STOPPING POWER OF FAST CHANNELED PROTONS IN THE IMPACT PARAMETER TREATMENT OF ATOMIC COLLISIONS

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The energy loss of protons, passing through crystals in a random direction with an energy $E \geq 1$ MeV, is due to electronic excitation and can be explained quantitatively by the Bethe-Bloch formula [1] for the average energy loss per unit path length or the electronic stopping power $S_r = -dE/dx$. In a channeling situation, however, small impact parameters are avoided and the Bethe-Bloch theory no longer applies.

To account for the channel stopping power $S_C$, Lindhard [2] referred to the equipartition rule for a free electron gas. According to this rule small momentum transfers or plasmon excitation and large momentum transfers or single particle excitation supply equal amounts to $S_r$. Assuming single particle excitation to be proportional to the local electron density $n(r) \approx 0$ in the channel, Lindhard concludes a reduction of $S_C$ by 50%. This was confirmed by experimental data [3] for Si, but subsequent measurements [4] for Ge supplied reductions by 75%.

We therefore suggest an approach from a tight binding approximation, where the energy loss is calculated for individual inelastic collisions of the protons with single crystal atoms. This is done in the impact parameter treatment of atomic collisions [4], describing each electron by a scaled hydrogenlike groundstate. We calculate the average energy loss $\Delta E(b_m,E)$, due to a collision with the crystal atom $m$ (Fig. 1) in first Born approximation. The average over the channel cross section amounts to an integral over all $b$ and yields the random Bethe-Bloch formula. For fast protons $\Delta E(b)$ decreases only slowly ($\sim 1/b^2$) for $b$ much larger than the dimensions of the electron distribution $a_0$, and many atoms in a layer perpendicular to the channeled proton trajectory contribute substantially to $S_C$. Then it is obvious that for very fast protons there is little reduction of $S_C$ as compared with $S_r$. Therefore equipartition and channeling are not related, though also in the tight binding approximation equipartition holds for small and large momentum transfers. For $b \leq a_0$ the energy loss $\Delta E(b)$ is slowly varying with a finite limiting value $\Delta E(b=0) \sim 1/E$. 

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We apply our results to the best channeled 4 MeV protons for axial channeling in Si and Ge. The valence electrons supply the full random value because the main contribution is due to impact parameters much larger than the channel radius. For the core electrons to be excited the best channeled protons in $<110>$ direction are not fast enough. Therefore the different ratios of $S_{<110>}/S_r$ for Si and Ge are due to the different electron numbers in the $L$ and $M$ shell of Si and Ge, which contribute to $S_r$ but not to $S_{<110>}$ for the best channeled protons. The results for $S_{<110>}/S_r$ and for $S_{<100>}$, $S_{<111>}$ are in good agreement with the experimental data by Clark [5] et al.

Theory

In the following theory we assume all electrons $i$ of the crystal to be localized, which amounts to a tight binding approximation. This is well justified for the core electrons. For the loosely bound valence electrons only the binding energy will enter into the channel stopping power for MeV protons, so that the approximation of localized wave functions is not reflected by $S_C$. In this model the stopping power of the channeled proton with energy $E$ in Fig. 1 is