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High energy channelling and the experimental search for the internal clock predicted by Louis de Broglie

J. Remillieux [a,*], X. Artru [a], M. Bajard [a], R. Chehab [a], M. Chevallier [a], C. Curceanu [b], S. Dabagov [b,c,e], D. Dauvergne [a], H. Guérin [a], M. Gouanère [a], R. Kirsch [a], J. Krimmer [a], J.-C. Poizat [a], C. Ray [a], Y. Takabayashi [d], E. Testa [a]

[a] IPNL, Université de Lyon, Université Lyon 1, CNRS/IN2P3, Institut de Physique Nucléaire de Lyon, UMR 5822, Villeurbanne, France
[b] LNF, INFN, Laboratori Nationali di Frascati, Italy
[c] RAS P.N. Lebedev Physical Institute, Leninsky pr. 53, 119991 Moscow, Russia
[d] SAGA Light Source, Tosu, Saga, Japan
[e] National Research Nuclear University MEPhI, Kashirskoe shosse 31, 115409 Moscow, Russia

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A B S T R A C T

This paper gives a short review of the past and recent activities of the *Atomic Collisions in Solids* Lyon-group, in collaboration with other groups, in the field of high energy channelling. The ion-channelling programme was performed at GANIL-Caen and at GSI-Darmstadt. The electron-channelling programme started at ALS-Saclay for relativistic incident energies and was then extended to SPS-CERN for ultra-relativistic energies. The last part of this paper presents the electron-channelling experiments performed originally at ALS-Saclay, then at BTF-Frascati and more recently at LS-Saga, in order to observe the electron "internal clock" predicted in 1924 by L. de Broglie.

1. Introduction

Past and recent activities of the *Atomic Collisions in Solids* Lyon-group, in collaboration with other groups, in the field of high energy channelling are shortly reviewed. In Section 2 we describe our atomic physics programme at GANIL-Caen and at GSI-Darmstadt using highly charged heavy ion channelling. In Section 3 we review our experiments at ALS-Saclay and then at SPS-CERN in the field of high-energy electron and positron channelling, in the relativistic regime of channelling radiation and in the super-relativistic regime, where Quantum Electro Dynamics effects dominate electron–crystal interactions. An application of these QED effects is currently developed, using aligned crystals as powerful sources of positrons for future accelerators. In Section 4 is discussed the possibility of using high energy electron channelling to observe the "internal clock" of particles, that has been predicted in 1924 by de Broglie, in its geometrical interpretation of quantum mechanics. In channelling experiments the incident energy of the axially channelled electrons is adjusted in order to obtain the resonance between the experienced interatomic distances and the distance travelled by the electrons during one period of their internal clock. Thirty years ago, a resonance was observed at ALS-Saclay. This experimental result stimulated a number of theoretical works on the possibility of observing the de Broglie clock. In order to try to confirm this rather preliminary result, two programmes have been recently opened, one at BTF-Frascati in Italy and the other one at LS-Saga in Japan.

2. Fast heavy ion channelling studies

From the beginning of GANIL-Caen, the properties of the ions of a few tens of MeV/u it could deliver, not fully stripped, with high electronic energy loss rates in matter, attracted the interest of several multidisciplinary groups for setting up channelling studies. Then a collaboration started, hosted by the CIRIL laboratory, that initially gathered solid state, atomic and nuclear physicists from the *Groupe de Physique du Solide de Paris VI-VII* (later named INSP), the *Institut de Physique Nucléaire de Lyon* (IPNL), the *Centre d'Etudes Nucléaires de Strasbourg*, the *Laboratoire des Solides Irradiés de Fontenay-aux-Roses*, the *Centre d'Etudes Nucléaires de Bordeaux*, and from CIRIL. The IPNL, INSP, and CIRIL groups have been continuously working on this programme, at GANIL and also later at GSI, for more than 20 years. The numerous references can be found in the report by Cohen and Dauvergne [1].

* Corresponding author.

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We started with a test experiment, that was the first channelling study with high energy heavy ions, in which we could observe channelling dips on the nuclear reaction products with 60 MeV/u Ar ions incident on a thin Ge crystal.

2.1. Charge exchange and energy loss studies

In the high-energy domain covered by GANIL, the dominant charge exchange processes in amorphous solids or randomly orientated crystals are Nuclear Impact Ionization (NII) and the non-Radiative Electron Capture, also called Mechanical Electron Capture (MEC). In contrast, charge exchange by channelled ions is dominated by ion–electron interaction processes that do not involve nuclear recoil during close collisions. For them the crystal target can be considered as a dense and non-homogeneous electron target. In Fig. 1 we schematize the various charge exchange processes on which we worked experimentally. All these studies with thin crystals combined photon or electron detection and charge–energy magnetic analysis of transmitted ions.

The first charge exchange study dealt with Radiative Electron Capture (REC) by 20 MeV/u Xe^{53+} ions incident on a thin Si crystal. In channelling conditions most incident ions were observed to be frozen in their incident charge state and we could observe the K, L, M REC lines, the orientation dependence of their shapes, and deduce REC cross-sections.

A more sophisticated REC study was performed a few years later with 60 MeV/u bare Kr ions incident on a thin Si crystal. Coincidences between X-rays and transmitted ions were used to sign electron capture or ionisation. Thanks to the high-resolution X-ray detection, the shape of K and L REC lines were used to infer impact parameter dependent Compton profiles from the various electronic shells of silicon.

We worked on Electron Impact Ionization (EII) at GANIL with 27 MeV/u Xe^{35+} ions channelled through a thin Si crystal. We could then deduce EII cross sections for Xe^{35+}–Xe^{45+} by 14.7 keV electrons. The associated energy loss measurements showed that for the best channelled projectiles the energy loss rate does not depend on the local density of valence electrons, but on their mean density in Si.

A similar study was performed later at GSI with 300 MeV/u U^{73+} ions where M- and L-shell cross sections were measured.

We studied the Resonant Transfer and Excitation (RTE) process, in which the capture of a bound target electron by a projectile ion is accompanied by the simultaneous ion excitation. In order to observe the resonance, in axial channelling conditions, the energy of the beam of Xe^{52+} ions was varied by small steps from 34 to 42 MeV/u, when sent onto a thin Si crystal, while keeping constant the beam characteristics at the target point, a particular performance of the GANIL accelerator team. The resonance was observed by means of the K_α radiative decay and by charge state and energy loss measurements. The shape of the resonance was compared to calculated electron Compton profiles.

Then we attempted to observe RT2E, the trielectronic capture (single electron capture accompanied by a double ion excitation). This was the first channelling experiment performed in the high-resolution spectrometer SPEG at GANIL. We just obtained an upper limit for the RT2E cross section.

At GSI we used the beam of highly charged decelerated ions extracted from the ESR for observing an original feature: these slow ions can be kept frozen in their initial charge state when channelled in a thin crystal and then, due to the Q^2 dependence of energy loss, lose much more energy than unchanneled ions rapidly capturing many electrons.

2.2. Surface emission studies

In an experiment performed at GANIL in the SPEG beam line, we studied backward and forward electron emission by a thin Si crystal traversed by 29 MeV/u Pb^{56+} incident ions. The electron emission, several tens per ion, was observed to be reduced for hyperchanneled ions, that interact mainly with Si valence electrons, and enhanced for projectiles entering the crystal very close to atomic strings.

In a recent experiment at GANIL we studied ionic sputtering by the surface of a Ge crystal. The energy loss of an incident ion at the entrance of an axially aligned crystal varies over an order of magnitude as a function of its transverse energy. This is expected to influence strongly the ion emission yield. In SPEG an ionic mass spectrometer was viewing the entrance face of a thin Ge crystal. In absence of ultra-vacuum conditions, we detected mainly organic molecular ions from the surface but the yields were found strongly correlated to the energy loss below the surface, i.e., reduced for channelled ions, and strongly enhanced for ions entering the crystal very close to an atomic string.

2.3. Nuclear fission time studies

At the end of the nineties our collaboration extended to nuclear physicists from GANIL, CEA-Saclay and IPN-Orsay and undertook a series of blocking experiments at GANIL to measure fission times with U and Pb ions incident on a Si crystal. The use of inverse kinematics made possible to detect both fission fragments. The shapes of axial and planar blocking dips were confronted to simulations, yielding fission times in the 10^{-18}–10^{-17} s range.

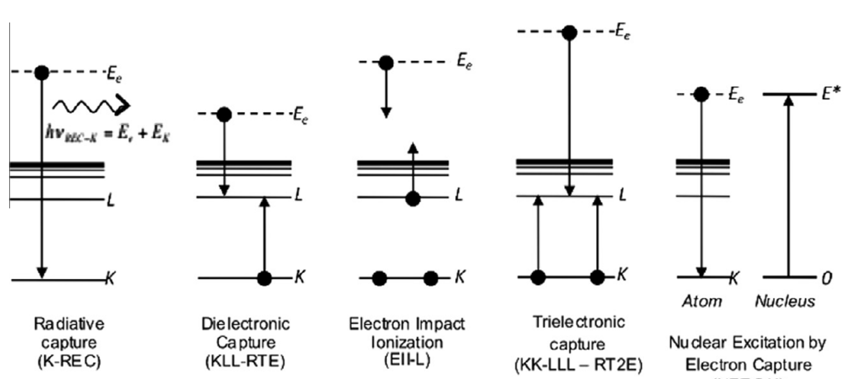

Fig. 1. Charge exchanges resulting from ion–electron interactions that have been studied in channelling conditions.