Relevance of Ion-Channeling for Direct DM Detection

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Based on work in progress with Nassim Bozorgnia and Paolo Gondolo

TAUP 09, July 3 2009

Channeling and Blocking Effects in Crystals

refer to the orientation dependence of ion penetration in crystals.

Channeling:

Ions **incident** upon the crystal along symmetry axis and planes suffer a series of small-angle scattering that maintain them in the open "channels" and penetrate much further *(ions do not get close to lattice sites)*

Blocking:

Reduction of the flux of ions **originating in lattice sites** along symmetry axis and planes *("blocking dip")*

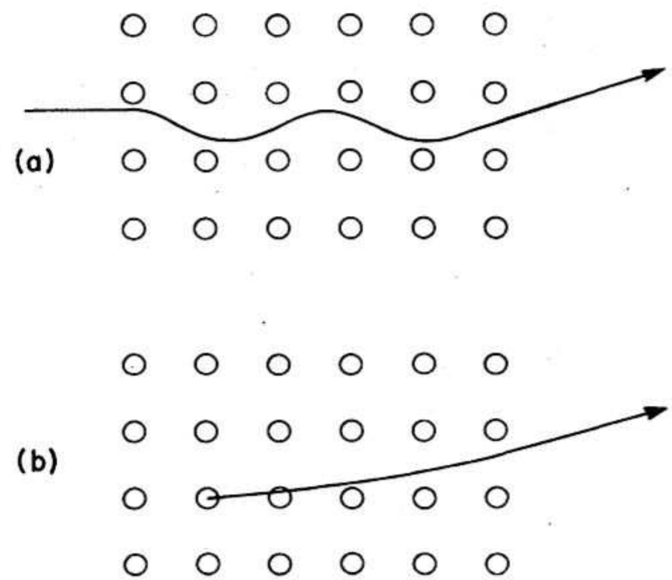

FIG. 1. Schematic illustration of (a) channeling and (b) blocking effects. The drawings are highly exaggerated. In reality, the oscillations of channeled trajectories occur with wavelengths typically several hundreds or thousands of lattice spacings.

(From D. Gemmell 1974, Rev. Mod. Phys. 46, 129)

Channeling and blocking in crystals is used in

- studies of lattice disorder

- ion implantation

- to locate dopant and impurity atoms

- studies of surfaces and interfaces

- measurement of nuclear lifetimes

- production of polarized beams

- etc.

Channeling effect observed in NaI (Tl) Altman et.al 1973

PHYSICAL REVIEW B VOLUME 7, NUMBER 5 1 MARCH 1973

Scintillation Response of NaI(Tl) and KI(Tl) to Channeled Ions*

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T. J. Rock
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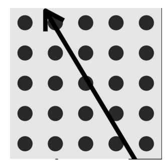
(Received 29 September 1972)

The scintillation pulse-height response of NaI(Tl) and KI(Tl) to ^{4}He and ^{16}O ions in the 2–60-MeV range has been studied with the ion beam aligned along low-index planes and axes and also aligned along a random direction. The scintillation efficiency increases by as much as 50% when the ion beam is channeled along a major symmetry direction. The effect of channeling has been observed by recording the pulse-height spectra for monoenergetic ions oriented along {100}, {110}, and {111} planes, and along ⟨100⟩, ⟨110⟩, and ⟨111⟩ axes. The increase in pulse-height response is in semiquantitative agreement with recent model calculations. Observation of this effect permits study of channeling phenomena in thick crystals that are scintillators. In particular, this paper reports a measurement of the critical angle for channeling of 15-MeV ^{16}O along a {100} plane.

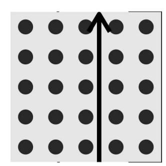
Channeling effect observed in NaI (TI) Altman et.al 1973

Sintillation output of a monochromatic 10 MeV ^{16}O beam through NaI(TI) scintillator

Left peak: Not channeled ions



Right peak: higher energy channeled ions



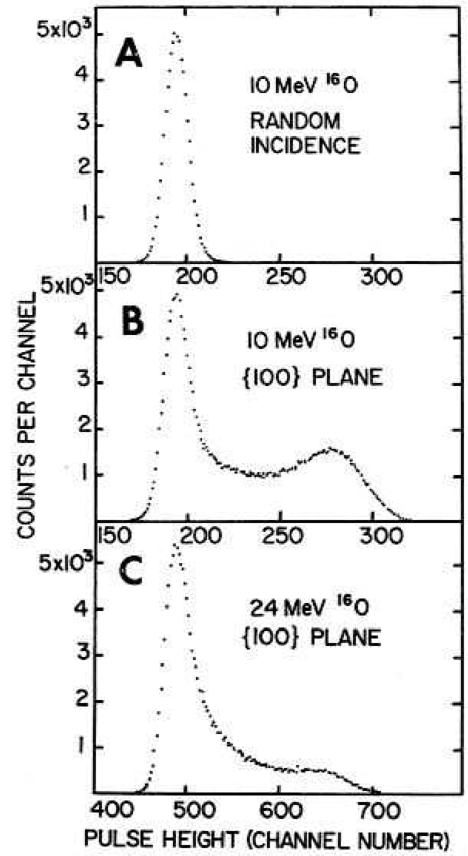


FIG. 2. (a) Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for incidence along a random direction. (b) Pulse-height spectrum from 10-MeV ^{16}O along a {100} plane. (c) Pulse-height spectrum from 24-MeV ^{16}O along a {100} plane. A light guide was used in all cases.

Channeling effect observed in NaI (Tl) Altman et.al 1973

Channeled ions produce more scintillation light
(because they loose most of their energy via electronic stopping rather than nuclear stopping)

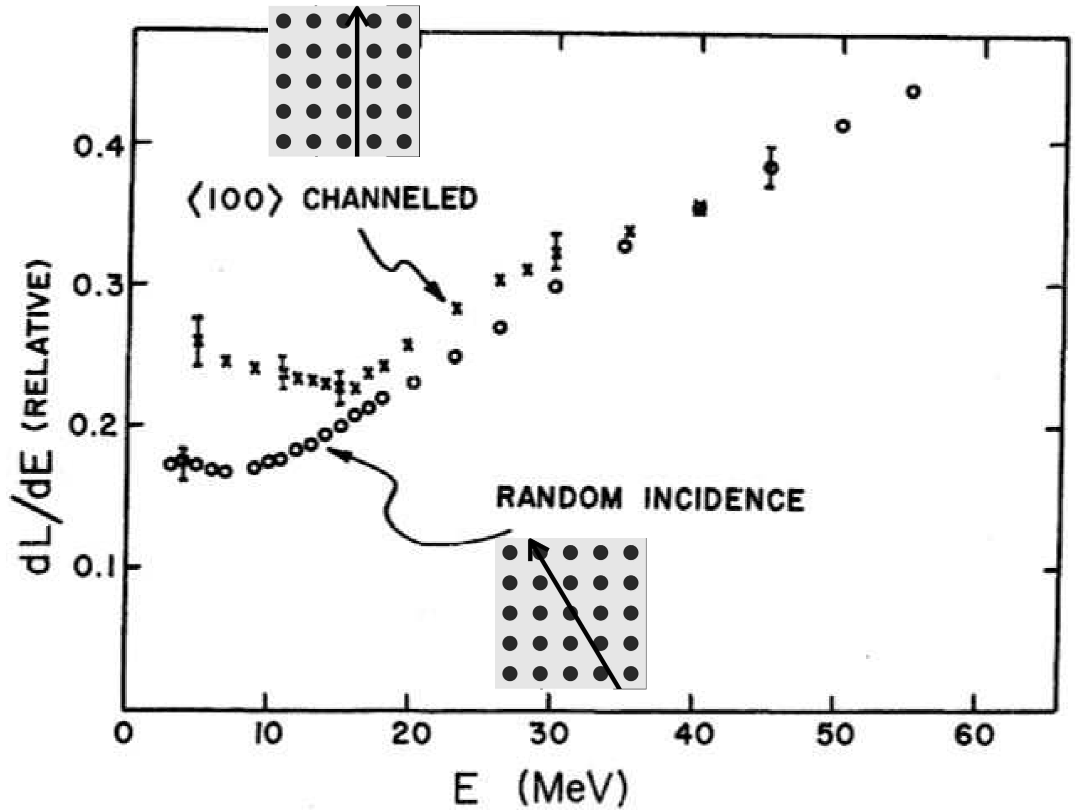
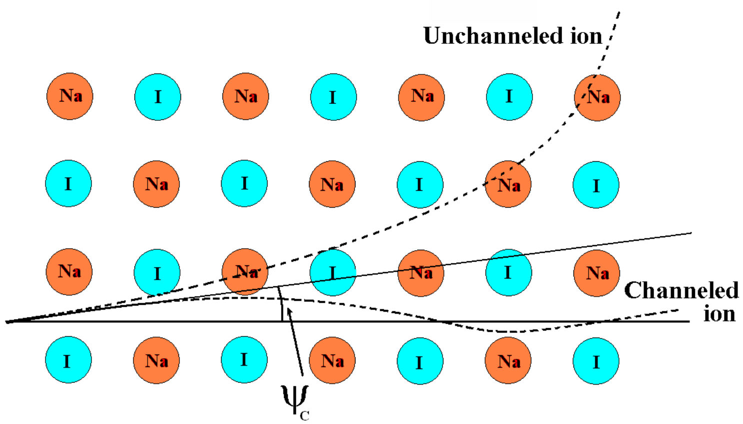
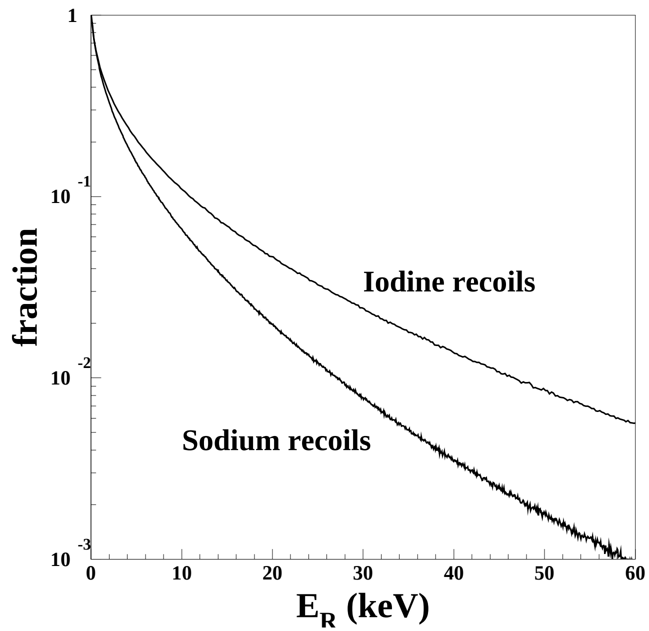


FIG. 11. Scintillation efficiency dL/dE as a function of incident-ion energy for ^{16}O ions on NaI(Tl), for both random incidence and for channeling along a ⟨100⟩ axis.

Channeling effect in DM detection:

When ions recoiling after a collision with a WIMP move along crystal axes and planes, they give their energy to electrons, so $Q = 1$ instead of $Q_I = 0.09$ and $Q_{Na} = 0.3$ (Drobyshevki, 07; DAMA- Eur. Phys. J. C 53, 205-2313, 2008)





Daily-Modulation due to Channeling

Avignone, Creswick, Nussinov 2008 (arXiv:0807.3758)

- The WIMP wind comes preferentially from one direction

- When that direction is aligned with a channel, the scintillation or ionization output is larger (Q=1 instead of $Q < 1$)

- Earth's rotation makes the WIMP wind change direction with respect to the crystal, which produces a daily modulation in the measured recoil energy (equivalent to a modulation of the quenching factor)

Daily-Modulation due to Channeling

- Avignone et al claim a modulation amplitude of $\sim 25\%$ as a somewhat simplistic estimate
- We set out to do a better calculation, and in the process understand channeling and blocking for DM detection.
- Our results are preliminary and our work in progress

Our calculation of the fraction of recoils that are channeled as function of recoil energy and direction:

- Use classical analytic models of the 60's and 70's, in particular Lindhard's model (Lindhard 1965, Komaki & Fujimoto 1970, Dearnaley 1973, Gemmell 1974, Appleton & Foti 1977)

  Continuum string and plane model, in which the screened Thomas-Fermi potential is averaged over a direction parallel to a row or a plane.

  Just one row, or one plane is considered.

  In the direction perpendicular the row or plane, the "transverse energy" $E_r\psi^2 + U(r)$, is conserved.

Our calculation of the angular distribution of recoil directions due to WIMPs:

- Use the "Radon transform" of the WIMP velocity distribution to write the recoil momentum $\vec{q}$ spectrum (Gondolo 2002, Phys.Rev.D 66, 103513)

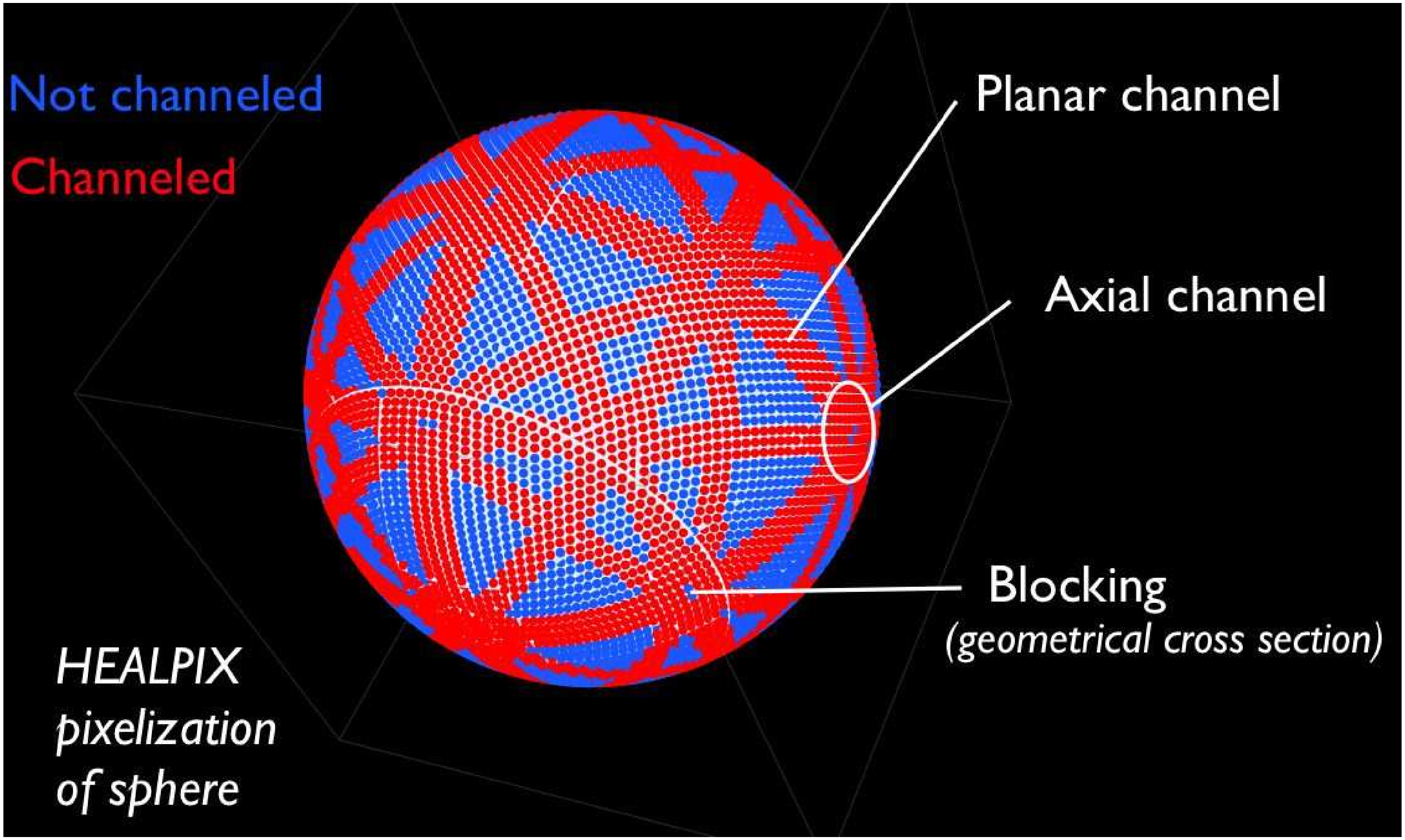
$$\frac{dR}{dE\ d\Omega_q} = \frac{\rho\sigma_0|F(q)|^2}{4\pi m\mu^2}\hat{f}_{\rm lab}(\frac{q}{2\mu}, \hat{q})$$

For a Maxwellian distribution with $\vec{V}_{\rm lab}$ with respect to the galaxy.

$$\hat{f}_{\rm lab}(\frac{q}{2\mu}, \hat{q}) = \frac{1}{(2\pi\sigma_v^2)^{1/2}} \exp - \frac{\left[(q/2\mu) + \hat{q}.\vec{V}_{\rm lab}\right]^2}{2\sigma_v^2}$$

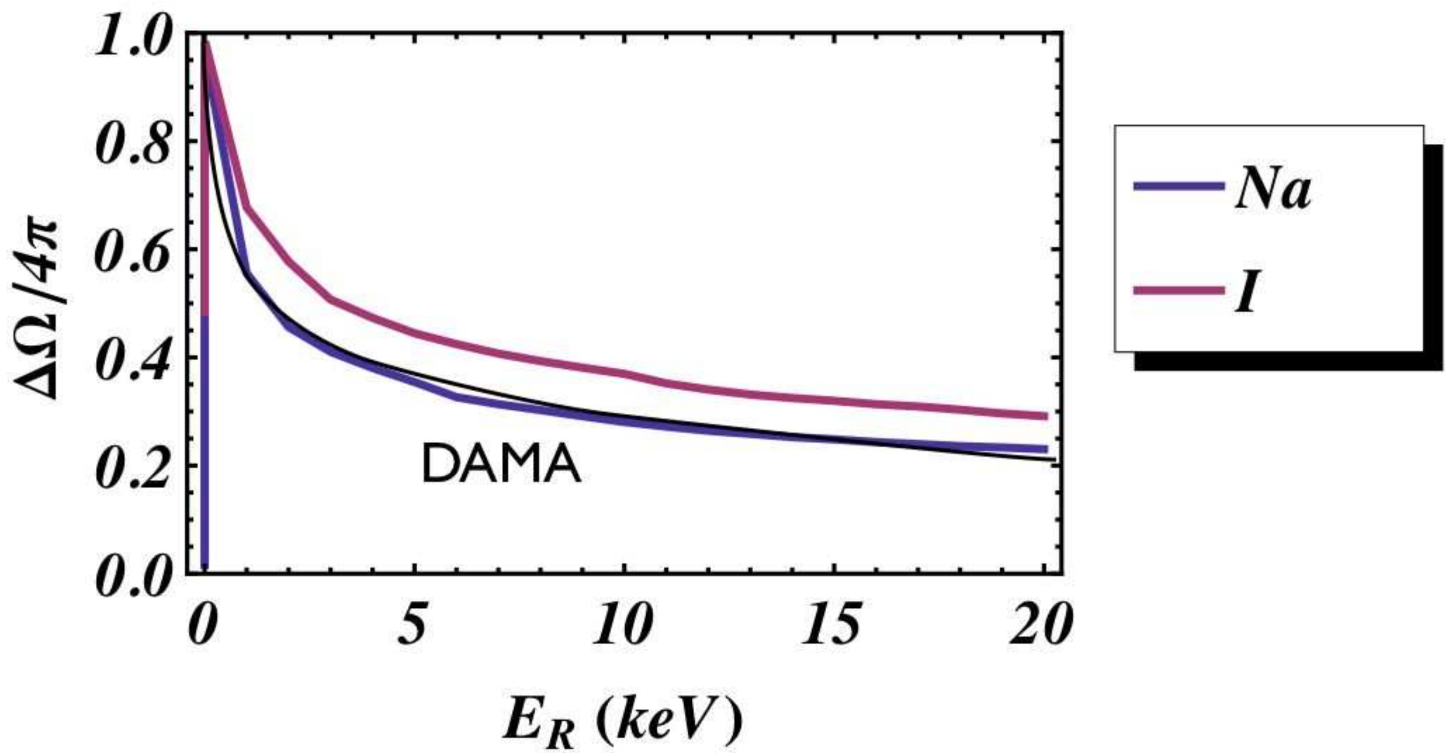
- Orient the crystal with respect to the galaxy.

Example of angular distribution of recoils



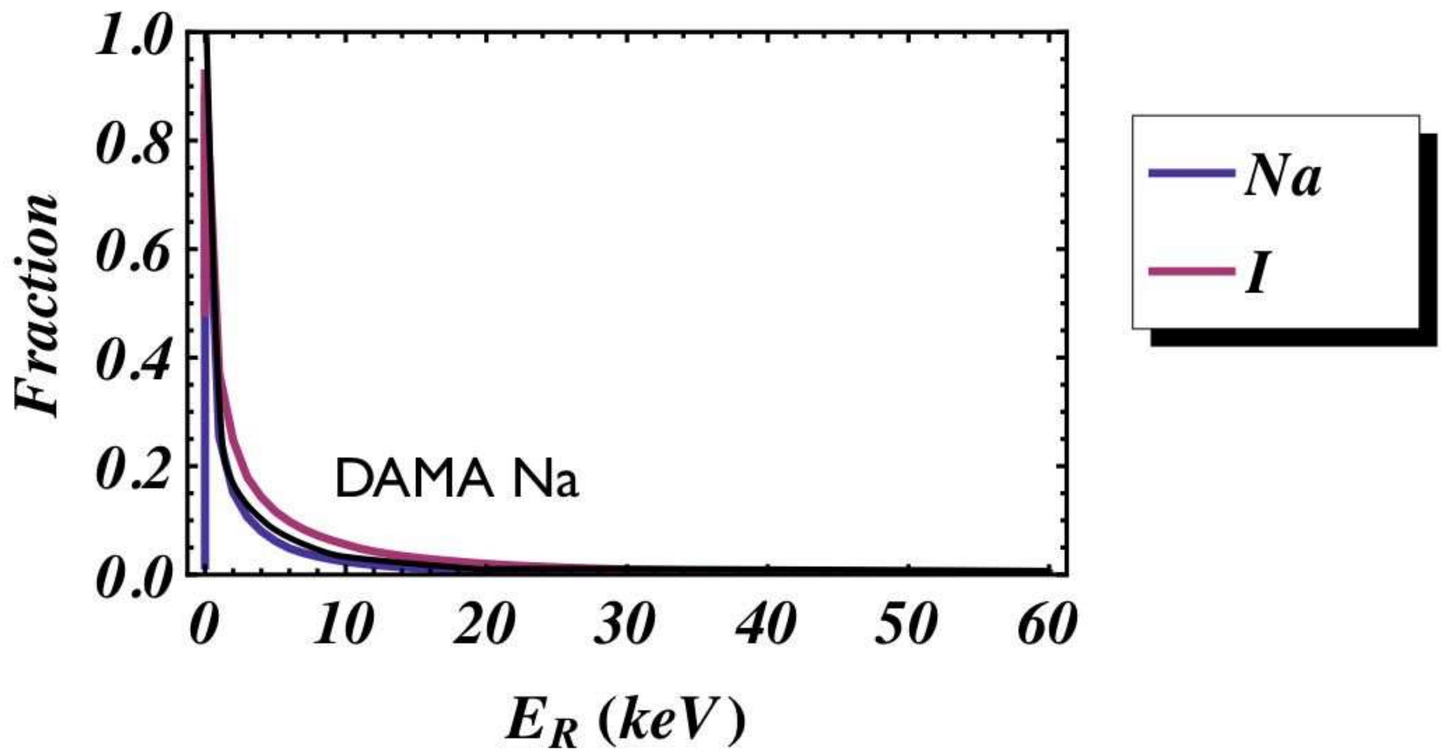
Reproduced DAMA calculations of channeled fraction

Our T-dependent analytic results include a naive geometrical blocking.



Reproduced DAMA calculations of channeled fraction

Also with dechanneling due to Tl doping (only first interaction)



Blocking effects not yet properly taken into account, and they are important!

- Recoiling nuclei start at or close to lattice sites

- In a perfect lattice no recoil would be channeled *("rule of reversibility")*.

- However, there are channeled recoils due to lattice vibrations!

“Channeling in blocking” Fujimoto et al 1971

phys. stat. sol. (a) 4, 485 (1971)

Subject classification: 17; 6; 22.1.1; 22.1.2

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Channeling Effects in the Blocking Phenomena

By

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K. OZAWA (b), M. MANNAMI (c), and T. SAKURAI (c)

The behaviour of the channeling peaks and blocking dips observed in the two-dimensional spectrum (energy and scattering angle) of the (111) planar blocking of protons transmitted through thin crystals of germanium and silicon is studied. The experimental results are compared with the calculations. The discrepancies between experiment and calculation are explained by the random scattering which smears out the blocking profile within the angular region estimated from the multiple Coulomb scattering.

"Channeling in blocking" Fujimoto et al 1971

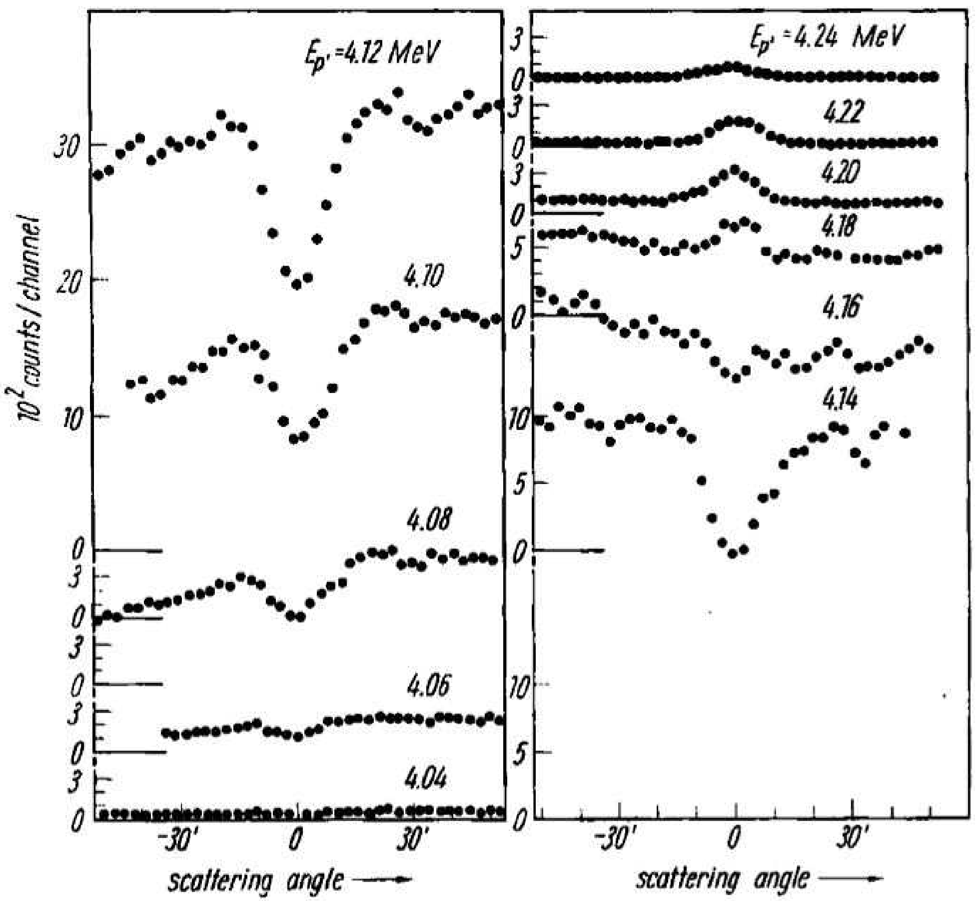


Fig. 2. Two-dimensional spectrum of protons scattered by thin crystal of germanium at an incident energy 4.50 MeV

“Channeling in blocking” Fujimoto et al 1971

The effect is due to vibrations of the lattice nuclei, as already understood in the 70’s:

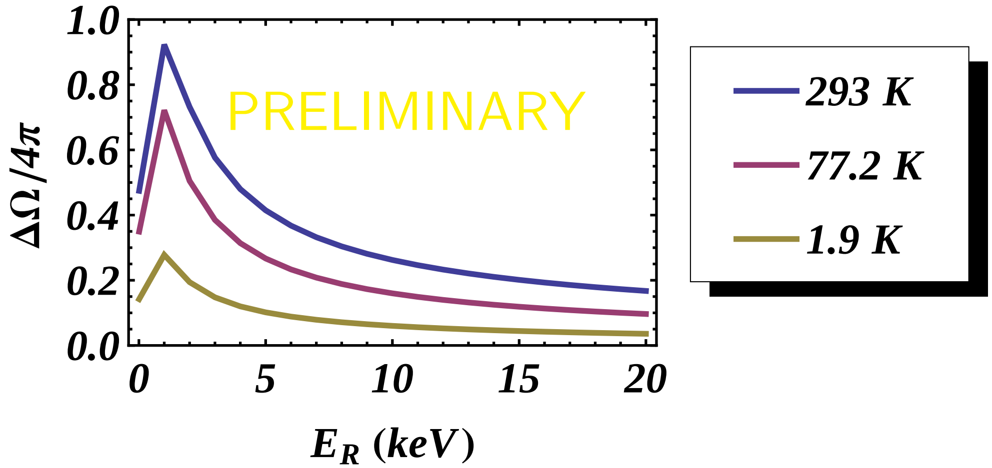
...

blocking patterns by using the formula derived by Lindhard. Komaki and Fujimoto [3] have studied the effect of an emitting atom on the planar blocking pattern and shown that the “channeling effect” is included essentially in blocking phenomena, that is, a part of particles scattered or emitted passes through channels of the crystal and loses energy amounts smaller than the other particles. This situation originates in the fact that the scattering or emitting atom is not exactly on a lattice site because of the thermal vibrations.

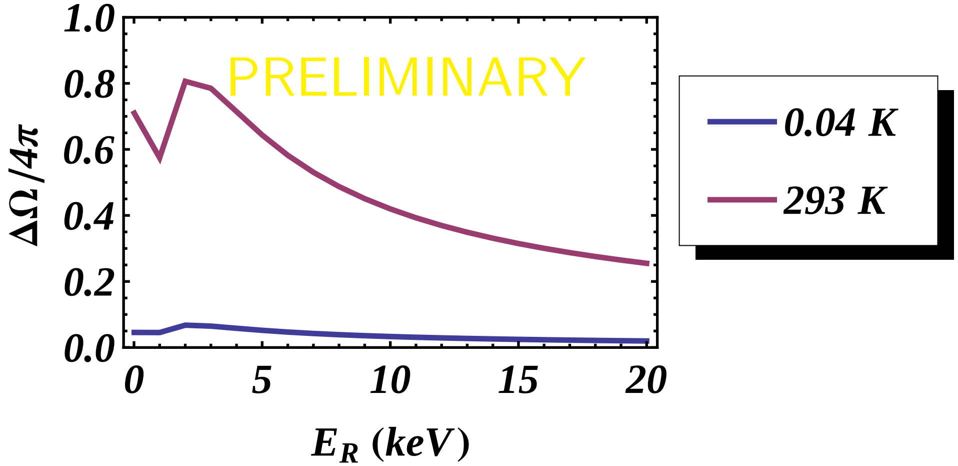
Channeling within blocking: depends on T

Very small at mK but can be important at room temperature!

Na in NaI crystal:

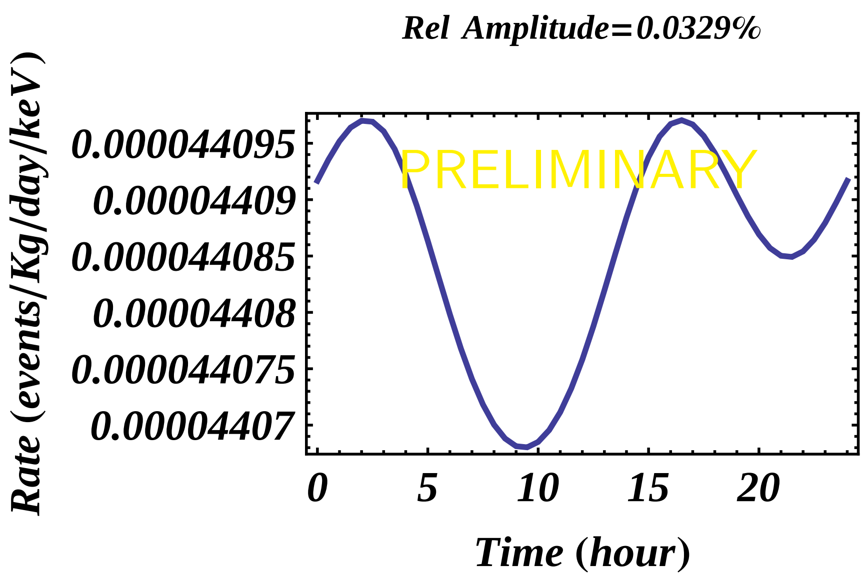


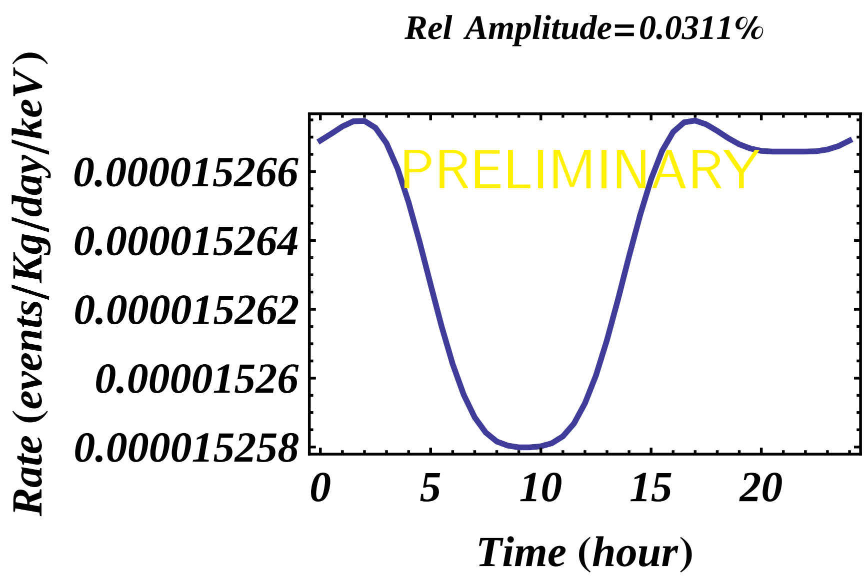
Ge crystal:



Daily modulation amplitudes:

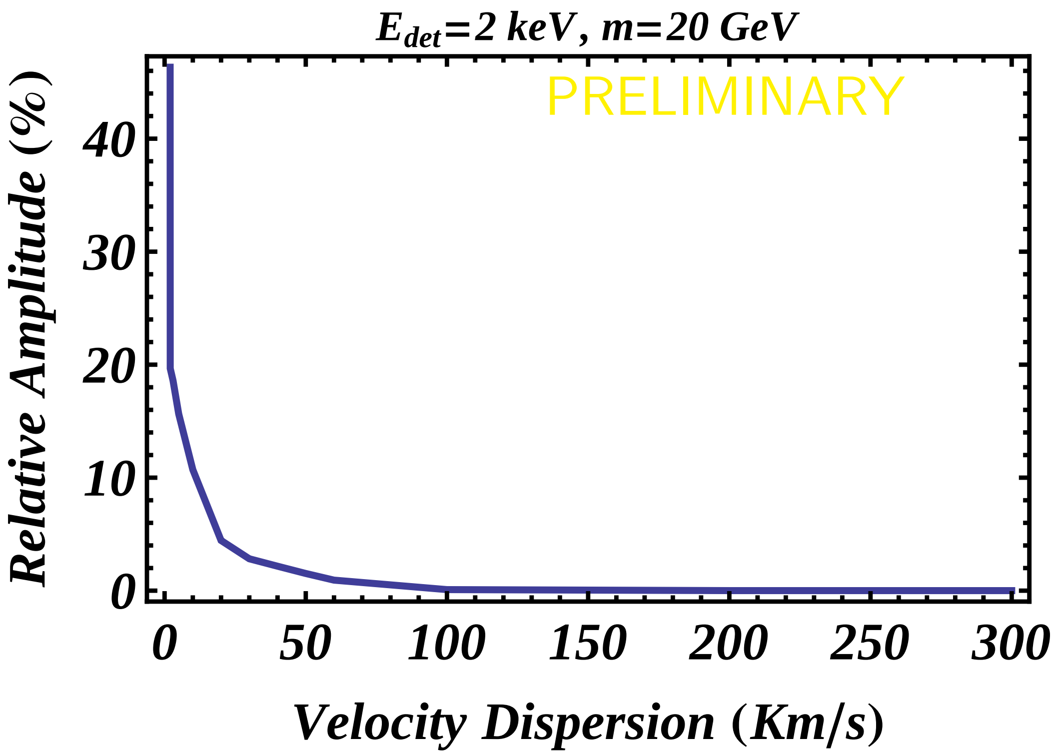
We find daily modulation amplitudes <<20% for the standard halo





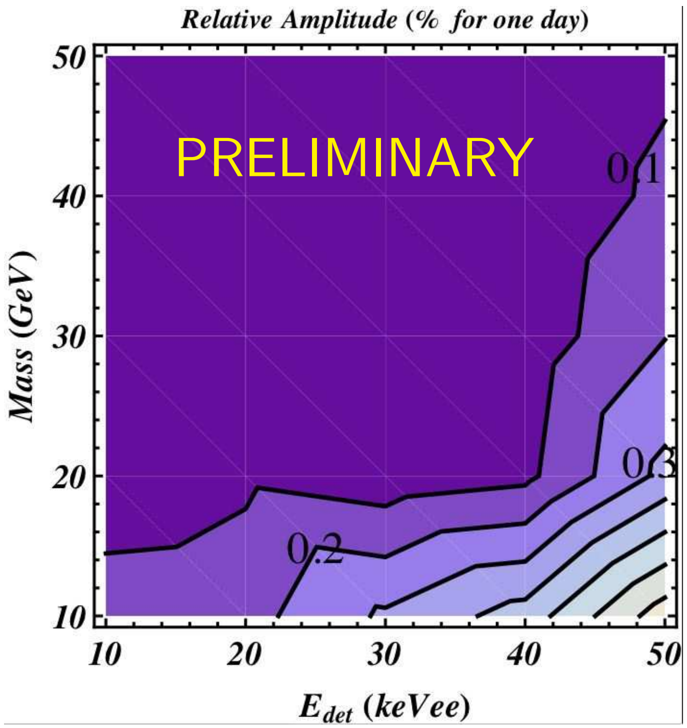
Daily modulation amplitudes depend on the velocity dispersion

Changing the dispersion in the standard halo WIMP velocity distribution:

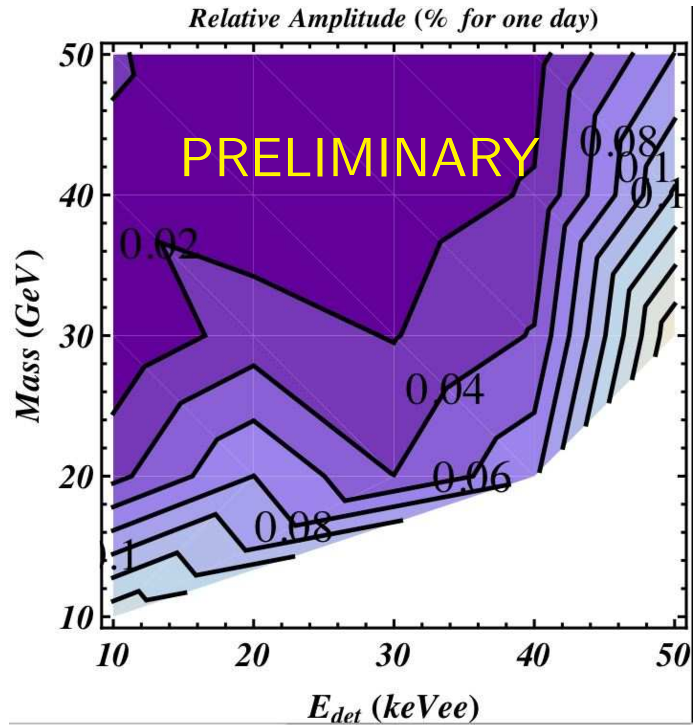


Daily modulation amplitudes: for the standard halo $<< 1$ %

As function of the detected energy and the WIMP mass:

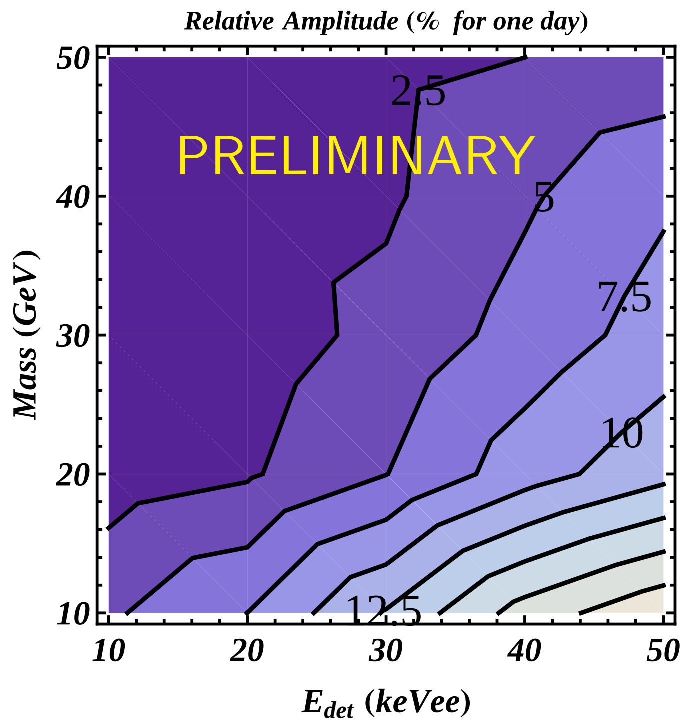


Maxwellian

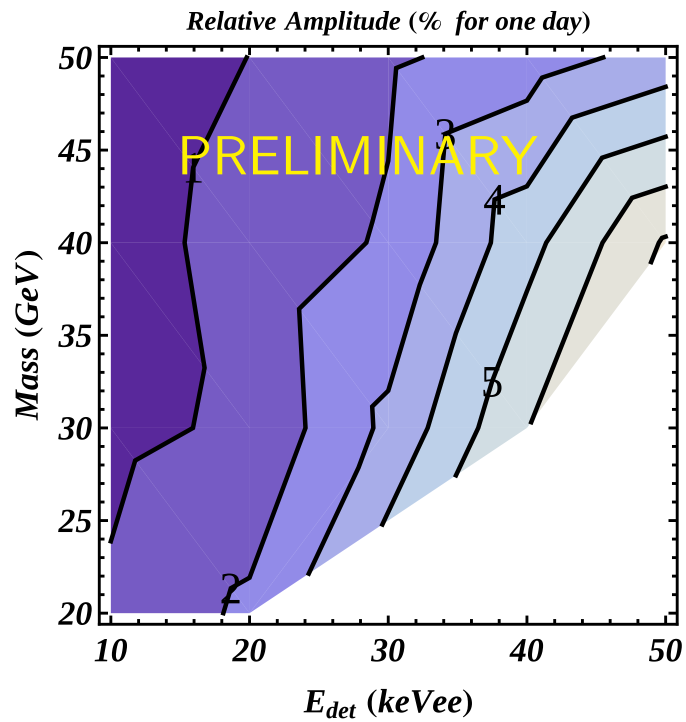


Maxwellian truncated at $v_{\rm escape}$

Daily modulation: might be used to detect low-dispersion halo components - such as a Thick-Disk ($v_{disk} = \sigma_{disk} = 50$ km/s)



Maxwellian



Maxwellian truncated at v_{escape}

Preliminary conclusions:

- Channeling in crystaline detectors can lead to a daily modulation of a WIMP signal, a Dark Matter signature without any background (Avignone, Creswell & Nussinov 2008)

- The daily modulation amplitudes are small ($<< 1\%$) for the standard halo model but would be larger for dark halo components with a smaller velocity dispersion.

- The effect of blocking is important to understand the channeling of recoil nuclei (and the effect is Temperature dependent, so that it may be negligible at mK and sizeable at room temperature). Bozorgnia, Gondolo and I are still incorporating a better treatment of blocking.

- Analytic results may not be enough to settle these issues and a Montecarlo simulation may be needed (many are used in other applications of channeling).