NEUTRAL COMPOSITE PARTICLE TRANSPORT IN CRYSTAL X-RAY ACCELERATORS

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The channeling of a particle-antiparticle pair in a crystal lattice is studied, showing reductions of energy losses only in the low γ regime, which is still attractive for particle sources. Neutron acceleration is also considered as a case of a strongly bound composite.

Introduction

The crystal X-ray accelerator[1] uses the crystal periodicity, or superperiodicity, as a linac structure for particle acceleration and the channeling effect[2,3] as a focusing field for guiding the beam. Let z be parallel to the channel axis and a, b be the lattice spacings, as shown in Fig. 1 ; moreover x, y, z is a cartesian frame and $r = [x^2 + y^2]^{1/2}$ as usual. a and b are about $5\mathring{A}$.

Other acceleration mechanism in solid state matter has been proposed[4,5] . For all these acceleration schemes, limitations arose from the dechanneling for progressive excitation of betatron oscillations from electron scattering (ionization) and — at large γ — from bremsstrahlung and channeling radiation emission[6] .

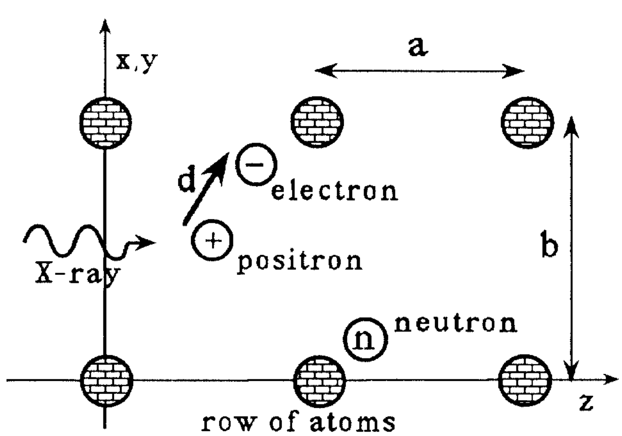

Fig 1) A pair in a crystal lattice

For muon or heavier particles of mass m_I the dechanneling momentum p_f scales as:

$$p_f = p_0 \left(\frac{2V_2 a_c^2 \alpha_g}{D} \right)^2 \qquad (1)$$

where p_0 is the injection moment, a_c is the channel width, V_2 is the restoring force constant of the channel potential $V(x)$ defined as $V_2 = V''/m_I c^2$, α_g measures the net accelerating gradient G as $\alpha_g = G/m_I c^2$ and D is the diffusion coefficient given by $D = 4\pi n_{val} r_I^2 L_R$; here n_{val} is the crystal valence electron density, r_I the ion classical radius and all the logarithmic dependencies from the energy are put in the factor $L_R \cong 10$.

It is natural to consider whether a neutral particle $Z = 0$ will show reduced energy losses and longer channeling times. This particle must be a composite of negative and positive particles, for example a particle-antiparticle pair, separated by a distance $\vec{d}$ such that each member of the pair can be resonantly accelerated by the accelerating field by the same amount:

$$d_z \cong \frac{\pi}{\omega} v_{ph} \qquad (2)$$

where v_{ph} is the phase velocity (along z) of the accelerating wave with frequency ω : in Ref. 1 it was considered that $\hbar\omega = 40\,KeV$.

From a subnuclear point of view, a neutron is a composite too and we will consider it later; the coupling to the accelerating field is only trough its magnetic moment in this case.

The pair separation $\vec{d}$

The transverse motion of each pair member is given by the hamiltonian:

$$H_{tr} = \frac{p_x^2 + p_y^2}{2\gamma m_I} + q\bar{V}(x, y) + \frac{V_{int}}{\gamma^2} \qquad (3)$$

where q is the charge, V_{int} is the usual internal electrostatic attraction, γ is the relativistic factor and $\bar{V}$ is the z-average of V , the crystal interatomic potential: $\bar{V} = (1/a) \int_0^a V(x, y, z) dz$. While positive particle are channeled near the minimum of $\bar{V}$ at $r = b/2$, negative particle are attracted near rows of atoms, and they must have an angular momentum L_z , satisfying

$$2H_{tr} < L_z^2 / b^2 m_I < b\bar{V}_{,r}(b)$$

in order to avoid collisions with the atoms. Therefore the transverse pair separation $d \equiv [d_x^2+d_y^2]^{1/2}$ is given by $d \cong b/2$. The neglected Coulomb interaction may affect this conclusion only at low γ and for heavier particle than the electron (indeed the positronium radius is about $b/5$.)

The longitudinal separation is quickly estimate from (2) and the kinematics[1] for $\gamma \gg 1$: we get $d_z = b/20 \cong .25 \mathring{A}$.

Screening of the charge

It is evident that if $\vec{d} = 0$, then the neutral composite will suffer no scattering from the crystal. We discuss the effects of the actual distance separately for $d_z \neq 0$ and $d_x, d_y \neq 0$. A single fast charge would push an electron at distance b with a force $F_\perp = q\gamma/b^2$ for a time $\Delta t_+ = b/\gamma v$. When a pair is considered, after a time $t_p = d_z/v$ the second member pull compensates the first member push; therefore the ionization efficiency of the pair nearly vanish when $t_p < \Delta t_+$, that is $b < \gamma d_z$. By considering that the usual and well-known ionization losses ΔE are due to the integration over the values of impact parameter $b < b_{max} \cong \hbar\gamma v/I$, we argue that they will reduce to

$$\Delta E' = \Delta E \frac{L - \ln(v\hbar/d_z I)}{L} \cong \tfrac{1}{2}\Delta E \qquad (4)$$

where I is the ionization energy and L the usual Coulomb logarithm.

Considering now a transverse pair separation $d = [d_x^2 + d_y^2]^{1/2}$ we see that the pair give a kick $\Delta p'$ to an electron at distance b (from its center) which is a considerable fraction of the kick Δp given by a single charge

$$\Delta p' = \Delta p' \left(\frac{d}{b} + O(d^2/b^2)\right) \qquad (5)$$

These reduction, even tough considerable, do not open new perspectives in the dechanneling limit (1). Moreover, in both cases, the kick difference must be absorbed by the pair binding, which decrease with γ . In the high γ regimes eventually the pair becomes unstable and dissociates. Therefore, we turn to consider acceleration at low γ , which was neglected in Ref. 1.

An alternative application of the present composite acceleration is to a porous crystal[6] or to a mesoscale accelerator[7] , in which the ratio d/b is much smaller than unity.

Wave velocity

While for obtaining a wave velocity $v_{ph} = c$ and group velocity $v_{gr} = O(c)$ the consideration of crystal superperiodicity was necessary, we show that the natural lattice periodicity is appropriate for slower waves: here the lattice longitudinal wavenumber is $k_a = 2\pi/a$, nearly equal to the transverse one: $k_b = 2\pi/b \cong k_a$. Indeed from eq. (12) of Ref. 1, with $k = k_b$, the phase velocity of the accelerating wave is

$$v_{ph} = c\frac{[\bar{k}_z^2 + N^2 k_b^2/4 + \omega_{pl}^2]^{1/2}}{\bar{k}_z + k_b} \qquad (6)$$

where N is the transverse mode number, ω_{pl} is the average crystal plasma frequency of order $k_b\alpha$ with α the fine structure constant and $\bar{k}_z$ is the wavenumber of the carrier wave (the accelerating wave is a sideband of the carrier). We also require that the group velocity $v_g = c^2\bar{k}_z/v_{ph}(\bar{k}_z + k_b)$ is positive, and as large as possible. Solving for $\bar{k}_z$ we get

$$\bar{k}_z = \gamma_{ph}^2\beta_{ph}^2 k_b + \\ \pm \gamma_{ph}^2\sqrt{\beta_{ph}^4 k_b^2 - \gamma_{ph}^{-2}\left[k_b^2(\tfrac{1}{4}N^2 - \beta_{ph}^2) + \omega_{pl}^2\right]} \qquad (7);$$

we note that terms in ω_{pl} can be neglected. Two solutions exist if $\gamma_{ph}\beta_{ph} > N/2$, so two interesting slow waves exist for $N = 1$ or 2 : for $N = 2$ both waves have positive v_g ; for $N = 1$ the solution with the negative sign in (7) has $v_g > 0$ only when $\beta_{ph} < \frac{1}{2}$, while the positive sign solution has always $v_g > 0$. Anyway we will choose the positive sign in (7), which correspond to higher v_g and frequencies. Note that $N = 1$ has a node at $x = b/2$, so is not effective on positive particles. For that reason, $N = 2$ seems a better choice for pair acceleration, but detailed study of pair position are needed (for example, Eq. (2) become $d_z = 0$). On the other side, $N = 1$ seems better for neutrons (see later).

Particle sources in crystals

Concepts of positron sources have been proposed, where the directionality[8] of crystal channels plays a role in enhancing the brightness of the emitted beam.

We speculate that a crystal (maybe with an auxiliary external B_z field) may directly convert a primary electron or proton beam into a secondary

$e^{\pm}$ or a more interesting $\mu^{\pm}$ beam, cooling the transverse moment of the created particles by a certain amount.

These sources would be a natural candidate for searching channeled particle pairs, or other neutral composites. The accelerating wave, in the low γ regime, would bunch the emitted beam.

Analogy in neutron acceleration

We consider a x polarized carrier wave; then (from Eq. (10) of Ref. 1) the sideband wave $k_s = (\bar{k}_z + k_b)$ has a magnetic field component

$$B_y = \frac{E_x}{\beta_{ph}} J_1\left(\frac{\omega_{pl}^2(k_b)}{2\bar{k}_z k_b c^2}\right) \exp[i(k_s z - \omega t)] \quad (8)$$

where $E_x = ia_x\omega\bar{k}_z^{-1/2}\sin(xk_bN/2)$ is the carrier amplitude.

Since the neutron has magnetic moment $\vec{\mu}$, which align with $\vec{B}$ parallel to $\hat{y}$, it feels a force:

$$F_z = F'_z = \mu\frac{\partial B'_y}{\partial z'} = 10^{-23}\frac{B'_y}{w'} \qquad (C.G.S) \quad (9)$$

where w' is the scale of the B variation, and the primes indicates quantities in the rest frame of the neutron.

By a Lorentz transformation of (8), we get $B'_y = B_y/\gamma_{ph}$ and $w' = \gamma_{ph}/k_s$ (and the sideband wave is purely magnetic in the neutron frame). The force is small,

$$F_z = \mu\frac{k_s B_y}{\gamma_{ph}^2} = \frac{5000eV/m}{\beta_{ph}\gamma_{ph}^2} \quad (10)$$

even for intense carrier $E_x = 10^{13}V/cm$, for small coupling of the Bessel function factor $J_1(\ldots) \cong 10^{-4}$; we take $k_s = 2k_b = 2.5\ 10^8 cm^{-1}$ in this estimate, since we note that the simple relation $\bar{k}_z > \frac{1}{4}N^2k_b$ is satisfied for all the possible values of β_{ph} by Eq. (7), with the positive sign and $N = 1, 2$.

The channeling of the neutron comes always from the force $(\vec{\mu}\cdot\nabla)\vec{B}$ and the electrostatic crystal field, which is seen as a transverse magnetic field $\vec{B}' = \gamma\beta\vec{E}_\perp$ from a neutron speeding along z ; also this magnetic field orient the neutron spin perpendicularly to z , consistently with neutron acceleration. The potential terms in the Hamiltonian (3) must be replaced by the effective potential $\bar{N}$, which is

$$\bar{N} = -\mu\beta\gamma[\bar{V}, x^2 + \bar{V}, y^2]^{1/2} + \ldots \quad (11)$$

when r is larger than the neutron wavelength, so to neglect nuclear interaction and higher orders in $\bar{V}$. The potential (11) is attractive, so the neutron must have an angular momentum L_z not to fall onto the row of nuclei (see Fig. 1).

We note that (10) represents only a simple and clearly identified acceleration mechanism, while detailed dynamics has to be worked out. In this connection Loeb and Stodolsky considered the dynamics of neutrino spin in magnetic fields in a primordial plasma[9] .

Conclusion

The neutral composite is interesting in the low γ regime. In the case of a pair, its constituents scatter freely when $\gamma d_z \gg a$ (still being effectively accelerated). In the case of neutron its coupling to the wave decreases with γ , with no scattering. The interest of neutron acceleration is obvious. Also applications to muon sources are possible.

References

[1] T.Tajima, M.Cavenago, "Crystal X-ray accelerator", *Phys. Rev. Lett.*, vol. 59, pp. 1440-1443 (1987)

[2] R.A. Carrigan, J. Ellison, (eds.) *Relativistic channeling* , Plenum, New York, 1987

[3] Y. Ohtsuki, *Charged Beam Interaction with Solids* , Taylor and Francis, New York, 1983

[4] R. Hofstadter , " The atomic accelerator" , Stanford University Report No. HEPL 560, 1968 (unpublished).

[5] P. Chen, R. J. Noble, "Channeled Particle Acceleration by plasma waves in metals " in Ref. 2

[6] B. Newberger, T.Tajima, F.R. Huson, W. MacKay, B.C. Covington, J.R. Payne, Z.G. Zou, N.K. Mahale, S.Ohnuma, "Application of Novel Material in Crystal Accelerator Concepts" *IEEE Trans. Part. Acc.*, **1**, 630-632 (1989)

[7] M.C. Downes, B. Merson, T.Tajima, to be published

[8] R. Chelab, F. Couchot, A. R. Nyaiesh, F. Richard, "Study of a positron source generated by photons from ultrarelativistic channeled particles", in *Proceeding of the 1989 particle accelerator conference, Chicago* , 1989

[9] A.Loeb, L.Stodolsky, "Relativistic spin relaxation in stochastic electromagnetic fields", *Phys. Rev.* , **D40**, 3520, (1989)