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This Week's Citation Classic®

Lindhard J. Influence of crystal lattice on motion of energetic charged particles. *Mat. Fys. Medd. Dan. Vid. Selsk.* 34:1-64, 1965. (Translated in *Usp. Fiz. Nauk SSSR* 99:249-96, 1969.) [Institute of Physics and Astronomy, Aarhus University, Denmark]

Using elementary principles of scattering in crystals, a comprehensive theory is deduced for a new phenomenon, now called channeling. When a swift charged particle moves nearly parallel to an axis or a plane of a crystal, there is conservation of energy in the transverse motion. Within a critical angle, there are strong dips in yield for close encounters of energetic ions with atoms. The influence of the strongly reduced multiple scattering is studied, as well as various subsidiary effects. [The *SCI*® indicates that this paper has been cited in more than 1,080 publications.]

Theory of String Effect and Channeling

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Thirty years ago, I was working on the theory of collisions between energetic ions and atoms. In 1963, we published a paper on range distributions of all heavy ions in all substances.[1] It was a simple theory with scaling properties of Thomas-Fermi type, and it was in accord with experiments. We observed, though, that in polycrystalline solids there were sometimes strange tails in range distributions.

The following year, I was much occupied with matters somewhat outside physics. I heard of some strange results for low energy ions; and in the early summer of 1963, John A. Davies came to visit Aarhus and I learned more about excess ranges.

I suddenly realized that this was not a low-energy phenomenon, but a low-energy remnant of a high-energy phenomenon of great simplicity. It was of great interest because of its vast practical applications (i.e., the determination of precise locations of dopant atoms, of interstitials, and of atoms in complicated crystals—in the bulk of the crystal as well as at surfaces). The question of ranges was only of secondary importance. The key was a basic "string effect" belonging to a collision between an ion and a row of atoms (a string). But the all-important point was that although each collision with an atom was a quantal perturbation, and the particle would pass through it with no shadow effect, still the total effect was classical motion in the smeared-out repulsive potential of the atoms along the string with a complete shadow at the center. I had approximate proof of this. Therefore, phenomena like nuclear reactions could be nearly extinguished for angles incident with the string less than a simple critical angle.

Very quickly, Karl Ove Nielsen, John A. Davies, and Erik Bøgh set up a most primitive old-fashioned experiment using proton reactions in aluminum and silicon. There were dips in yield by a factor of five, with the expected angular width. We were quite enthusiastic about it. Nielsen, who was the prime mover of the experiment, also forced me to publish quickly; within a few weeks, two papers were published together in *Physics Letters*.[2,3]

There followed one year of hard but exhilarating work before my *Classic* paper was finished. I tried to outline all of the basic features of the theory, the approximate conservation laws, and the effect of irreversibility. This laid a line for much further experimental and theoretical work.[4] Following the tradition inherited from Niels Bohr, I published in the proceedings of *Det Kongelige Danske Videnskabernes Selskab*. The paper was quickly translated and published in the Russian journal *Uspekhi Fizicheskikh Nauk*. We also published a detailed quantum theoretical treatment.[5]

1. **Lindhard J, Scharff M & Schiøtt H E.** Range concepts and heavy ion ranges. (Notes on atomic collisions, II.) *Mat. Fys. Medd. Dan. Vid. Selsk.* 33:1-42, 1963. (Cited 3,020 times.) [See also: **Lindhard J.** Citation Classic. (Thackray A, comp.) *Contemporary classics in physical, chemical, and earth sciences.* Philadelphia: ISI Press, 1986. p. 47.]
2. **Lindhard J.** Motion of swift charged particles, as influenced by strings of atoms in crystals. *Phys. Lett.* 12:126-8, 1964. (Cited 135 times.)
3. **Bøgh E, Davies J A & Nielsen K O.** Experimental evidence for the extinction of (p,γ) yields in single crystals. *Phys. Lett.* 12:129-30, 1964. (Cited 70 times.)
4. **Van den Berg J A, Zalm P C & Stephens G A, eds.** Section III. Channeling and dechanneling. Section IV. Channeling radiation. *Nucl. Instrum. Meth. Phys. Res. B* 67:173-278, 1992.
5. **Lervig P, Lindhard J & Nielsen V.** Quantal treatment of directional effects for energetic charged particles in crystal lattices. *Nucl. Phys. B* 96:481-504, 1967.

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