Experimental observation compatible with the particle internal clock

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ABSTRACT. The particle internal clock conjectured by L. de Broglie in 1924 was looked for in a channeling experiment with ~80 MeV electrons traversing a 1-µm thick silicon crystal aligned along the <110> direction. Part of them undergo what is called the rosette motion, in which they interact with a single atomic row. When the electron energy is finely varied, the rate of electron transmission at 0° shows an 8% dip within 0.5% of the resonance energy, 80.874 MeV, for which the frequency of atomic collisions matches the internal clock frequency. Our observation is compatible with the de Broglie hypothesis.

RESUME. L’horloge interne d’une particule conjecturée par L. de Broglie en 1924 a été recherchée dans une expérience de canalisation avec des électrons de ~80 MeV traversant un cristal de silicium de 1-µm d’épaisseur. Une partie d’entre eux subissent ce qu’on appelle le mouvement de rosette, au cours duquel ils n’interagissent qu’avec une seule rangée d’atomes. Quand on fait varier finement l’énergie des électrons, le taux de transmission des électrons à 0° présente un creux de 8%, en moins de 0.5% de l’énergie de résonance, 80.874 MeV, pour laquelle la fréquence des collisions atomiques égale la fréquence de l’horloge interne. Notre observation est compatible avec l’hypothèse de de Broglie.

In the beginning of quantum mechanics, L. de Broglie [1][2] associated a particle of mass m_0 in its rest frame with an internal frequency $\nu_0=m_0c^2/h$ and a wave $\psi_0=a_0\exp(2\pi i\nu_0 t)$. The wave length $\lambda=h/p$ in the laboratory was then deduced by a Lorentz transformation. However, despite the success of the wave hypothesis, the internal clock frequency was never observed, nor is it known if it is an observable or if it ever exists! The aim of the present experiment was to deal with such a possibility, i.e. to put this frequency in evidence for electrons, connecting it with some kind of interaction.

We shall assume that this interaction occurs at the electron position in the laboratory with a periodic "amplitude". In the laboratory the electron internal frequency is $\nu=\nu_0/\gamma$, and the distance covered during the clock period is $\ell=\beta c/\nu=hp/(m_0c)^2$. A direct observation of this frequency could be to look for a regular pattern in the ionization points of the particle trajectory in an emulsion plate. However in order to observe a distance of at least 10 microns it would require a fairly high energy (10^{19} eV protons or 10^{13} eV electrons), that is at the limit of the highest primary cosmic rays. An observation not so direct but under better control is possible with the help of the axial channelling effect in a single crystal [3][4].

When the incident direction of fast negative projectiles as electrons is close to a major axial direction of a thin single crystal, electrons are attracted towards atomic strings, which they see mainly as continuous positive charges. Then they suffer multiple nuclear scattering effects that are stronger than when the beam is sent along a random direction. As shown in Fig.1 the probability of transmission through a thin crystal at small angle to the incident beam direction depends strongly on the crystal orientation. The transmission probability exhibits a large dip centred on the axis direction. However its deepest part appears to be filled by a sharp peak. This well known feature is due to the process called "rosette motion": when the incident beam direction is very close to the axial direction, some electrons with a small but non-zero angular momentum with respect to an atomic row may be trapped in a spiral motion around this atomic row. These electrons suffer reduced multiple scattering effects and have a high transmittivity. The important point is that electrons undergoing rosette motion interact essentially with a single atomic row throughout the crystal. At the resonance energy, the electrons for which the maximum "amplitude" is just in phase with the atomic centers will suffer a greater interaction, while those whose maximum "amplitude" is just in between will travel with a reduced interaction. The mean effect should not be zero because the potential is not linear in z (the electron flight path). A crude estimation of the effect on channelling motion shows that it would be included within ± 0.5 % of the resonance energy.

The experiment was performed as a by-product of the study of the "planar channelling radiation from 54 to 110 MeV electrons in diamond and silicon"[5] at the Accélérateur Linéaire de Saclay (ALS). The 1-μm thick silicon crystal (lattice constant 5.431 Å) was aligned along the <110> direction (interatomic distance in the row d= 3.84 Å). The resonance momentum of electrons, for which $d=\ell$, is 80.874 MeV/c. The experimental set-up is shown in Fig.2. The external electron beam from the ALS was restricted to a very small emittance(1 mm)^{2}x(0.1 mrad)^2,by a pair of collimators D1 and D2,of 1 mm diameter and located 10 m apart. The beam line included two spectrometers (bending magnets and quadrupoles) SP1 and SP2. The slit SL1 was adjusted to ensure a momentum resolution $\Delta p/p \sim 10^{-3}$. A removable set of scintillators SC1 was used to center the beam spot on the crystal target. The vertical and horizontal angular divergences of the beam were equal to 0.1 mrad and the beam spot was 1 mm^2. The Si crystal was mounted on a two-axis goniometer that could be moved by steps of 85 μrad. The detectors of transmitted electrons consisted of two scintillators SC2 (3x3 mm^2) and SC3 (10x10 mm^2) and were located 3 meters after the crystal. The small angular acceptance scintillator SC2 was used as a counter and the large angular acceptance scintillator SC3 as a monitor. The bending magnet M was carefully calibrated by the floating wire method in order to obtain an absolute measurement of the bending power. All magnets were controlled by nuclear magnetic resonance probes.

The currents in the spectrometer SP_1 and SP_2 were designed to work in the achromatic mode. In this way the beam momentum onto the crystal could be varied within 1% without current adjustment in the spectrometer by simply moving the slit SL_2. This allowed the study of very fine momentum changes by varying only the position of SL_2 and the current in M.

The crystal orientation was obtained with the 80 MeV/c electron beam by angular scans that yielded planar dips on the rate of SC_2 monitored by SC_3. A typical scan of the counting rate versus the crystal tilt angle θ is shown in Fig.1. As discussed above it shows the channelling dip with a width of 8 mrad and the "rosette" motion peak in the center. A scan like the one in Fig.1 was periodically performed during the beam momentum scans to ensure that the beam alignment had not changed.

The energy measurements were performed at $\theta=0^0$ with 3 beam momentum adjustments of the spectrometer: 80.874 MeV/c (central), 80.065 MeV/c (-1%) and 81.683 MeV/c (+1%). At each beam adjustment the momentum onto the crystal was varied in small steps (0.083 %) by moving the slit SL_2 and the current in M. The total scan domain was ± 1.5 %. A multiplying correction was applied to the raw data at the central momentum adjustment in order to compensate for monitoring loses at high rate, assuming that the physical effect should be energy symmetric. This correction is symmetric around the central value 80.874 MeV/c by beam construction. We use the semi-empirical formula: $\text{Correction}(P)=1-C_0\exp[-(P-P_0)^2/2C_0\Gamma_P^2]$ where P is the electron momentum in MeV/c, P_0=80.874 MeV/c, Γ_P is the momentum spread of the beam before the spectrometer=0.809 MeV/c. In order to calculate C_0, 4 momentum intervals are chosen according to the assumption that the physical effect should be energy symmetric. The 4 intervals have 5 bins each (one bin=0.0674 MeV/c) and their centers P_1,P_2,P_3 and P_4 are respectively at 80.267,80.537,81.615 and 81.952 MeV/c. The condition "slope(P_1-P_4) = slope(P_2-P_3)" fixes the value C_0 = 0.0354. The beam intensity was reduced at adjacent energies and no corrections were needed there. The results are presented in Fig.3. The statistical errors are low (~0.6%) and correspond to the size of the dots.

A 8% dip is seen at 81.1 MeV/c, near the central momentum of 80.874 MeV/c. We can attribute it to an internal clock interaction. The observed minimum is at a momentum 0.28 % higher than predicted, but this is compatible with the accuracy of our floating wire calibration (±0.3%). Our conclusion would mean that an observation could also be possible at harmonic frequencies, for example at corresponding momenta of 40.437 MeV/c, 161.748 MeV/c, etc… probably with reduced intensity. It is also possible that the fundamental frequency is not at a corresponding momentum of 80.874 MeV/c but at 161.748 MeV/c, if we take into account the square of the amplitude instead of the amplitude.

One must consider what other effects could produce such a resonance. V.V.Okorokov [6] has been the first one to predict that fast ions grazing atomic rows could be excited if they carry some internal clock. In fact electronic excitation has been extensively observed with heavy ions carrying electrons [7]: the so-called resonant coherent excitation occurs if the collision frequency (or a multiple of it) with the atomic rows matches the frequency corresponding to the atomic transition. In our case an internal clock could be associated with the rosette motion itself. Earlier we have shown that the transverse energy levels of electrons channelled along a planar direction were quantized [5]. Later others [8] have shown that discrete levels appear also in rosette motion bound states. However we can rule out a coherent resonant transition between rosette motion levels, because well discrete levels need time to be defined which is not the case for a thin crystal like the one we used. In the present case the corresponding level width is estimated to be ~30 eV, which for the axial channel well depth of ~200 eV, would give rise to a coherent resonant width of more than 15%, rather than the 1% effect observed here.

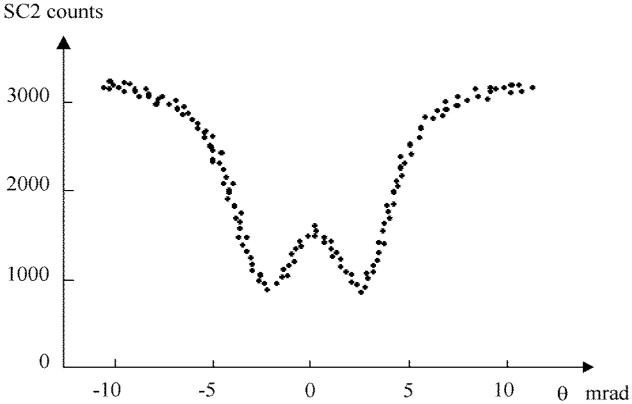

Fig.1

Fig.1. Dots:80 Mev/c incident electrons; counting rate of SC2 with respect to the crystal tilt angle θ.

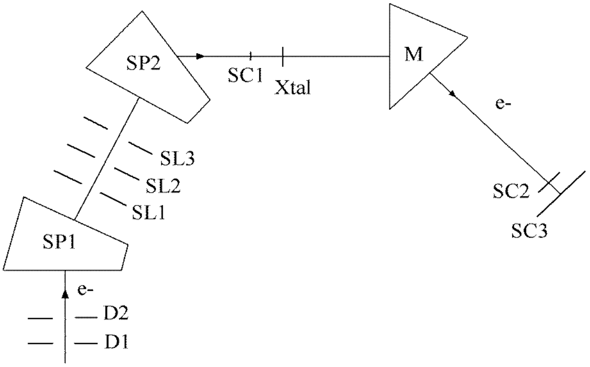

Fig.2

Fig.2. Experimental set-up. D1 and D2 are collimators (1mm in diameter, 10 m apart). SP1 and SP2 are two spectrometers (bending magnets and quadrupoles) with SL1, SL2 and SL3 slits. SC1 is a removable scintillator used to center the beam onto the 1-μm thick <110> silicon crystal. M is the last bending magnet. SC2 is a 3x3 mm^2 detector. SC3 is a 10x10 mm^2 monitor.

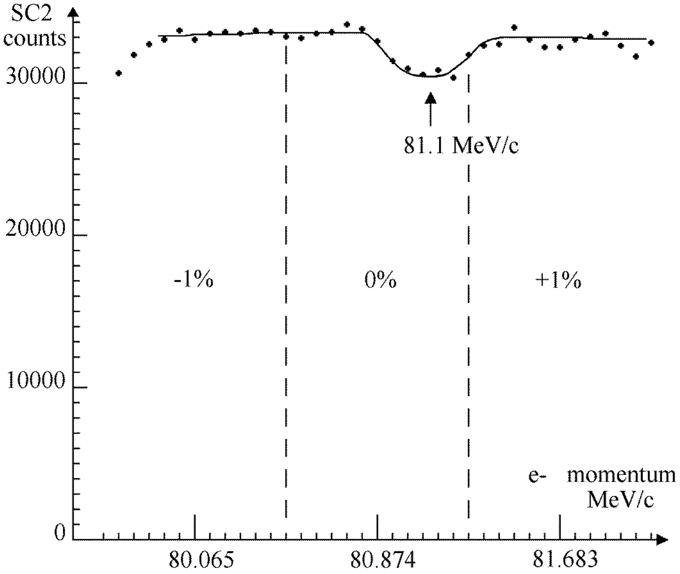

Fig.3. Dots: SC2 experimental counts vs. electron momentum at $\theta=0^0$ for the 3 spectrometer settings,-1%,0% and +1%,per fixed count in the monitor ($SC3=10^5$). The dots are corrected data and the full line is to guide the eyes.

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(Manuscrit reçu le 26 mai 2005)