GAMMA RAY OPTICS

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Outline

- Motivation
- Gamma Ray Optics
  - Diffractive
  - Refractive
- Measurements
  - Refractive index
  - Pair creation threshold
- Outlook
- Conclusion
Motivation: nuclear Photonics

Hadron (p, n, d, α,...) + Energy produces excited nucleus:
• Only partially selective
• Limited penetration power
• Complex excitations

Photon $h\nu$
• Scanning photon energy and selective excitation from ground state
• Measurement of absorption or de-excitation

Requirement: brilliant tunable gamma ray source
New brilliant sources based on Compton back scattering

$\gamma_0 = \frac{E_0}{m_c c^2}$

yields $\sim 4 \gamma_0^2$ Doppler upshift

http://www.eli-np.ro/
Motivation

All techniques base on $\gamma$-ray driven excitation of a nucleus:
Spectrum delivered by Compton Backscattering source

Monochromatization: $\Delta E/E \sim 10^{-3}$

This means we have $10^9$ photons/s @ 1MeV
Spectral requirements nuclear point of view

\[ \Delta E \approx \frac{4.1 \times 10^{-15}}{\tau} \leq 1 \text{ eV} \]

\( \tau \sim 10^{-15} \ldots 10^{-6} \text{ s} \)

Broadening due to thermal motion:

\[ \Delta E_{Th} = E_\gamma \frac{v_{Th}}{c} = E_\gamma \sqrt{\frac{3k_B T}{mc^2}} \rightarrow \frac{\Delta E_{Th}}{E_\gamma} < 5 \cdot 10^{-5} \]

In most cases dominating

Example:

\( \tau > 10^{-15} \text{ s}, \ E_\gamma = 1 \text{ MeV}, \ T = 300 \text{ K} \)

\( \Delta E = 50 \text{ eV} \)
What is really required from a nuclear point of view

Example:

\[ \tau > 10^{-15} \text{ s}, \quad E_\gamma = 1 \text{ MeV}, \quad T = 300 \text{ K} \]
\[ \Delta E = 50 \text{ eV} \]

The dominating number of photons is not used:

@ 1MeV: we absorb max. 5% of photons

- Peak/Background bad
- Detector might be overloaded
  - (95% of $10^9$ photons/s)
What is this talk about?

Photon source

ELI-NP new brilliant source for \(\gamma\)-rays

Optics

Sample

Optics

Detector

Do we need to something here?
What can we do here?
Monochromatization via Crystal Diffraction

\[ I(\theta) \propto \frac{\sin^2 \theta \sqrt{1+y^2}}{1+y^2} \]

\[ y \propto \frac{\theta - \theta_B}{\lambda_y}, A \propto \lambda_y, E = \frac{hc}{\lambda_y} \]

\[ \text{FWHM} = 2 \frac{hc}{E_y} \]

\[ n\lambda_y = 2d \sin \theta_B \]

\[ \theta_B \approx n \frac{hc}{E_y} \]

\[ \frac{\Delta E}{E_y} \approx \frac{\Delta \theta_B}{\theta_B} = \text{const} \]

10^{-6} - 10^{-5} resolution constant over energy

1000 keV

10^{-8} - 10^{-7}\text{rad}

10^{-2}\text{rad}
How to realize diffraction

- Resolution is limited by divergence of incoming beam
- A beam with $10^{-8}$ rad divergence is needed
Double crystal geometry

Non-dispersive

dispersive
In-pile target position
- $5 \times 10^{14}$ neutrons cm$^{-2}$ s$^{-1}$
- Capture rate: $<10^{16}$
- Gamma emission rate $<10^{16}$
ILL as photon source

Beam Brilliance vs. Energy (keV)

- 0.1% band width
- 0.0001% band width

- ESRF ID15
- APS
GAMS5 operating in dispersive and nondispersive geometry
Diffraction efficiency of a perfect crystal

How does a crystal reflect, if the beam divergence fits its acceptance width?
How much do we really diffract?

$10^9 \text{s}^{-1}$ for 1keV

$5 \times 10^7 \text{s}^{-1}$ for 50 eV

$I_0 \times \frac{\Delta \theta_{\text{Diff}}}{\Delta \phi_{\text{Div}}} \times R^2$

Max. count rate for HpGe detectors
Could be $10^4 \text{s}^{-1}$

→ We need to improve throughput by 2 orders of magnitude

~$10^{-8} \text{rad}$
Approach 1: Correcting completely the divergence by refractive optics

\[ I_0 \times \frac{\Delta \theta_{\text{Diff}}}{\Delta \varphi_{\text{Div}}} \times R^2 \]

10^{-4} 10^{-2}

Could be pushed to by 1000

Could be pushed to by 10

Normal single crystals scheme:

Lens - single crystals scheme:

Requires lens system for g-rays: REFRACTION @ \( \gamma \)-ray Energies?
Refractive Index

\[ n(E) = 1 + \delta(E) + i\beta(E) \]

If \( \neq 0 \) then one can build refractive optics.

A. Snigirev et al., Nature Vol 384, 1996

For X-rays \( \delta = -10^{-5} \ldots -10^{-6} \)
For X-rays refractive optics is known.

And for Gamma Rays $\delta \sim 1/E^2$?
Measuring the refractive Index

We use crystal as collimator to generate beam with $< \mu \text{rad}$ divergence.

Deviation is detected by second crystal as analyzer.
Measuring the refractive Index for $\gamma$-Rays

Si prism, 160 degree, faces optically polished

Alignment stages

Prism installed between the two crystals
Results

For higher energies we find sign change.

This is what we expect from virtual photo effect only.

How to explain this?
Possible Explanation (D. Habs)

Refractive index is related to forward scattering amplitude

\[ n(E) = 1 + \delta(E) + i\beta(E) \]

\[ \delta(E) = \frac{\lambda^2 N_C A_{rf}}{2\pi} \]

Kramers-Kronig dispersion relation:

\[ A_f = A_{rf} + iA_{if} \]

\[ A_{rf}(E) = \frac{E^2}{4\pi^2\hbar c} \left( \frac{2}{\varepsilon\rightarrow 0} \int_0^\infty \frac{A_{if}(E)}{E^2 - \varepsilon^2 - i\varepsilon^2} dE \right) \]

\[ A_{rf}(E) = \frac{E^2}{2\hbar c} \lim_{E^2 \rightarrow 0} \frac{\text{abs}(E)dE}{(E + i)^2} \]

If we want to explain positive index of refraction we need to look for processes, which increase strongly with energy.
Possible explanation (D. Habs)

\[ (E) = \frac{\hbar^2 c^2}{2E^2} N_c \times A_{rf}(E) \]

\[ A_{rf}(E) = \frac{E^2}{2\hbar c} \lim_{E \to 0^+} E^2 \frac{\text{abs}(E)dE}{(E + i)^2} \]

There is a correlation between absorption and refraction.

Absorption cross section:
- Up to 500 keV Photo effect is dominating
- Pair creation sets in from 1022 keV
- Rising with \( E_\gamma \) would produce positive \( A_{rf} \)
- Exact knowledge of \( \sigma_{Pair} \) needed
New Measurement @ ILL

10 g of Gd$_2$O$_3$
$10^{16}$ captures per second

Two copper crystals as tunable monochromator

8 fold segmented BGO as pair spectrometer
Measurement of the Pair creation cross section

A clear enhancement of all experimental data with respect to classical Bethe-Heitler calculation

Normalization to calculations

At present no theoretical explanation available

M. Jentschel et al, Phys. Rev. C. 84(5) 2011
The complete picture

More processes to be considered: elastic and inelastic Delbrück scattering
(Calculations by D. Habs and M. Günther from LMU/MPQ Munich)
Results (comparison with expectation)

Next measurements: very near future

- Physics: measurement of Z-dependence
- precision Prism would be needed
- thick material → homogeneity?

Interferometric measurement

Possible working range:

Calculation for Si:
- ~ 0.8 period phase shift
- enough to detect sign
- for higher Z materials stronger effect expected
First test of techniques and applications: still this year

We can work on nuclear resonance fluorescence of $^7\text{Li}$ and test all techniques right now.

From PhD Thesis S. Baechler, Uni Fribourg
Conclusion

• Crystals can be used as optical elements for $\gamma$-rays
  • Beam splitter
  • Collimator
  • Monochromator
  • (lens)

• Refractive Optics for gamma rays is possible
  • Refractive index \( \neq 0 \) for $\gamma$-rays
  • Investigations of more materials planned

• Combining Refracting and Diffracting Optics – very promising
• ILL is perfect test bench to develop technologies