CHANNELING IN DIRECT DARK MATTER DETECTION

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Based on work in progress with G. Gelmini and P. Gondolo

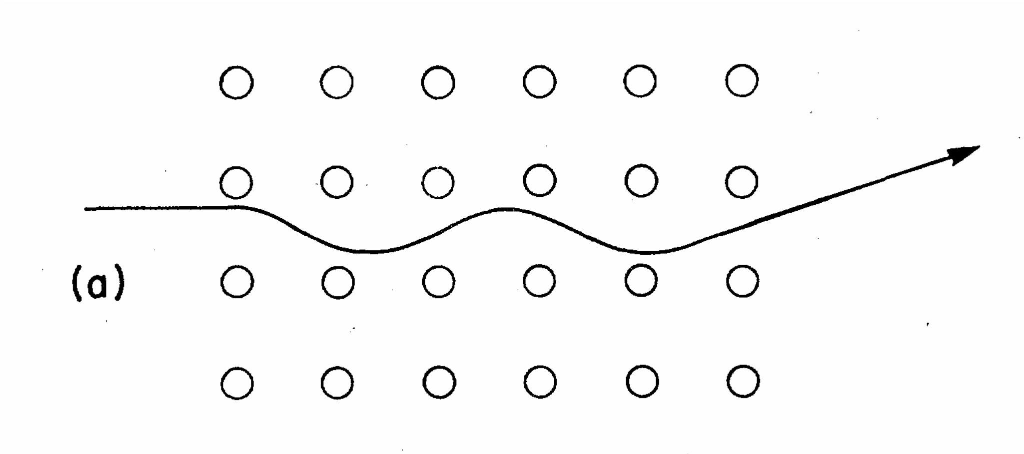
Outline

- Channeling and blocking in crystals
- Channeling effect in direct dark matter detection
- Basic idea for daily modulation
- Channeling fraction for
  - Incoming particles
  - Recoiling nuclei
- Conclusions and future prospects

Channeling and Blocking in Crystals

(a) Channeling:

If an *incident* ion is along the symmetry axis or planes of the crystal, it will have a series of small-angle scatterings which will maintain it in the open channels. The ion will penetrate much further into the crystal than in other directions.

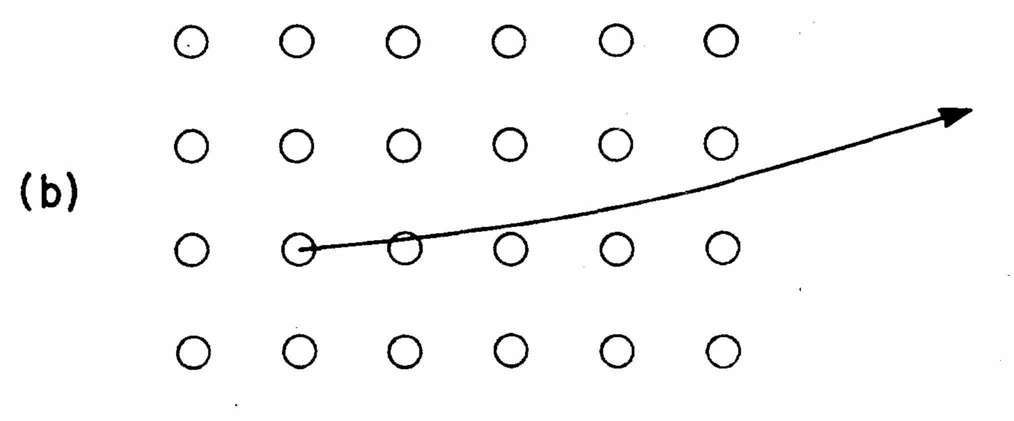


From D. Gemmell 1974, Rev. Mod. Phys. 46, 129

Channeling and Blocking in Crystals

(b) Blocking:

If an ion *originating* in the lattice sites is along the symmetry axis or planes, there is a *reduction* in the flux of the ion when it exits the crystal creating a "blocking dip".



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

Channeling and Blocking in Crystals

- Channeling and blocking in crystals is used in:
  - crystallography
  - studies of lattice disorder
  - ion implantation
  - finding the location of dopant and impurity atoms
  - studies of surfaces and interfaces
  - measurement of short nuclear lifetimes
  - production of polarized beams
  - etc.

Observation of Channeling Effect in NaI (Tl)

- Channeling effect in NaI (Tl) was first observed in 1973 by Altman et al. ***(Phys. Rev. B7, 1743)***.
- They observed that the scintillation output of a monochromatic 10 MeV ^{16}O beam through NaI (Tl) scintillator has two peaks:
  - peak with ***lower*** scintillation output:
    non-channeled ions
  - peak with a ***higher*** scintillation output:
    channeled ions

Observation of Channeling Effect in NaI (Tl)

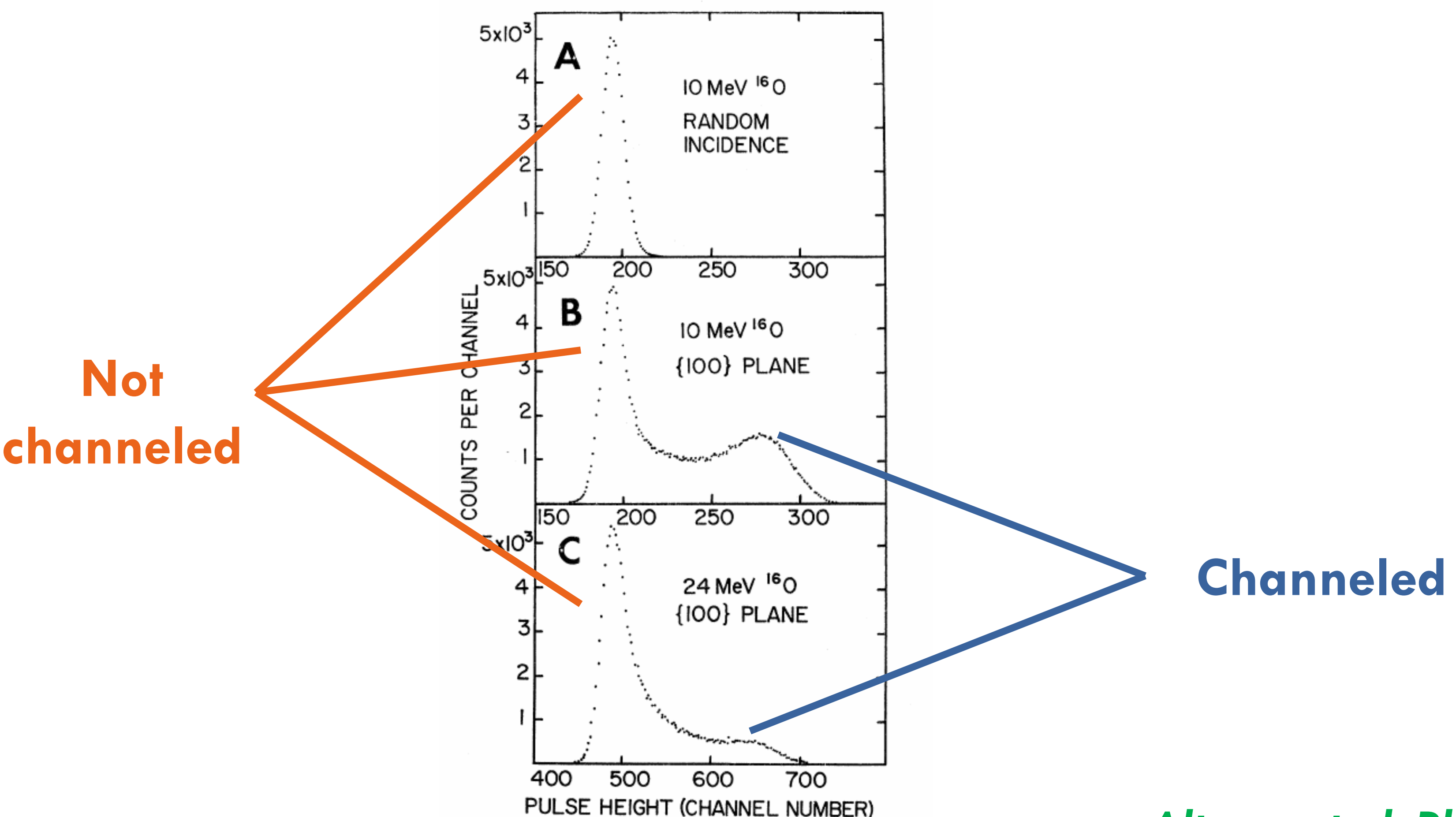


FIG. 2. (a) Pulse-height spectrum from 10-MeV ^{16}O on NaI(Tl) for incidence along a random direction. (b) Pulse-height spectrum from 10-MeV ^{16}O along a {100} plane. (c) Pulse-height spectrum from 24-MeV ^{16}O along a {100} plane. A light guide was used in all cases.

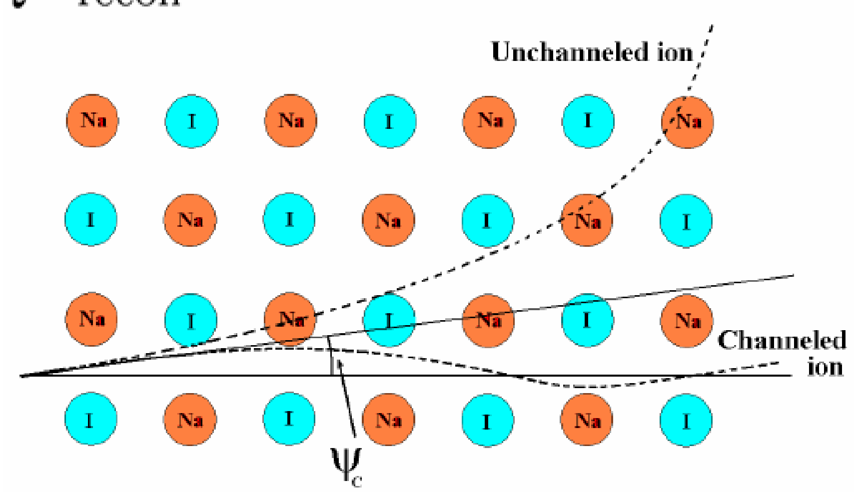
Altman et al. Phys. Rev. B7, 1743

Channeling Effect in Direct DM Detection

- The importance of channeling effect for direct DM detection was pointed out for NaI by the DAMA collaboration *(DAMA- Eur. Phys. J. C53, 205-2313, 2008)*.

$$E_{\text{measured}} = QE_{\text{recoil}}$$

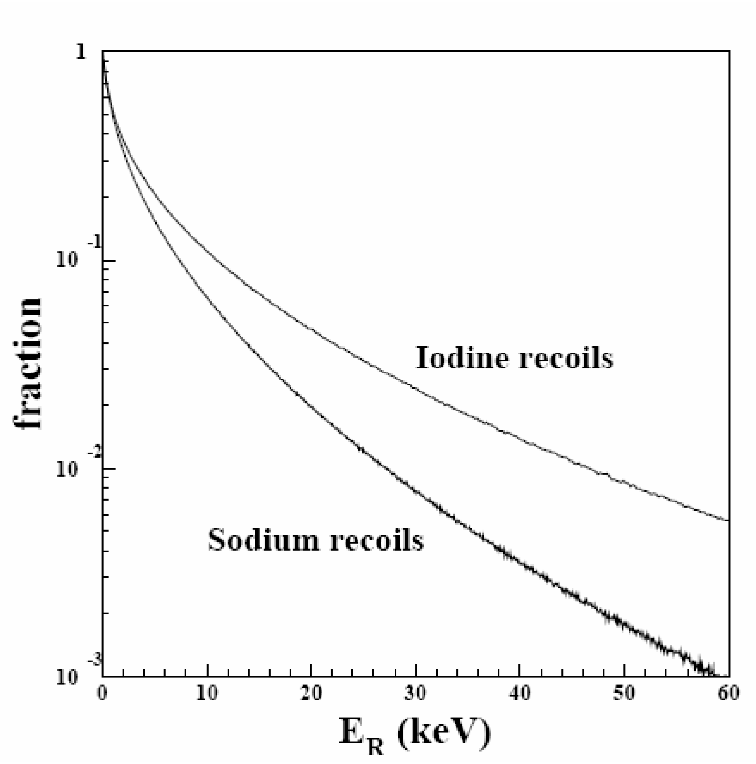
- When Na or I recoils move along a channel, their quenching factor is $Q = 1$ instead of $Q_{Na} = 0.3$ and $Q_I = 0.09$, since they give their energy to electrons.



DAMA- Eur. Phys. J. C53, 205-2313, 2008

Channeling Effect in Direct DM Detection

- The DAMA collaboration found that the fraction of channeled recoils is large for low recoil energies.



DAMA- Eur. Phys. J. C53, 205-2313, 2008

Basic Idea for Daily Modulation

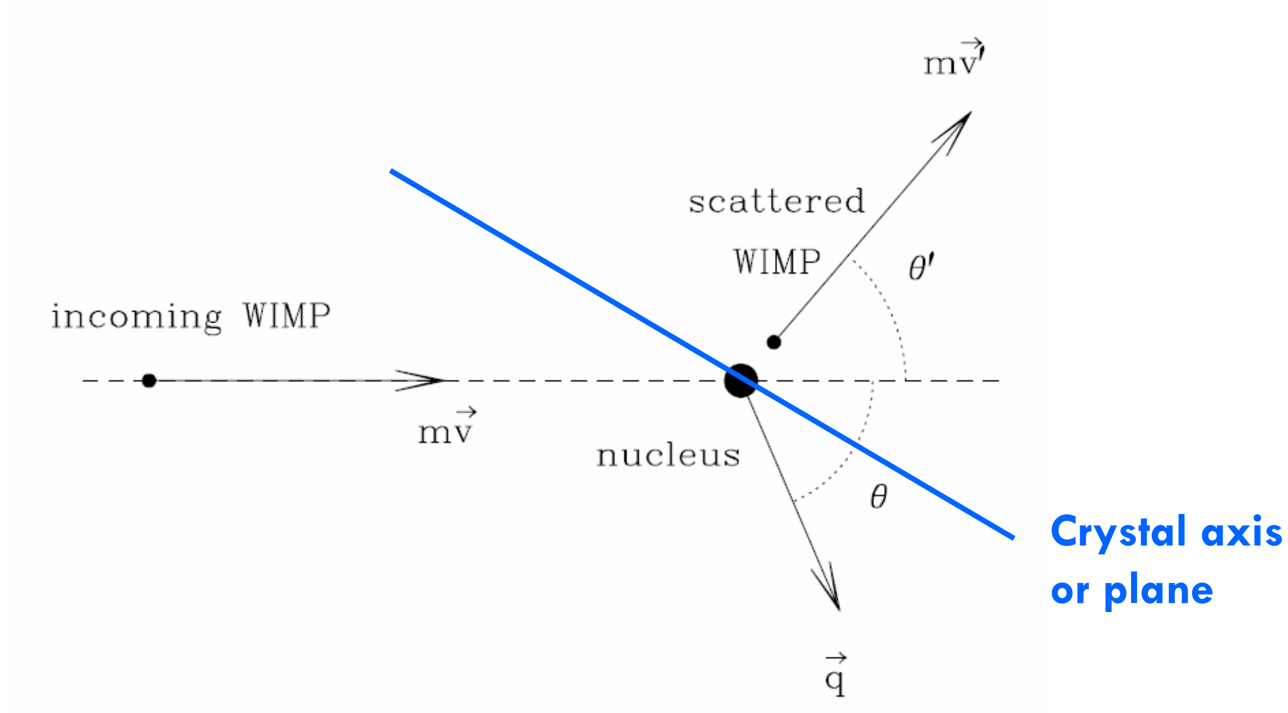
- The WIMP wind comes preferentially from one direction, due to the motion of the Earth with respect to the galaxy.
- When that direction is aligned with a channel, the scintillation or ionization output is larger ($Q = 1$ instead of < 1).
- Earth's daily rotation makes the WIMP wind change direction with respect to the crystal.
- This produces a daily modulation in the "measured" recoil energy (as if the quenching factor were modulated).

Basic Idea for Daily Modulation

- If this daily modulation is measured it would have no background ⇨ Ideal for DM search.
- Avignone et al. mention a modulation amplitude of ~25% as a somewhat simplistic estimate.
  Avignone, Creswick, Nussinov 2008 (arXiv:0807.3758)
- We set out to do a better calculation and in the process understand channeling and blocking for DM detection with analytic models.
- Our results are preliminary and our work is in progress.

What we need:

- Consider the WIMP-nucleus elastic collision for a WIMP of mass m and a nucleus of mass M.



From Gondolo 2002, Phys. Rev. D 66, 103513

What we need:

- We need to determine the probability $p(E, E_R, \hat{\mathbf{q}})$ that an energy E is measured when the recoil is in the direction $\hat{\mathbf{q}}$ with energy E_R .
- The recoil nucleus can either be channeled or not channeled:

Channeled

$$p(E, E_R, \hat{\mathbf{q}}) = \chi(E_R, \hat{\mathbf{q}})\delta(E - E_R) + [1 - \chi(E_R, \hat{\mathbf{q}})]\delta(E - QE_R)$$

?

Not Channeled

where $\chi(E_R, \hat{\mathbf{q}})$ is the fraction of channeled nuclei with recoil energy E_R in direction $\hat{\mathbf{q}}$.

Modeling of Channeling

- Our calculations are based on classical analytic models developed in the 1960's and 70's, in particular Lindhard's model *(Lindhard 1965, Komaki & Fujimoto 1970, Dearnaley 1973, Gemmell 1974, Appleton & Foti 1977)*.
- We use the continuum string or plane model, in which the screened Thomas-Fermi potential is averaged over a direction parallel to the row or plane.
- Only one row or one plane is considered.
- In the direction perpendicular to the row or plane, the "transverse energy" $E_\perp = E \sin^2 \psi + U$, is conserved.

Our Calculations

- Compute the channeling fraction for:
  - Incoming particles
  - Recoiling nuclei

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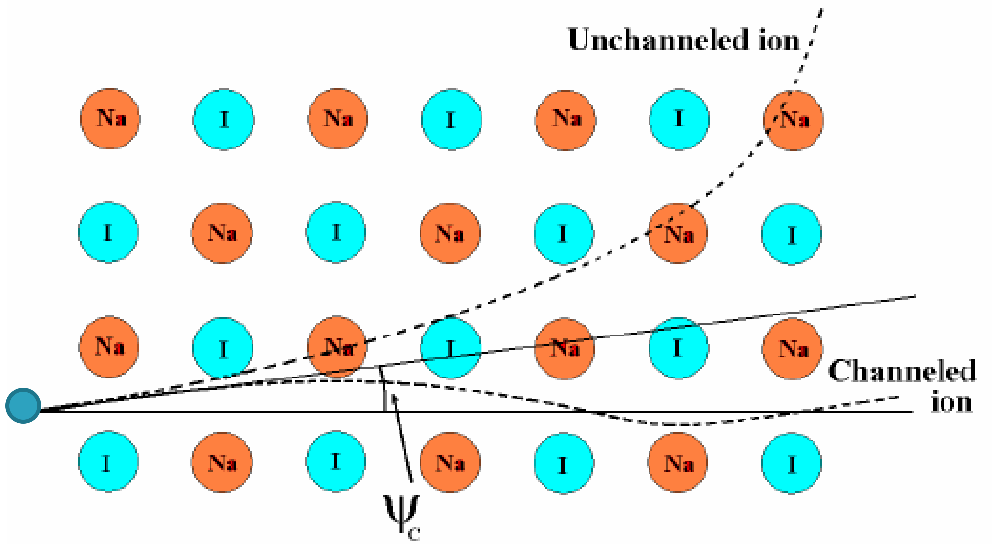
Channeling of Incoming Particles

- Low energy incident ions are considered to be channeled if they are incident upon a string or plane of atoms at some angle ψ smaller than a critical angle ψ_c *(Lindhard 1965)*.



DAMA- Eur. Phys. J. C53, 205-2313, 2008

Channeling Fraction of Incoming Particles

- We will integrate the channeling probability over direction to find the total fraction of channeled nuclei:

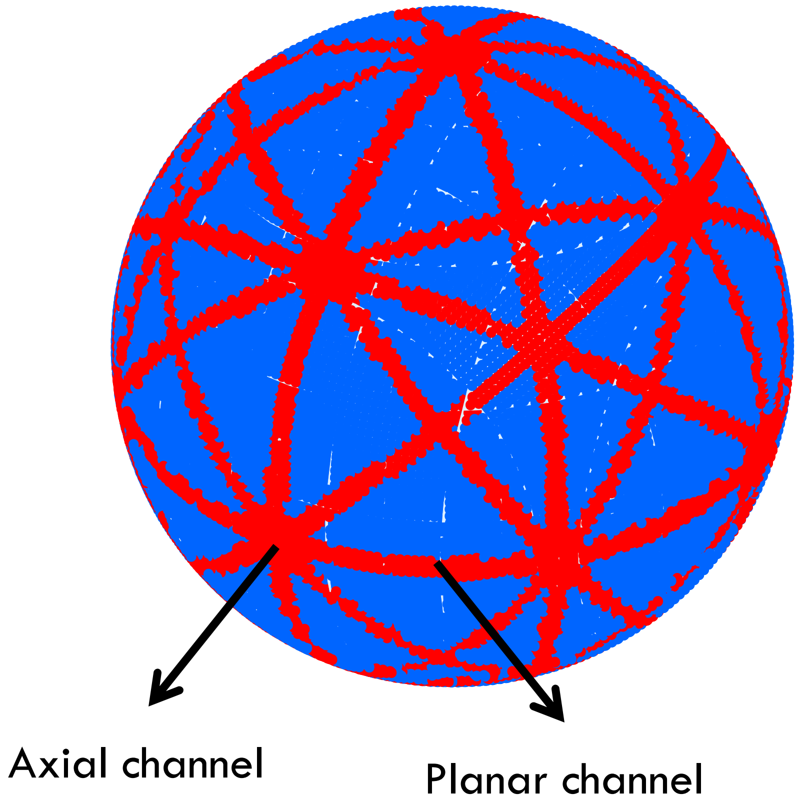
$$P(E) = \frac{1}{4\pi}\int \chi(E, \hat{\mathbf{q}})d\Omega_q$$

where $d\Omega_q$ is an infinitesimal solid angle around $\hat{\mathbf{q}}$

- We used the Hierarchical Equal Area isoLatitude Pixalization (HEALPix) method to compute the integral.

Fraction of channeled Na

Using the HEALPix pixalization of the sphere for incident energy of 50 keV



For each axial channel:

$$\chi_{\text{axial}}(E,\psi) = 1$$

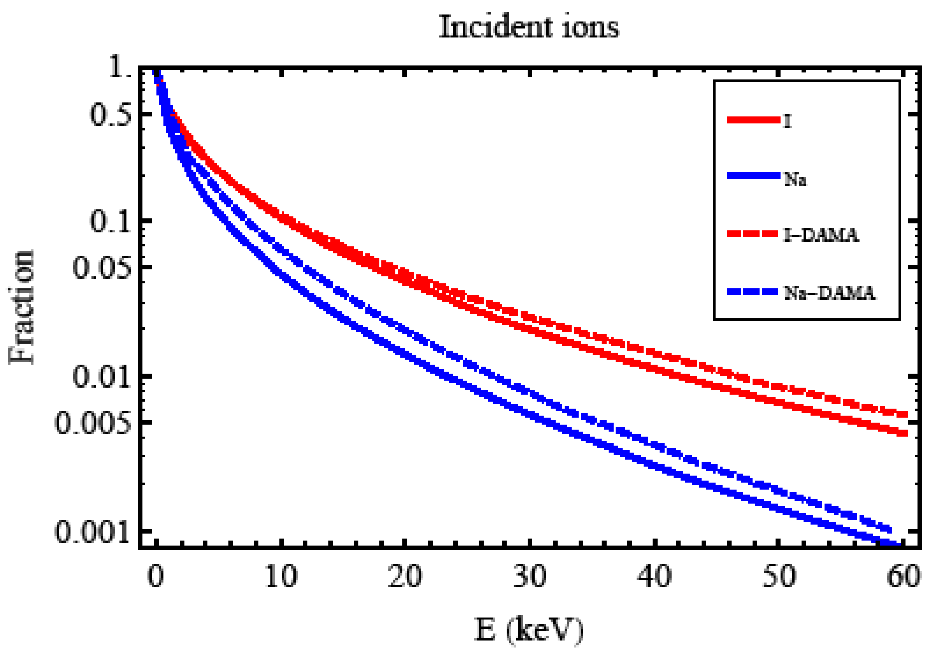
$$\text{if} \quad \psi < \psi_c^{\text{axial}}$$

For each planar channel:

$$\chi_{\text{planar}}(E,\psi) = 1$$

$$\text{if} \quad \psi < \psi_c^{\text{planar}}$$

Channeling Fraction of Incoming Particles



- We agree with DAMA results to a good approximation.
- Our result is based on analytic calculations with basic assumptions, whereas DAMA is using Monte Carlo.

Our Calculations

- Compute the channeling fraction for:
  - Incoming particles
  - Recoiling nuclei

Our Calculations

- Compute the channeling fraction for:
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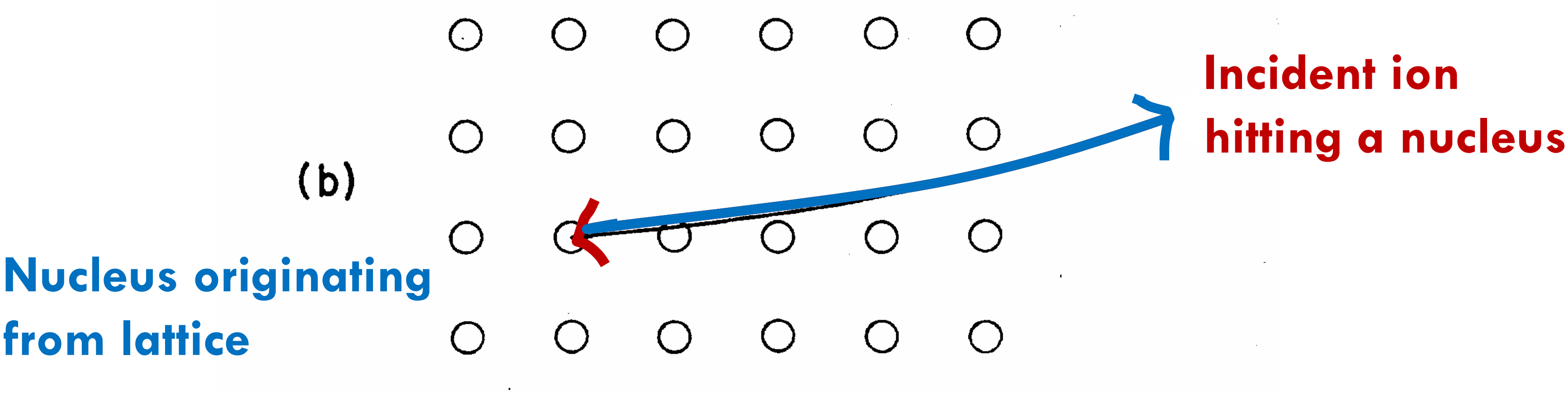
Channeling of Recoiling Nuclei

- Recoiling nuclei start at or close to the lattice sites
- In a perfect lattice no recoil would be channeled (*"rule of reversibility"*).



- However, there are channeled recoils due to *lattice vibrations* as already understood in the 70's.

Channeling of Recoiling Nuclei

- For a given E_R and ψ, the condition for channeling is given by:

$$E_R sin^2\psi + U(r_i) < U(r_c)$$

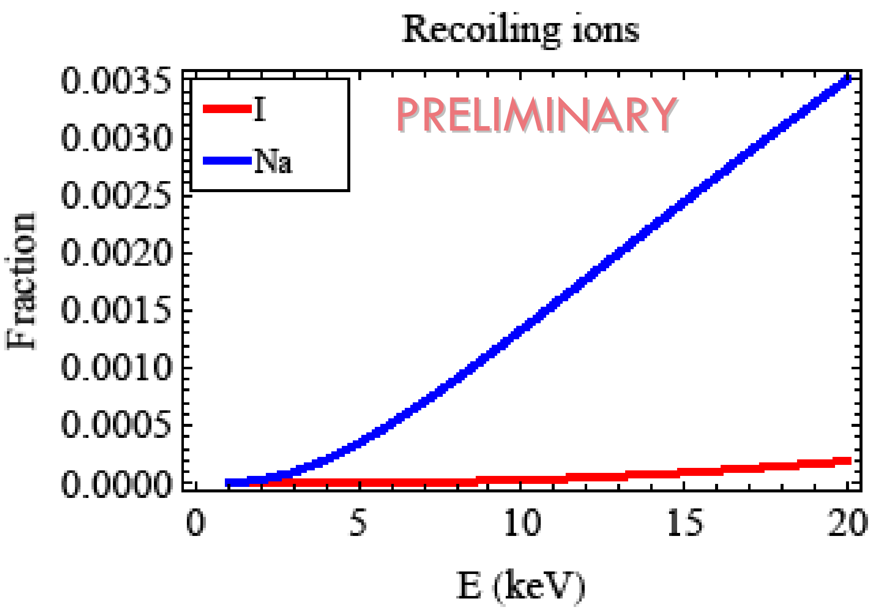
initial distance (r_i)

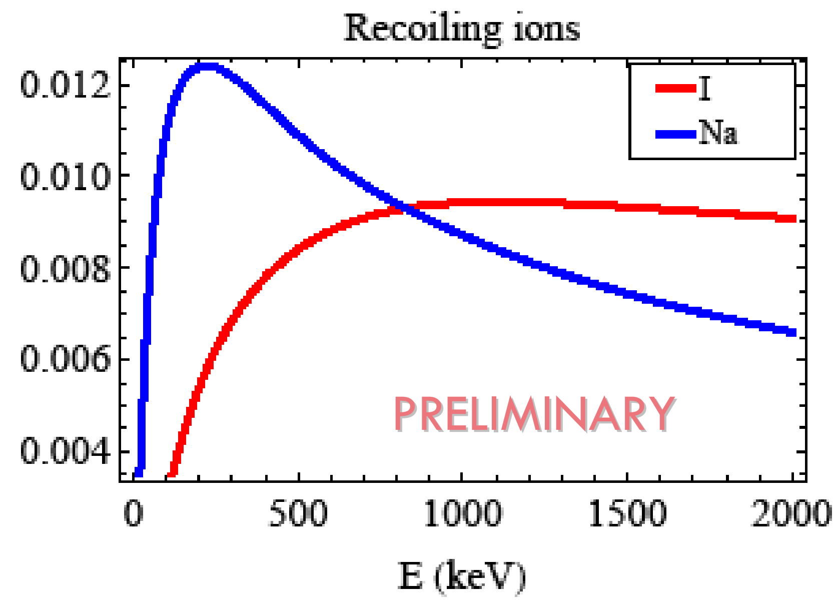
Smallest possible minimum distance of approach (r_c)

- The distribution function of the emitting atom due to thermal vibrations can be represented by a Gaussian.
- The fraction of channeled nuclei recoiling at angle ψ with the axis is equal to

$$\chi_{\text{axial}}(E_R, \psi) = \int_{r_{i,\text{min}}}^{\infty} dr g(r)$$

Fraction of Recoils that are Channeled





- This result now differs from DAMA results.
- These are upper bounds to what we can expect to be the true fraction.

Preliminary Conclusions

- Channeling in crystalline detectors can lead to a daily modulation in a WIMP signal.
- Channeling of recoiling nuclei and incoming particles have different mechanisms. We were able to reproduce DAMA results for incident ions, but for recoiling nuclei the channeling fraction is much smaller.
- Small channeling fractions would mean small daily modulation amplitudes for the SHM.
- Daily modulation amplitudes strongly depend on the velocity dispersion of the WIMP, and would be larger for dark halo components with a smaller velocity dispersion.

Future Prospects

- We are writing a paper about the channeling fractions for NaI, Ge and Si.
- We will evaluate the daily modulations for NaI, Ge and Si to obtain more accurate results.
- Analytic results may not be enough, and we may collaborate with other groups to carry out sophisticated Monte Carlo simulations to confirm our results.

Thank You!

Additional

Channeling of Recoiling Nuclei

- We want to find the probability that the particle will go in the 1st or 2nd or … or 26th channel.

- The total channeling prob. for each energy and direction is computed using a recursion of the addition rule in probability theory over all axial and planar channels:

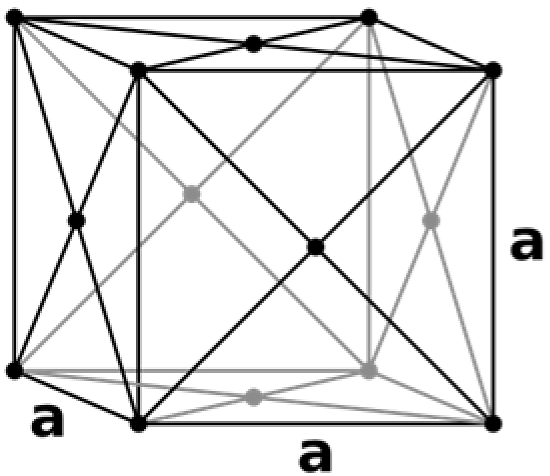
  S +D ruE ,@ S +D ,. S +E , S +D ,S +E ,

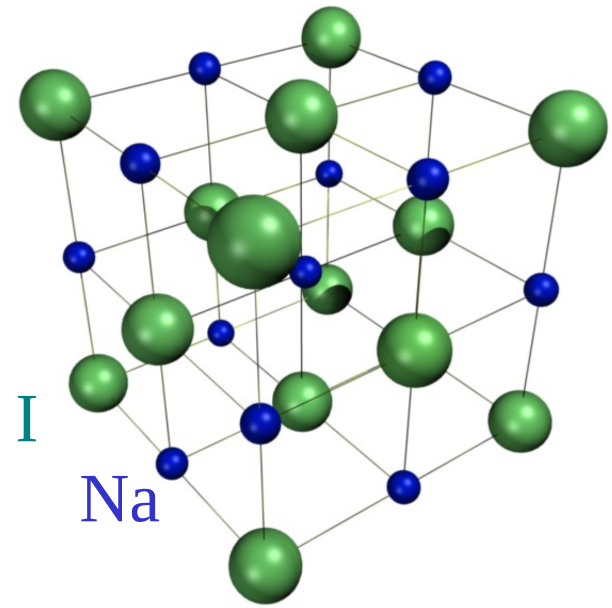
- We can continue this recursive computation until we find the probability that the particle will go into either of the 26 channels:

  S +Fk4 ruFk5 ru === ruFk59,@ ¯+H U > ,

Structure of NaI

- NaI is a diatomic compound which is composed of two interpenetrating f.c.c. sublattices

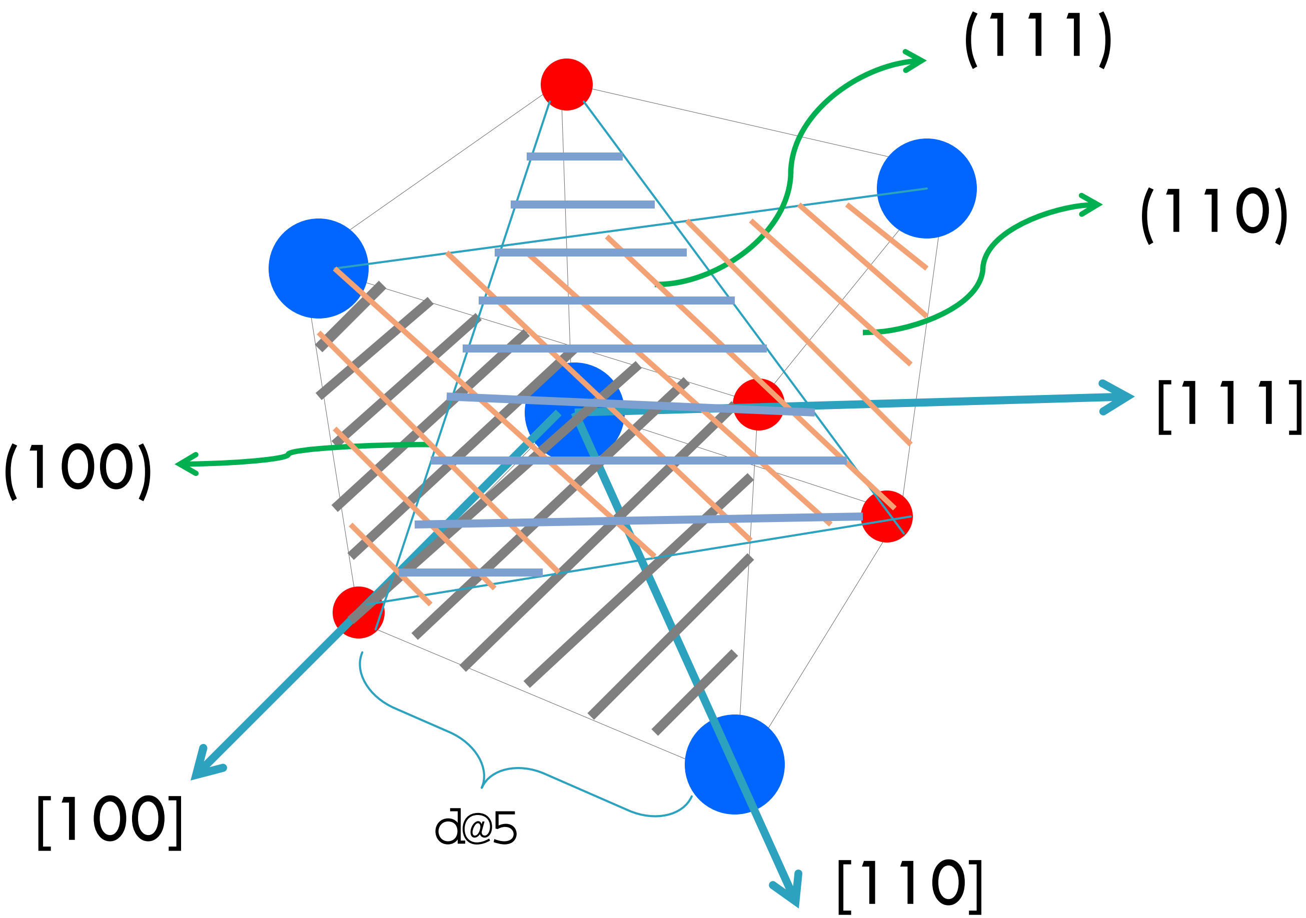




http://commons.wikimedia.org/wiki/File:Nacl-structure.jpg

Structure of NaI

- Unit cell of NaI crystal:



Structure of NaI

- We will only consider the lower index crystallographic axis and planes:
  - For axial channeling we consider:

$$<100>,\ <110>,\ <111>$$

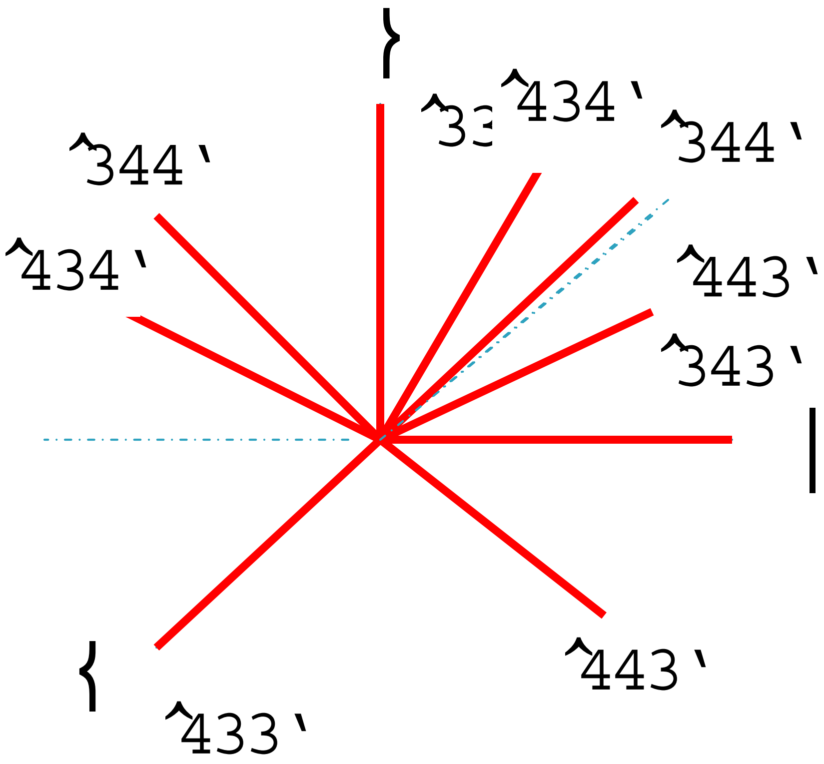
  - For planar channeling we consider:

$$\{100\},\{110\},\{111\}$$

- We have a total of 26 channels:
  - 13 Axial
  - 13 planar: perpendicular to the axial channels

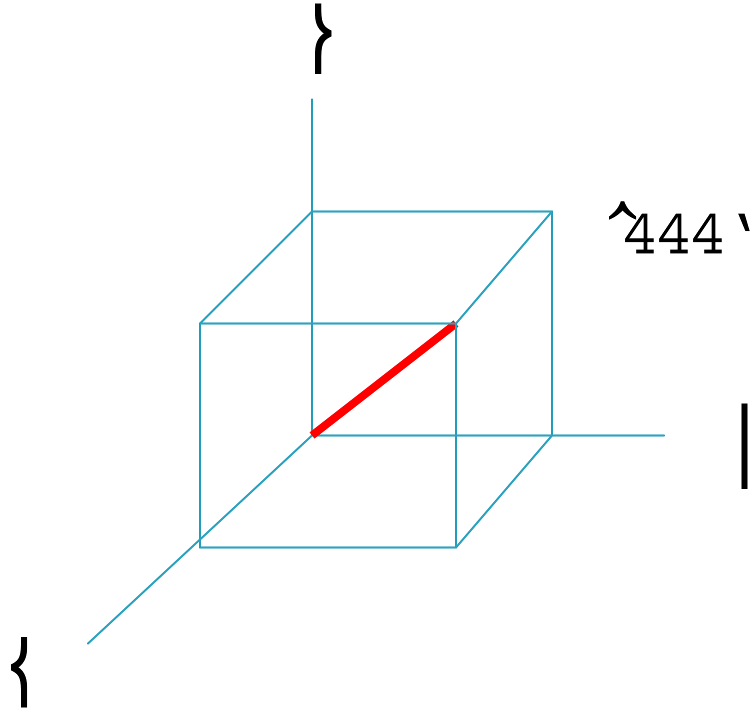
Structure of NaI

- 13 axial channels:



Structure of NaI

- 13 axial channels:



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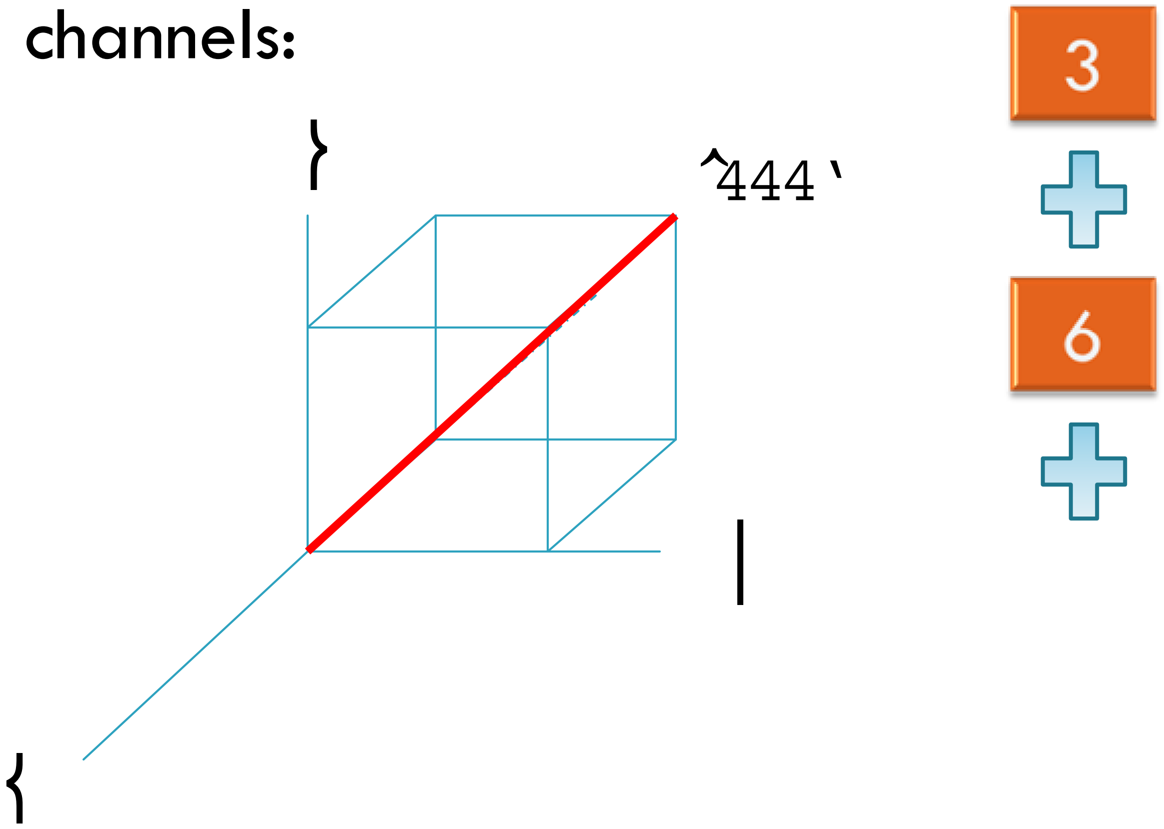
+

Structure of NaI

- 13 axial channels:



Structure of NaI

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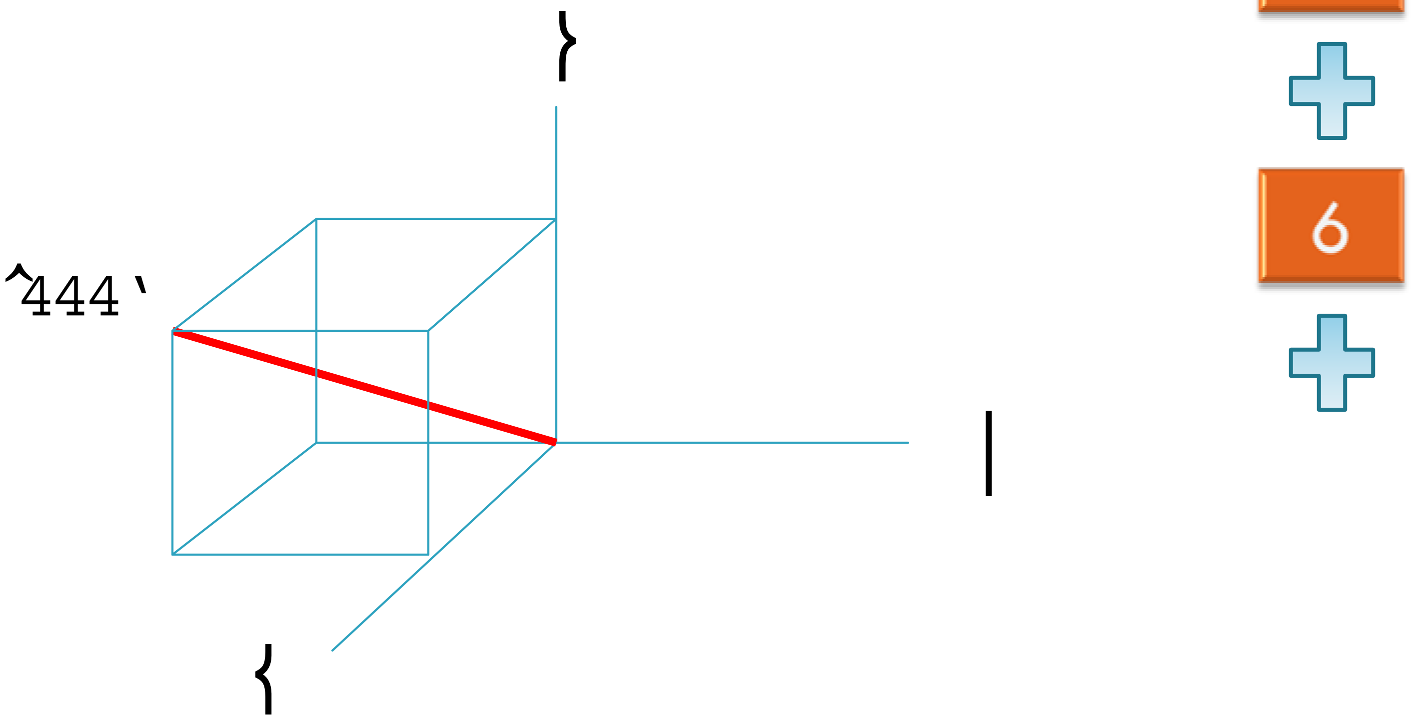

Structure of NaI

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