Channeling 2014, Capri-Naples, Italy
Joseph REMILLIEUX, IPNL, Lyon, France

High Energy Channeling and the Experimental Search for the Internal Clock Predicted by L. de Broglie

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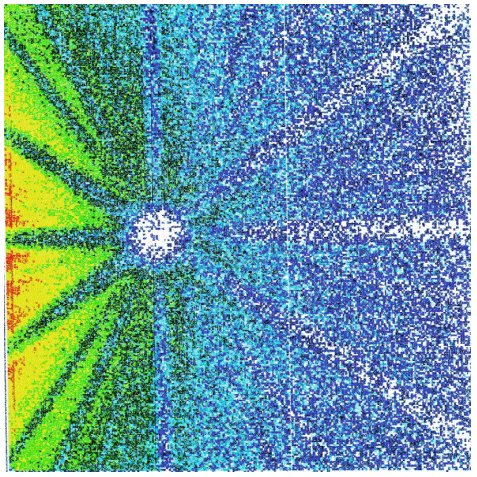
I- Ion channeling
II- Electron channeling
III- Search for an electron internal clock

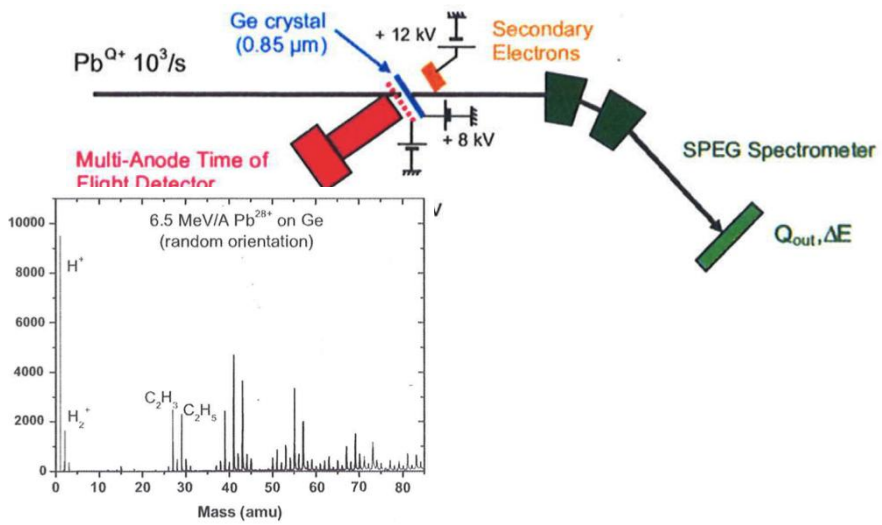
I- Heavy ion channeling and blocking

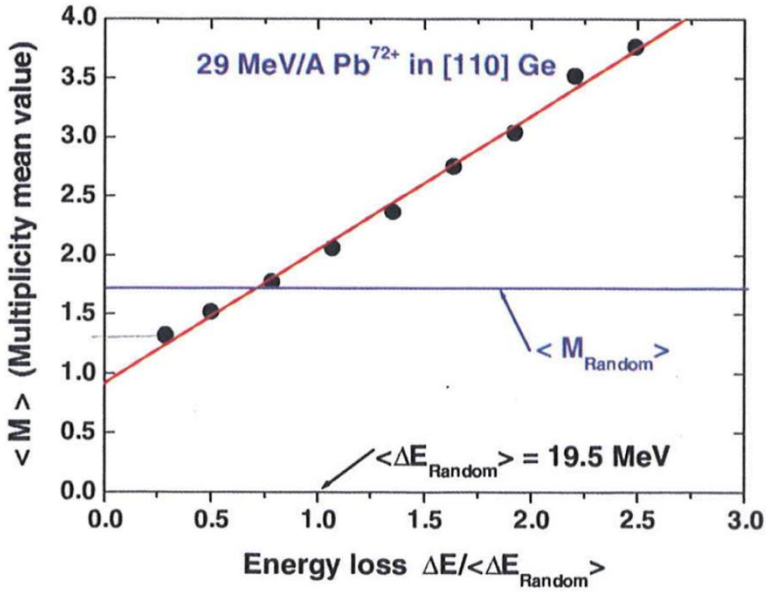
Lyon-Paris-Caen-Albany

- Atomic and nuclear interactions of MeV/u to GeV/u channeled ions with the « quasi-free Xtal electron gas »
  - Radiative Electron Capture REC
    - the inverse of Photo-Ionisation @ GANIL-Caen and GSI-Darmstad
  - Resonant Transfer and Excitation RTE and RT2E
    - RTE, the inverse of Auger Transition, @ GANIL
    - RT2E, a trielectronic interaction: only upper limit of σ, @ GANIL
  - Nuclear Excitation by resonant Electron Capture NEEC
    - the inverse of Internal Conversion:
      - only an upper limit for the excitation σ of 14 KeV transition in ^{57}Fe, @ GANIL
      - **project @GSI-FAIR: excitation of 45 KeV trans. in ^{238}U**
- Xtal blocking and nuclear fission times
  - Measurement of 10^{-17}s to 10^{-19} s lifetimes
    - experiments with Pb and U beams, @ GANIL
      - In Si Xtal
      - In Ge and Ni Xtal -> production of super-heavy nuclei



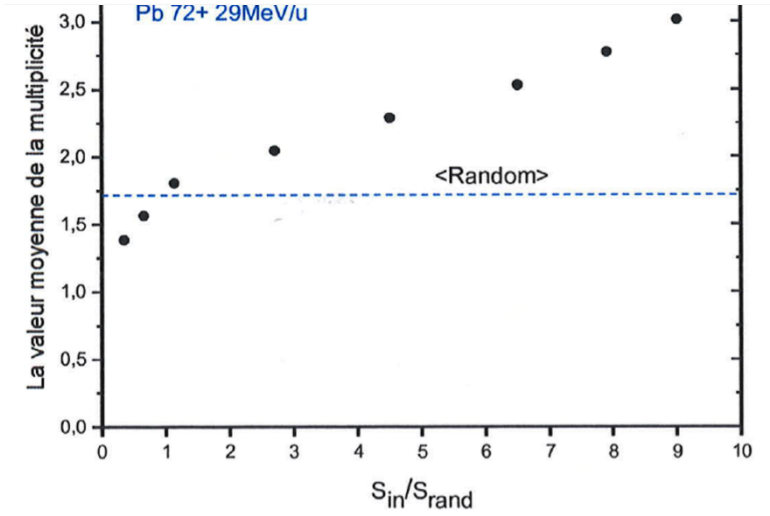
Ion desorption from a thin aligned Ge Xtal under impact of fast Pb ions





Desorption rate of surface impurities

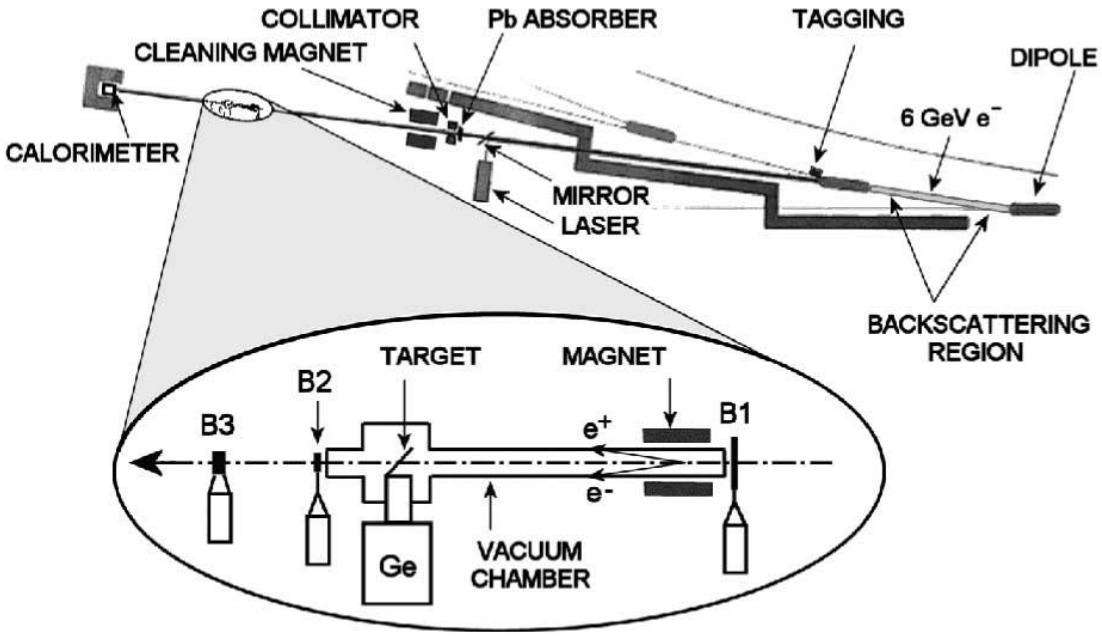
- is linked to the local energy deposited by the ions at the crystal entrance
  - i.e depends on their impact parameter to the closer string



Vacuum-assisted heavy ions photoionisation at relativistic energies

- Photoionisation with GeV photons, @ ESRF-Grenoble (GRAAL beam line)

  - High energy photons are produced by Compton backscattering of a laser beam with the synchrotron e^- beam



  - Measurement of K-shell ionisation cross sections in Au and Ag amorphous foils
    - evidence for an ionisation channel increasing linearily with target thickness

    due to (e^+e^-) pair creation, on nuclei or on electrons, from the negative-energy-continuum

- To be explored with aligned Xtal targets
  - Crystal-assisted photoionisation along <ijk> axis is expected
    - when the coherence length for pair creation becomes > $d_{<ijk>}$

II – High energy electron channeling

Lyon-Annecy-CERN-Albany

Radiations along Xtal planes at relativistic energies:

synchrotron radiation

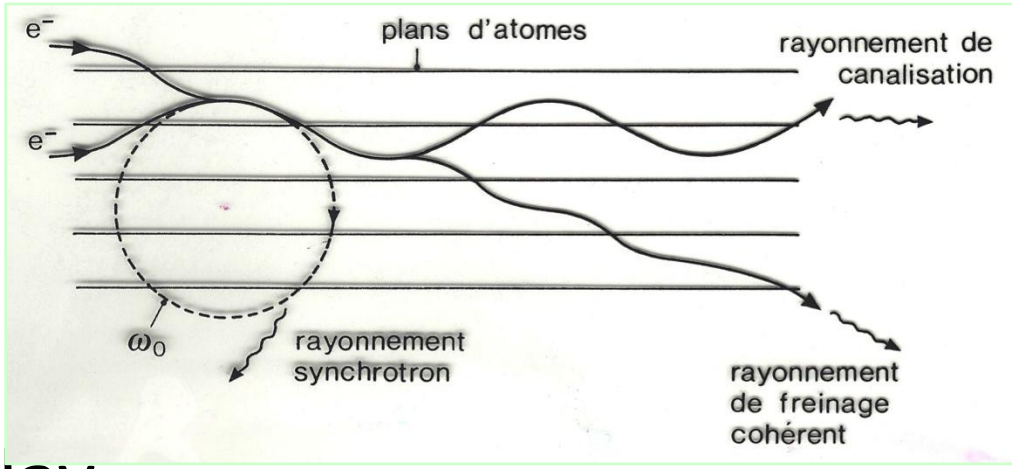
- quasi-continuum

coherent bremsstralhung

- 1 resonance + harmonics

channeling radiation

- discrete lines (M.Kumakhov)



- Experiments @ ALS-Saclay
  - 20-100 MeV electrons in a diamond Xtal (1µm thick)
    - study of channeling radiation spectra
      - from the pseudo-atomic « Xtal-electron » system
    - by-product: first observation of a resonance (?)
      - in the electron « rosette motion »
      - compatible with de Broglie « internal clock »

Radiations at ultra-relativistic energies

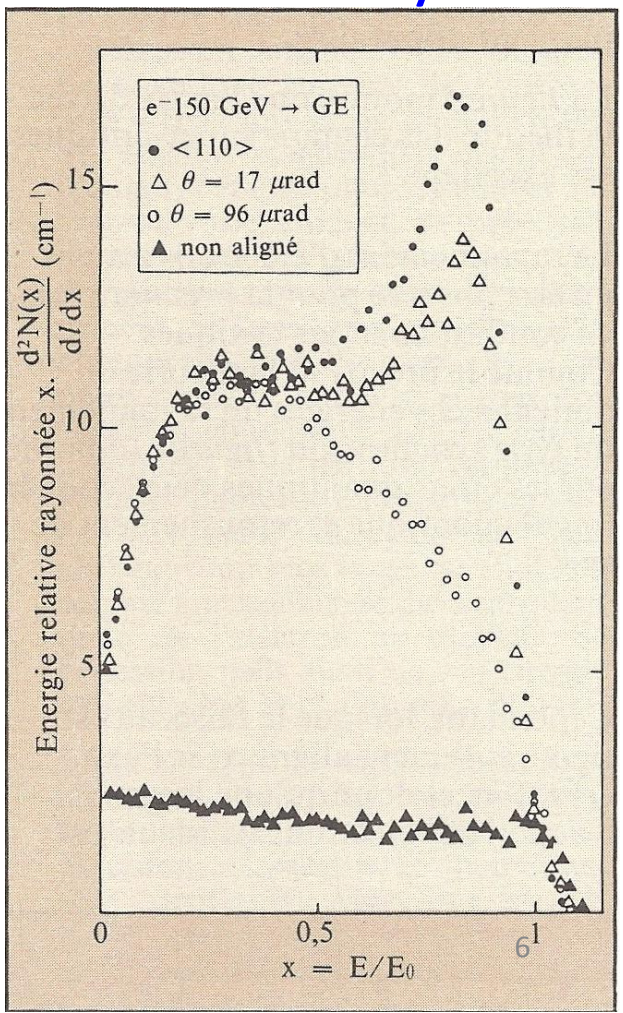
At incident electron energies > 100 GeV

- an aligned crystal => super-critical fields laboratory
  - B > 10^9 Teslas, E > 10^{16} V/cm
  - with strong-field QED effects
    - on pair creation and on radiation

- Experiments in Ge Xtal, @ CERN
  - Axial channeling of 20-150 GeV e^-

    Evidence for a strong radiation peak
    - due to a cascade of cooling events

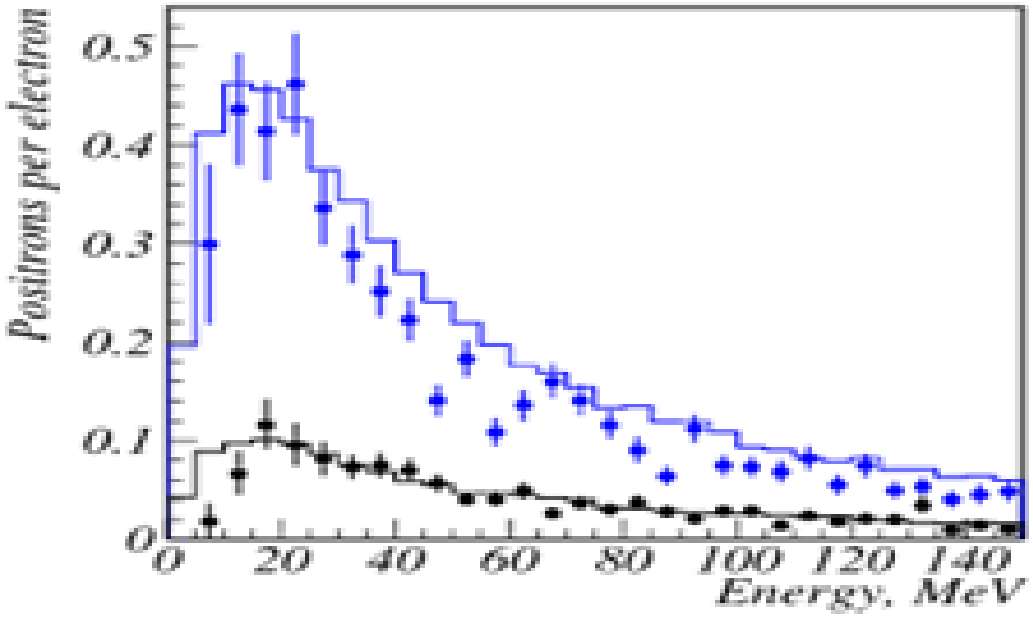
      in the rosette motion
      - by radiations and pair creations



Application of channelling radiation to the development of an intense positron source

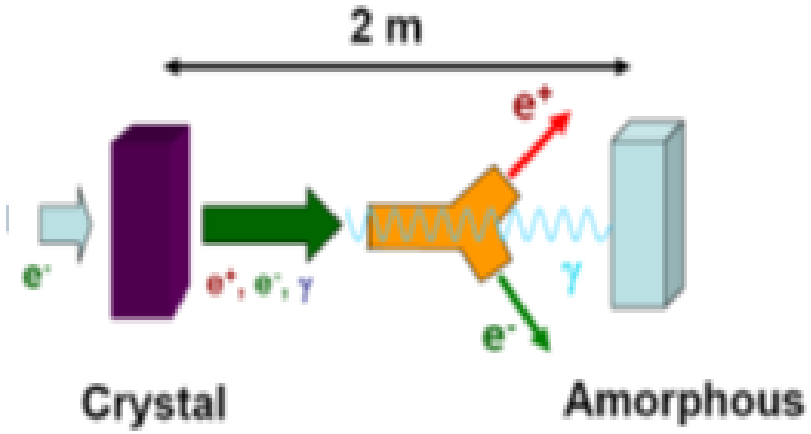
Lyon-Orsay-Novosibirsk-Tomsk-KEK-CERN-IHEP

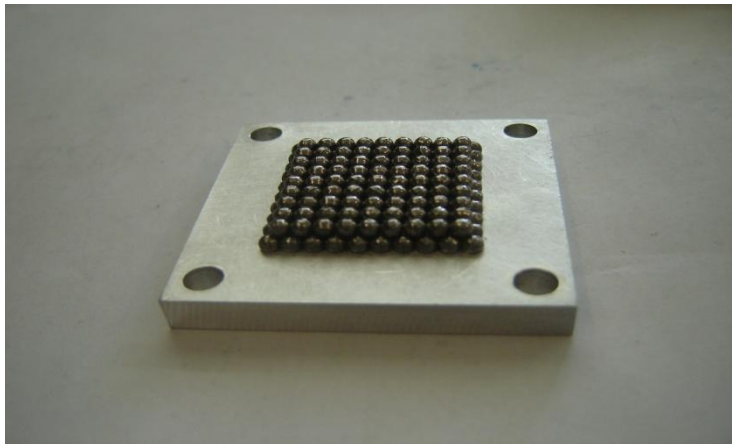
- Aligned crystal targets in GeV electron beams
  - Experiments in W crystals @ LAL-Orsay and CERN (WA103)
    - positron production enhanced by a factor 4 along <111> axis



  - Such a Xtal positron source, has been used for 1 year @ KEKB

- **Toward an hybrid positron source for CLIC project**
  - photons are first produced in an aligned Xtal target
  - positrons are then produced in a granular amorphous target, for better heat dissipation





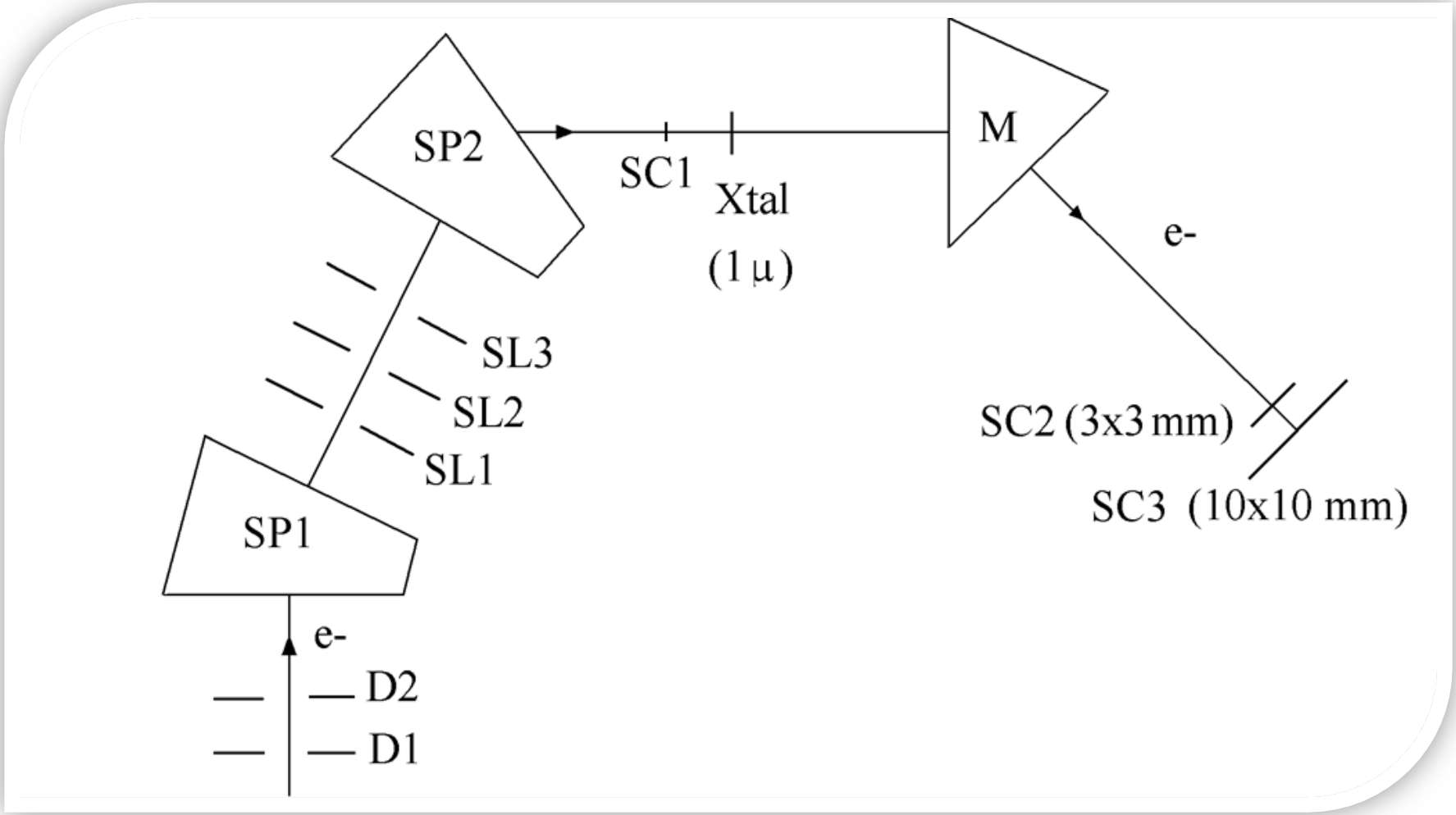
  - Next step, @ KEK: test of the granular converter
    - made @LAL-Orsay, with W balls (2.2mm in diameter)

III – Search for an electron internal clock

Lyon-Annecy-Albany-CERN-Saga

- Back to the Louis de Broglie thesis (1924):
  - in the geometrical interpretation of Q.M.
    - any massive particle is surrounded, in its rest frame, by a wave $\Psi = a_0 \exp(2\pi i \nu_0 t)$ with $\nu_0 = m_0c^2/h$ ($\approx 10^{21}$ s^{-1} for e^-)
  - for a particle moving at velocity β
    - the wave frequency, in the lab frame, is $\nu = \gamma\nu_0$
    - the displacement of the particle, during one period of its "internal clock", is $d_{\text{internal clock}} = c\beta\gamma/\nu_0$
      - a distance of the order of **a few Å for 100 MeV e^-** (≈ interatomic spacings !)
- The idea: the "rosette motion" of an electron around an <ijk> axis could be perturbed by its internal clock, when its velocity β is adjusted in order to fit the spatial resonant condition $d_{\text{internal clock}} = d_{<ijk>}$
  - in Si <110>, the resonance energy is expected at **81 MeV**

The first experiment @ ALS – Saclay 1980

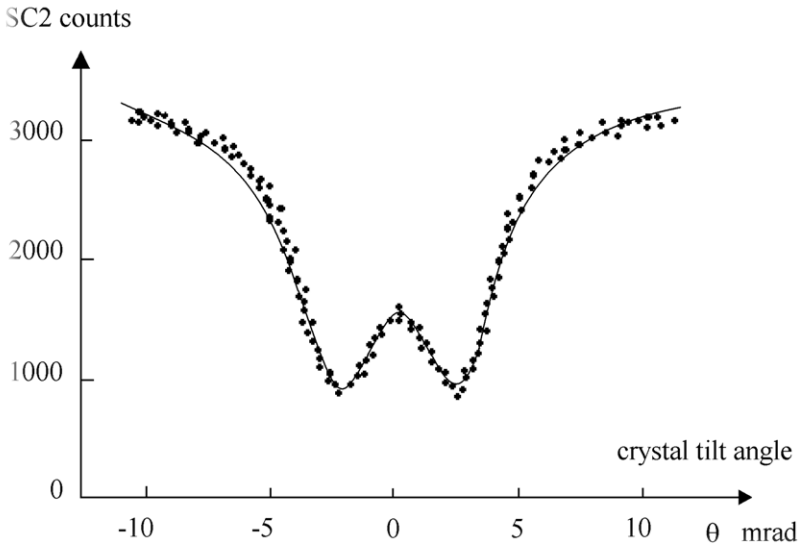


Set up to measure changes in the angular divergence of transmitted electrons

Electron energy scan along <110> axis

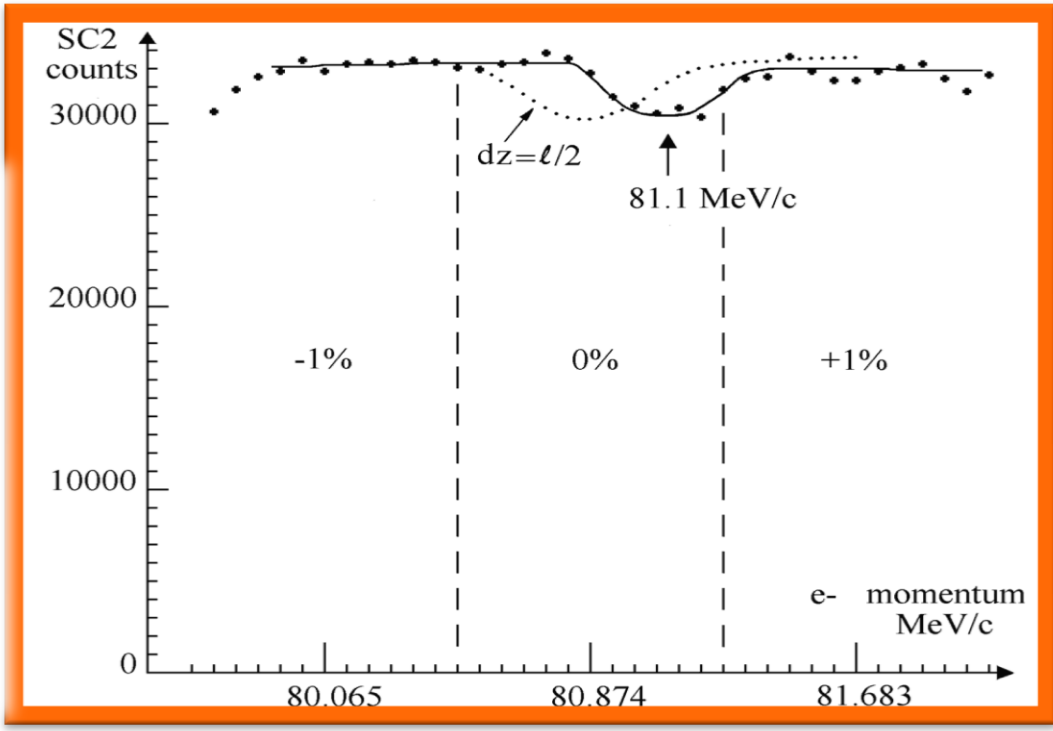
- Rosette motion signature

  in a 1µm thick Si crystal



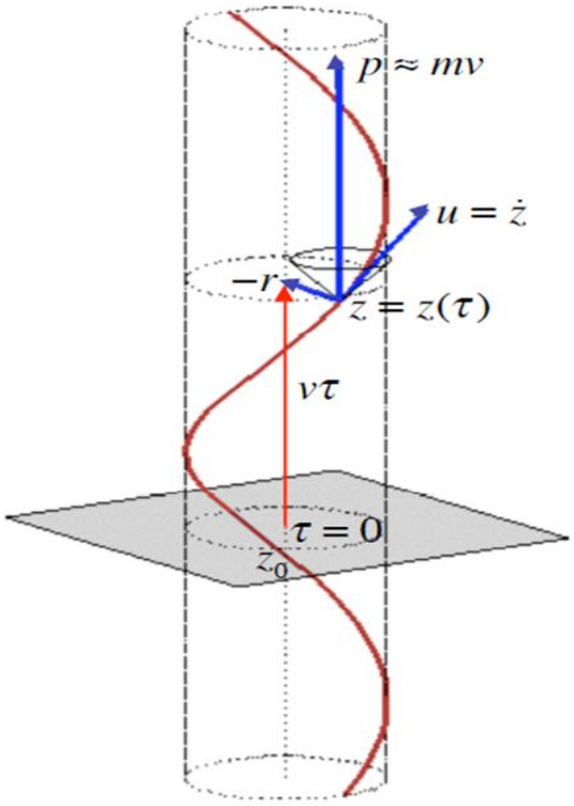
- Expected resonance

  at ≈ 81 MeV/c



Alternative interpretations

- Zitterbewegung resonance at $\nu_{ZBW} = 2\,\nu_{de\ Broglie}$
  - first introduced by E.Schrödinger (1930)
    - then revisited by D.Hestenes (2007)
- Crystal-assisted Trident production
  - at the energy threshold for ($e^-e^+e^-$) production of electrons in channeled states
    - a pseudo-resonance and harmonics
- Other theoretical works and simulations
  - G.Oshe (Acton-USA), four-dimensional model
  - M.Bauer (Mexico), self-adjoint time operator
  - B.Azadegan (this conference) electron trajectories
  - and also: M.Rivas (Bilbao), E.Recami (Bergamo), …



- Other experimental evidences in very slow ion-laser interactions

  "**zitterbewegung motion**" of trapped ions, R. Gerritsma et al, Nature 2010

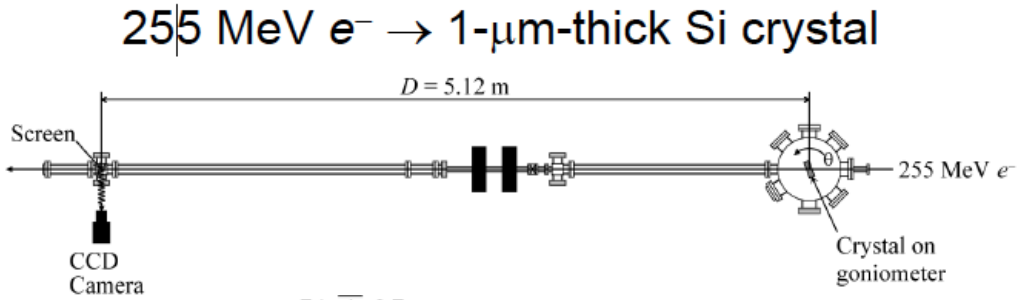
  "**a clock directly linking time to a particle mass**", S.Y. Lan et al, Science 2013

Further *RICCE* experiments

Research of Internal Clock by Channelling of Electrons

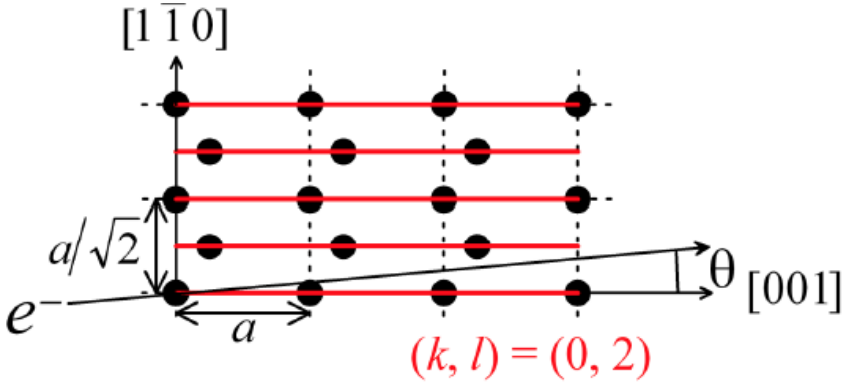
- *RICCE* @ LNF- BTF - Frascati
  - the BTF facility is a secondary (e^+/e^-) beam line
    - 80 – 160 MeV electrons have been channeled in Si and Ge Xtal
    - but … despite various improvements of the beam line optics
      - we were unable to step the incident energy
        - » without inducing small changes in the beam direction at the Xtal
- Future of *RICCE* @LNF - Frascati
  - possibly on the new channelling beam line @ SPARC ?

A new program *RICCE* @ SAGA-LS-Japan



- Linac e- beam

- Search for clock resonance
  - in (220) planar alignment
    - expected at θ= 9.12 deg
      - no planar resonance observed
      - but high index axes
        <1,1,9> , <3,2,26>, …
  - future: axial directions
    - <100> at 114 MeV, <210> at 255 MeV, …



- Another suggestion to cross the resonance at a fixed incident beam energy
  - tilt the crystal along a series of high index axes with close $d_{<ijk>}$ values, in order to cross the $d_{internal\ clock}$ value