Fig. 2 is shown a scan S2·S3 across the undeflected, dechanneled and fully deflected beams for the bend angles (a) 11.9 and (b) 19.8 mrad. All three parts of the beam are clearly identifiable.

An advantage of working with fully stripped heavy ions as compared to, e.g., protons, is the possibility of a large background rejection. Since the energy loss is roughly proportional to the square of the charge, an In^{49+} ion gives a signal in a scintillator which by far exceeds that of a minimum ionizing particle. Thus, measurements can be made essentially background-free. This is demonstrated in Fig. 2(b) for angles between 11.9 and 19 mrad, where the dechanneling is expected to be negligible (in a three-point bending device, the local curvature of the crystal decreases beyond the central support pin).

In Fig. 3 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 had such a position that it was incident on the crystal endface and 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. All charge states (typically down to $Z \simeq 20$) can be identified (for clarity only the high-Z part is shown). In particular the nuclear-charge pick-up reaction leading to $Z = 50$ can be extracted. 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 areas extracted from the Gaussian fits normalized to the number of incoming In^{49+} were used to determine the fragmentation probability, p_f, as a function of charge number. These fragmentation probabilities for the bent aligned crystal were then compared to the results for the randomly oriented crystal by the fragmentation probability suppression $\eta = (p_f^{\text{random}} - p_f^{\text{bckg.,r}})/(p_f^{\text{crystal}} - p_f^{\text{bckg.,c}})$ with subtrac-

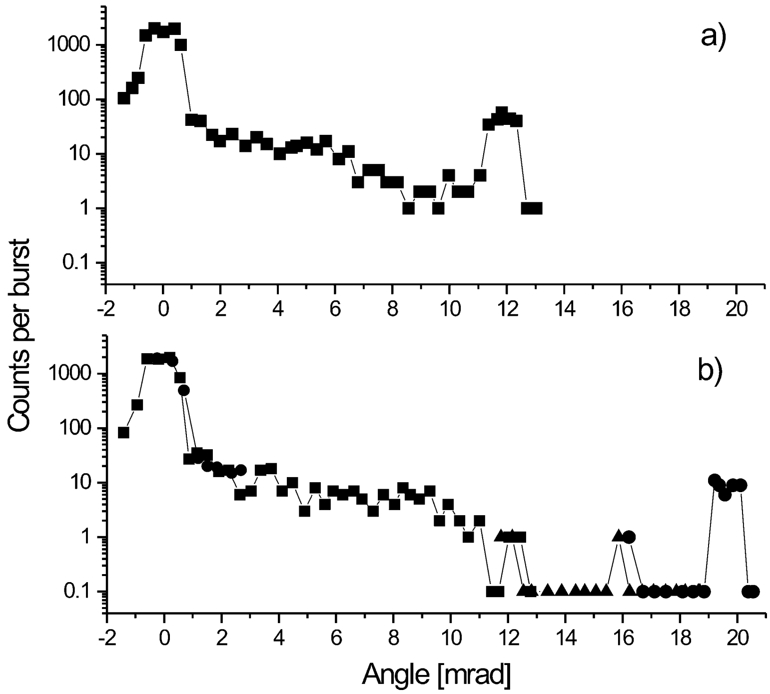

Fig. 2. Scan of a scintillator coincidence across the undeflected, dechanneled and fully deflected beams for the bend angles (a) 11.9 and (b) 19.8 mrad. Data points with zero counts have been put at 0.1 to enable their display on a logarithmic scale.

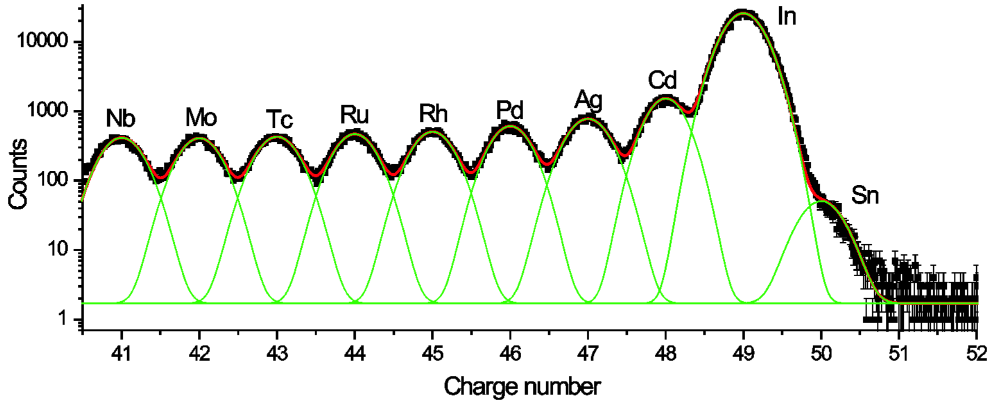

Fig. 3. The high-Z part of a typical charge spectrum observed in the downstream MUSIC2 for the randomly oriented crystal. Gaussian fits plus a constant and the resulting sum are shown. The different elements can be clearly identified, for details, see text. The error bars indicate a 1σ statistical uncertainty.

tion of the measured values without target. For the deflected beam, the background is difficult to measure as there are no particles deviated to this region. We have thus taken the conservative approach of not subtracting the background from the crystal signal for this case, i.e., $p_f^{\text{bckg.,c}} = 0$ in the denominator (but still the background is accounted for in the numerator of η, i.e., $p_f^{\text{bckg.,r}} \neq 0$). For the direct beam, background subtraction amounts to $\simeq 50\%$. Moreover, the method to determine the position of the crystal on MUSIC1 is not useful for the randomly oriented target. This means that in the case of a varying position signal,

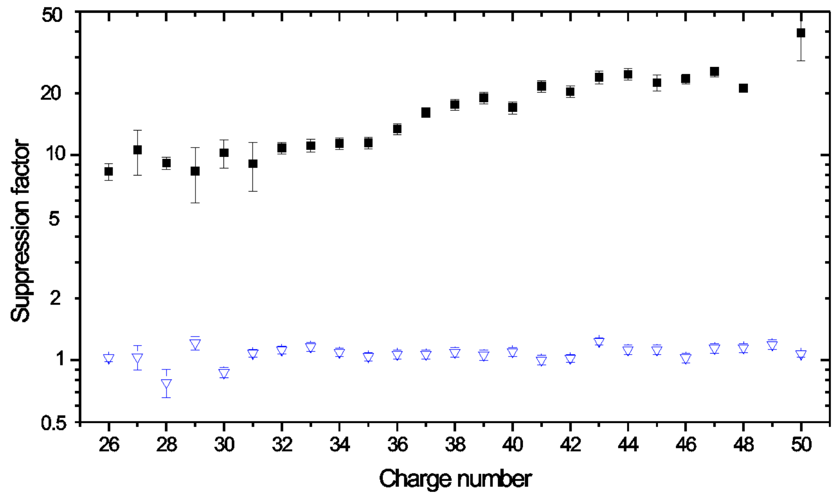

Fig. 4. The fragmentation probability suppression η for nuclear-charge changing probability versus charge number for the direct beam (open triangles) and the bent beam (filled squares), both for a bend angle of 7.5 mrad.

non-interacting ions may be included in the event selection which leads to a value of η that is artificially too small. Thus, the suppression factor—in particular for $Z = 50$ where the counts in the aligned case is consistent with zero—is a lower limit. Along the same lines it should be mentioned, that for the large bend angles, ions emerging in the straight beam may not have sampled the whole 60 mm of the crystal which could also lead to a value of η that is artificially too small.

As seen in Fig. 4 there is a strong suppression of a factor up to 25 for the channeled ions for fragmentation compared to the non-channeled ions. The suppression becomes progressively smaller for lower charge number, but even for the lightest fragments detected it is a factor 10. Furthermore, the nuclear-charge pickup channel is suppressed significantly more—by a factor of $\simeq 40$—showing that this type of reaction must be a short-range phenomenon. The overall behaviour of η with Z is partly explained by the limited number of counts for the channeled beam for $Z \lesssim 46$ and the approximation $p_f^{\text{bckg.,c}} = 0$. Given that the particle must be fully deflected to be counted, one would expect a higher suppression for low Z than for high Z, contrary to observations. For the undeflected beam, the background is about 50% for high Z-values, dropping slightly to about 35% for low Z. Using these numbers to estimate the background for the deflected beam, η increases by about a factor 3, but the overall tendency for η to rise with Z gets slightly stronger. Insufficient account of background is therefore not an explanation of the tendency.

Another effect may be part of the explanation for the large suppressions observed for proton-loss: If the ion dechannels it will not be fully deflected and therefore not contribute to p_f^{crystal}. For the pick-up reaction, however, this is unlikely to be significant since an increase of charge leads to a deeper transverse potential and the momentum of the π^- is too low (typically much smaller than 0.1 GeV/c [17,18]) to lead to an appreciable change of angle of the In^{49+} ion.

As a cross-check, the direct beam data sets are all consistent with a suppression factor of 1, indicating that systematic effects such as background subtraction or charge dependent angular distribution of fragments are insignificant. In the case of the bent beam, however, the suppression factor includes the deflection efficiency to some extent as a particle has to be fully deflected to contribute.

In Fig. 5 the suppression factors for the fragments and the pick-up channel are shown for the three deflection angles and for the 7.5 mrad data set also for an incidence angle $\psi_p/2$. As expected, the suppression factor becomes larger for larger bend angles roughly speaking because those ions that are guided all the way through the bent crystal are necessarily well channeled from the beginning. However, the indication that $Z \simeq 40$ has a stronger suppression than, e.g., $Z \simeq 45$ for the 11.9 mrad data set is not understood. For the

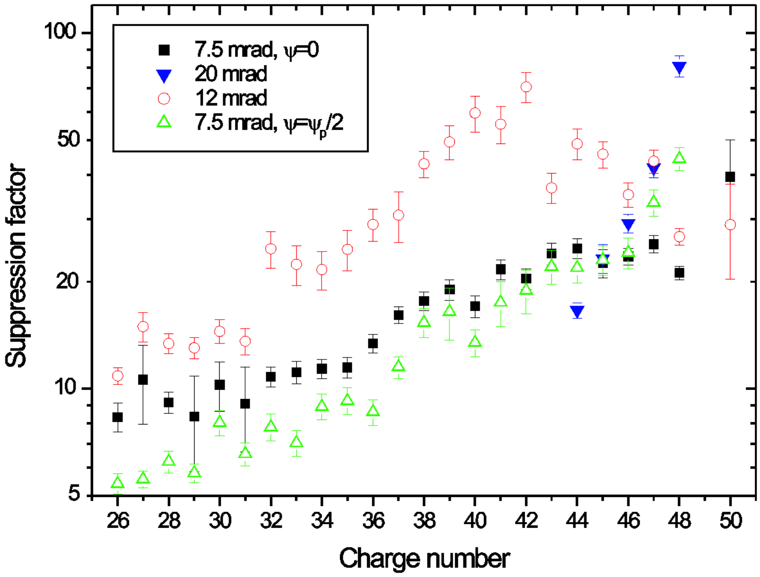

Fig. 5. The fragmentation probability suppression η versus charge number in the upper region of Z for the bent beam for angles 7.5 mrad (filled squares: perfect alignment, open triangles: aligned at $\psi_p/2$), 11.9 mrad (open circles) and 19.8 mrad (filled triangles).

7.5 mrad deflection angle, $\eta(Z)$ is slightly larger for $\psi = \psi_p/2$ than for $\psi = 0$ in the cases of $Z = 47$ and $Z = 48$. This is in contrast to smaller values of Z and is not expected. The scarcity of data points for the 19.8 mrad deflection angle is due to the small deflection efficiency which precludes identification of fragments below $Z = 44$.

The fragmentation probability suppression η for In^{49+} to remain in its initial charge state is -12 and -19 for the 7.5 and 11.9 mrad data sets. Taking $p_f^{\text{random}} \simeq 0.5 p_f^{\text{bckg.}}$ this corresponds to an increase of the effective interaction length by a factor 12 and 19, respectively. Therefore, for the channeled ions the crystal only presents 1.0% and 0.6% of an interaction length instead of the random value 13%, i.e., the large majority of heavy ions exit in the same charge state as they enter the crystal even in a crystal as long as 60 mm. We emphasize that the suppression factor is not the suppression for the channeling phenomenon as such, but the suppression under the condition that the ions are deflected through the full bend angle. This is the figure of merit for the motivation discussed in the introduction, i.e., a potential extraction scheme based on a bent crystal.

We have obtained similar results for the fragmentation probabilities in amorphous Pb, W, Sn and Ge targets and these will be published later [19].

5. Conclusion

We have shown experimentally a large suppression of the probability for proton-loss during deflection of fully stripped relativistic heavy ions in a bent crystal. Furthermore, we have presented deflection efficiencies for these ions for angles up to 19.8 mrad. The results are promising for a potential application of the deflection and extraction of relativistic ions from an accelerator, as the large majority will exit in the same charge state as they enter the crystal. For such an application we note however that the question of radiation damage to the crystal remains experimentally unaddressed in the case of heavy ions. Finally, we have presented evidence for the almost complete absence of nuclear-charge pickup under channeling conditions, corroborating earlier results in amorphous targets which show that this is a close-encounter electromagnetic process [1].

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