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Coherent Bremsstrahlung from Fast Neutrons

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Introduction

Bremsstrahlung emitted from fast neutrons

Coherent Bremsstrahlung from Fast Neutrons

Conclusion

Neutron has spin (and anomalous magnetic moment) and therefore can interact with electromagnetic field. Schwinger [1] was the first who predicted that the fast neutrons due to their spin can be scattered by electric field of an atom.

The physics of this scattering is explained in a following way: in a neutron rest frame the magnetic field appears and the neutron magnetic moment interacts with it. Electromagnetic Schwinger scattering of the fast neutrons was experimentally discovered in 1956 [2].

1. Schwinger J. // Phys. Rev. **73** (1948) 407.
2. Alexandrov Yu.A., Bondarenko I.I. // ZhETP, 1956 **31** 726 (in Russian).

It is well known that when the fast charged particle penetrates through aligned crystal, there appear coherent scattering [(a thin crystal) [1] and channeling effect (thicker crystal) [2].

In analogy with scattering of charged particles by a crystal, we may suppose that when the fast neutrons enter the crystal, one can expect both the coherent scattering of neutrons and neutrons channeling .

1. Ter-Mikelian M.L. High Energy Electromagnetic processes in Condensed Media (Wiley - Interscience - New-York, (1972).
2. Baier V. N., Katkov V. M., Strakhovenko V. M.. Electromagnetic Processes at High Energies in Oriented Single Crystals, World Scientific Publishing Co, Singapore, 1998

Coherent Schwinger neutrons scattering in a crystal has been considered in the following papers :

- A.N. Dyumin, I. Ya. Korenblit, V.A. Ruban, B.B. Tokarev, JETP Letters, 31 (1980) 413.
- V. G. Baryshevskii, A.M. Zaitzeva, Izv. VUZov, 3 (1985) 103.
- Yu.P.Kunashenko, Yu.L.Pivovarov, Charged and Neutral Particles Channeling Phenomena (Channeling 2008): Proceedings of the 51st Workshop of the INFN Eloisatron Project - Erice, Italy, October 25 - November 1, 2008. - Erice: World Scientific, (2010) 794.
- Yu.P.Kunashenko, Il Nuovo Cimento (2011), v.034.

The first experimentally on coherent Schwinger neutrons scattering in a crystal was done in: Dyumin A.N., Ruban V.A., Tokarev B.B., Vlasov M.F.// Pis'ma v ZhETP, 1985 **42** 61 (JETP Letters, 1985 **42** 61)).

Another mechanism of a neutron interaction with electromagnetic field is the photon emission from neutrons. Radiation of photons from relativistic neutron in magnetic field was theoretically studied in the following papers :

- Ternov, I. M.; Bagrov, V. G.; Khapaev, A. M. Soviet Physics JETP, 21 (1965) 613.
- V.L. Lyuboshitz, Yad.Fiz. 4 (1966) 269.
- V.A. Bordovitsyn, I.M. Ternov, V.G. Bagrov , Phys. Usp. 38 1037–1047 (1995)

In a present report we develop theory and study ordinary bremsstrahlung and coherent bremsstrahlung emitted from fast neutrons passing through crystal parallel to crystal axis. We calculate the dependence of the neutron bremsstrahlung cross-section on the neutron energies, emitted photon energies and photon emission angles.

Bremsstrahlung emitted from fast neutrons

$$d\sigma_{fi} = \frac{2\pi}{\hbar}\left|M_{fi}\right|^2 \delta\left(E_i - E_f - \hbar\omega\right)\frac{1}{J}d\rho, \quad d\rho = \frac{d^3\vec{p}_f}{(2\pi\hbar)^3}\frac{d^3\vec{k}}{(2\pi)^3}, \quad J = \frac{V}{v} \ (V=1)$$

Radiation cross-section

$$M_{fi} = \sum_\alpha \int \left\{ \frac{\langle f|V_S|\alpha\rangle\langle\alpha|V_R|i\rangle}{E_i - E_\alpha} + \frac{\langle f|V_R|\alpha\rangle\langle\alpha|V_S|i\rangle}{E_i - E_\alpha} \right\}$$

Matrix element

$$V_R = \vec{\mu}\vec{H} = \vec{\mu}\,rot\vec{A} = \vec{\mu}\sum\sqrt{\frac{2\pi\hbar c^2}{\omega_k}}\left[i\vec{k},\vec{e}_k\right]\left(\hat{a}_k \exp\left[i\vec{k}\vec{r}\right] - \hat{a}_k^{\,+}\exp\left[-i\vec{k}\vec{r}\right]\right), \quad \vec{\mu} = \mu\vec{\sigma}$$

Orator of neutron interaction with radiation field

$$V_S = i\frac{\mu\hbar}{mc}\vec{\sigma}\left[\vec{E},\vec{\nabla}\right]$$

Orator of neutron interaction with atom

Wave functions

$$|i\rangle = \mathrm{X}_i \exp[i\vec{k}_i\vec{r}]|0\rangle \quad |f\rangle = \mathrm{X}_f \exp[i\vec{k}_f\vec{r}]|1\rangle \quad \mathrm{X}_1 = \begin{pmatrix}1\\0\end{pmatrix}, \ \mathrm{X}_2 = \begin{pmatrix}0\\1\end{pmatrix}$$

$$\left|M_{fi}\right|^2 = \frac{\pi\hbar^2}{2m\,\hbar\omega^3}\,\mu^4\,\frac{Z^2e^2}{q^4}\left|\vec{A}_{fi}\cdot\vec{e}\right|^2$$

We take into account $k << k_i, k_f;$

$$\vec{A}_{fi} = \left(\vec{S}_{fi}\cdot\vec{k}\right)\vec{K} - \left(\vec{K}\cdot\vec{k}\right)\vec{S}_{fi} \qquad \vec{S}_{fi} = \left\langle \mathrm{X}_f\middle|\vec{\sigma}\middle|\mathrm{X}_i\right\rangle$$

$$\vec{K} = \left[\vec{k}_f,\vec{k}_i\right], \qquad \vec{q} = \vec{k}_i - \vec{k} - \vec{k},$$

After average over photon polarization one have

$$\left|M_{fi}\right|^2 = \frac{\pi\hbar^2}{2m\,\hbar\omega^3}\,\mu^4\,\frac{Z^2e^2}{q^4}\left(\left(\vec{A}_{fi}\cdot\vec{A}^*{}_{fi}\right) - \left(\vec{A}_{fi}\cdot\vec{n}\right)\left(\vec{A}^*{}_{fi}\cdot\vec{n}\right)\right)$$

There are two ways of bremstrahlung: with and without changing spin orientation. On the first case spin lies in the plane of neutron scattering and perpendicular to initial direction of neutron motion. On the second case spin direction coincides with line of initial neutron motion.

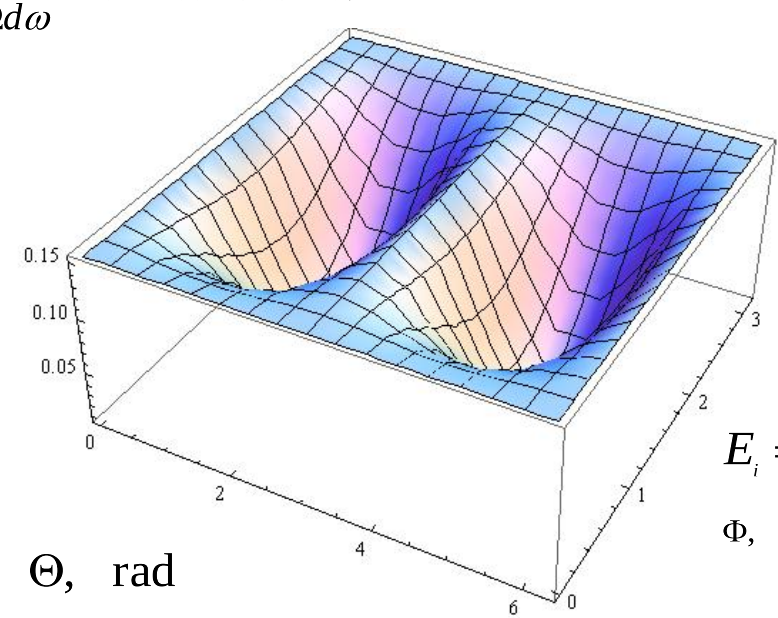
$$d\sigma_{\uparrow\uparrow} = \frac{Z^2\alpha^3\mu^4\omega\hbar^5}{4m^5\pi^2c^5}\,\frac{k_f k_i R^4\left[Cos\Theta^2 + Cos\Phi^2 Sin\Theta^2\right]Sin\Theta_n^{\ 2}}{\hbar^2c^2\left[\left(1+k_i^{\ 2}+k_f^{\ 2}\right)R^2 - 2k_f k_i R^2 Cos\Theta_n^{\ 2}\right]}\,d\Omega d\Omega_n d\omega$$

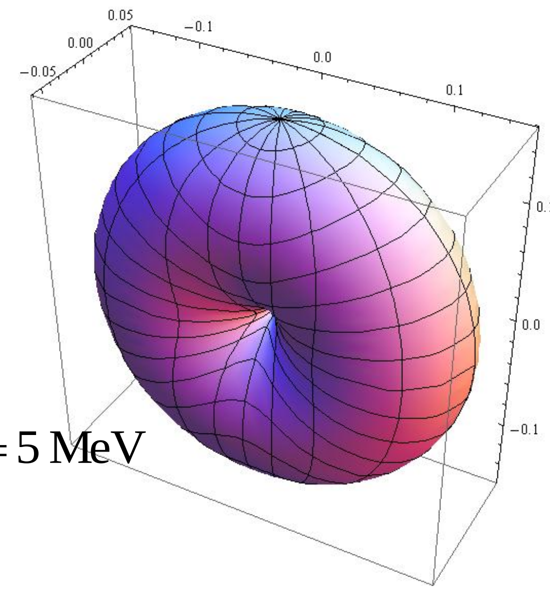
$$d\sigma_{\uparrow\uparrow} = \frac{Z^2\alpha^3\mu^4\omega\hbar^5}{m^5\pi^2c^5}\,\pi\,\frac{\left(\left(-2k_f k_i R^2 + \left(1+k_i^{\ 2}+k_f^{\ 2}\right)R^2\right)Arctg\left[\frac{2k_f k_i R^2}{\left(1+k_i^{\ 2}+k_f^{\ 2}\right)R^2}\right]\right)\left(Cos\Theta^2 + Cos\Phi^2 Sin\Theta^2\right)}{\hbar^2c^2k_f k_i R^2}\,d\Omega d\omega$$

$$k_i = \sqrt{2mE_i}/\hbar, \quad k_f = \sqrt{2m\left(E_i-\omega\right)}/\hbar$$

Indicatrix of radiation from neutron $\frac{d\sigma_{\uparrow\uparrow}}{d\Omega d\omega}\times 10^{15}$ barn/st/MeV

$\frac{d\sigma_{\uparrow\uparrow}}{d\Omega d\omega}\times 10^{15}$ barn/st/MeV





$E_i = 100$ MeV, $\omega = 5$ MeV

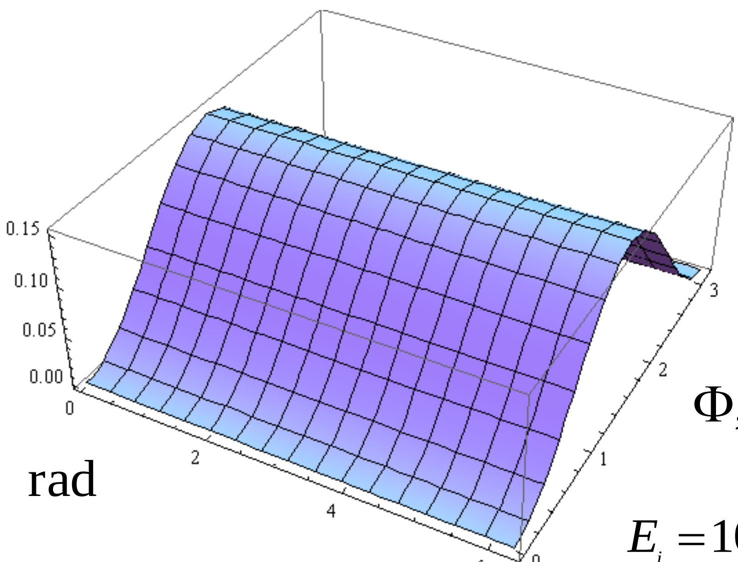
Φ, rad

Θ, rad

$$d\sigma_{\uparrow\downarrow} = \frac{Z^2\alpha^3\mu^4\omega\hbar^5}{4m^5\pi^2c^5}\frac{k_f k_i R^4 Sin\Theta^2 Sin\Theta_n{}^2}{\hbar^2c^2\left[\left(1+k_i{}^2+k_f{}^2\right)R^2-2k_f k_i R^2 Cos\Theta_n{}^2\right]}d\Omega d\Omega_n d\omega$$

$$d\sigma_{\uparrow\downarrow} = \frac{Z^2\alpha^3\mu^4\omega\hbar^5}{m^5\pi^2c^5}\pi\frac{\left(\left(-2k_f k_i R^2+\left(1+k_i{}^2+k_f{}^2\right)R^2\right)Arctg\left[\frac{2k_f k_i R^2}{\left(1+k_i{}^2+k_f{}^2\right)R^2}\right]\right)Sin\Theta^2}{\hbar^2c^2k_f k_i R^2}d\Omega d\omega$$

$\frac{d\sigma_{\uparrow\downarrow}}{d\Omega d\omega}\times 10^{15}$ barn/st/MeV

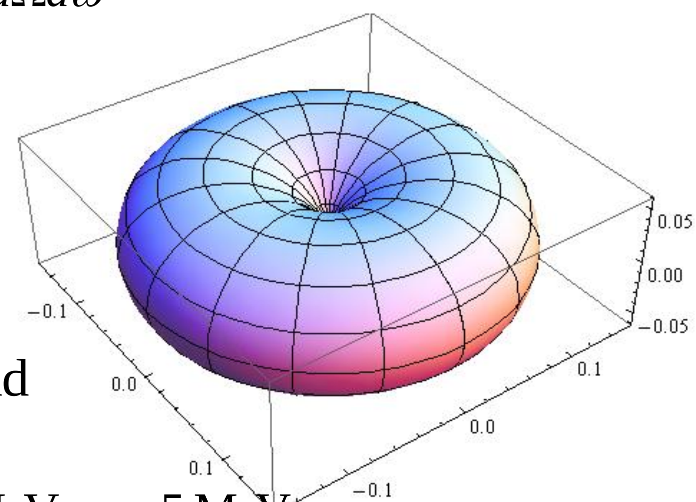


Φ, rad

Θ, rad

Indicatrix of radiation from neutron

$\frac{d\sigma_{\uparrow\downarrow}}{d\Omega d\omega}\times 10^{15}$ barn/st/MeV



$E_i = 100$ MeV, $\omega = 5$ MeV

$d\sigma_{\uparrow\uparrow} \sim \left[Cos\Theta^2 + Cos\Phi^2 Sin\Theta^2\right]Sin\Theta^2$

$d\sigma_{\uparrow\downarrow} \sim Sin\Theta^2$

$\Phi = 0: \quad d\sigma_{\uparrow\downarrow} = d\sigma_{\uparrow\downarrow}$

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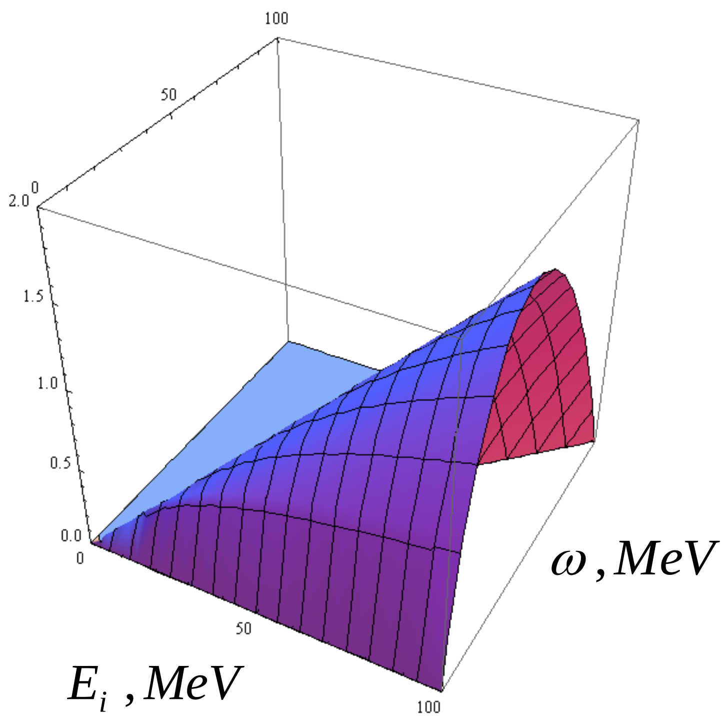
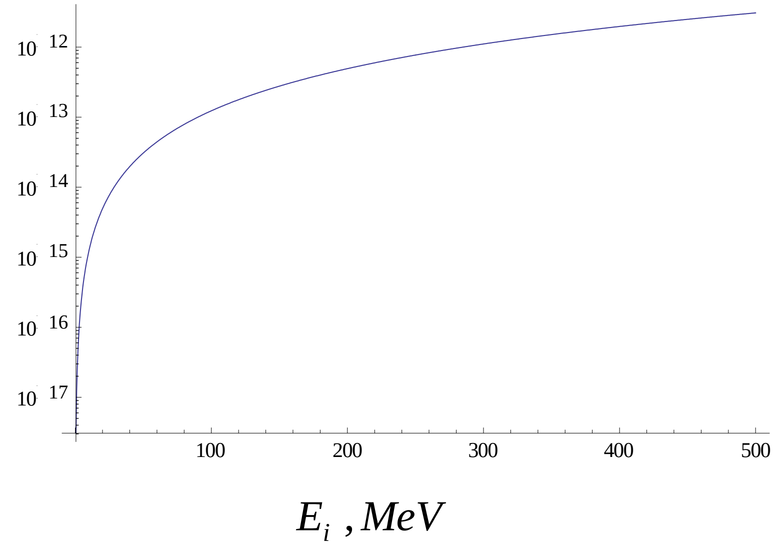
$$d\sigma_{\uparrow\uparrow(\uparrow\downarrow)} = \frac{32}{3}\frac{Z^2\alpha^3\mu^4\omega\hbar^5}{m^5\pi^2c^5}\pi\frac{\left(\left(-2k_fk_iR^2+\left(1+k_i{}^2+k_f{}^2\right)R^2\right)Arctg\left[\frac{2k_fk_iR^2}{\left(1+k_i{}^2+k_f{}^2\right)R^2}\right]\right)}{\hbar^2c^2k_fk_iR^2}d\omega$$

$$\frac{d\sigma_{\uparrow\uparrow(\uparrow\downarrow)}}{d\omega}\times 10^{15} \quad \text{barn/MeV}$$



$$\sigma_{\uparrow\downarrow(\uparrow\downarrow)} = \int \frac{d\sigma_{\uparrow\downarrow(\uparrow\downarrow)}}{d\omega}d\omega \quad \text{(barn)}$$



Coherent Bremsstrahlung from Fast Neutrons

$$d\sigma_{cr} = d\sigma_{coh} + d\sigma_{incoh} \,, \qquad d\sigma_{coh} = I(\vec{q})\exp\left(-q^2\overline{u^2}\right)d\sigma_1 \,,$$

$$d\sigma_{incoh} = N\left[1-\exp\left(-q^2\overline{u^2}\right)\right]d\sigma_1 \qquad I(q_z) = N_z \frac{(2\pi\hbar)}{d_z}\sum_n \delta(q_z - g_z n), \qquad g_z = \frac{(2\pi\hbar)}{d_z}$$

$I(\vec{q})$ - is an interferential multiplier, which is responsible for appearance of coherent effects

$S(\vec{q})$ - the crystal structure factor $\quad \exp\left(-q^2\overline{u^2}\right)$ – is the Debye – Waller factor

$\overline{u^2}$ – mean-square displacement of crystal atoms from equilibrium positions

$$g_z = \frac{(2\pi\hbar)}{d_z}$$ One dimensional reciprocal lattice vector

$$d\sigma_{\uparrow\downarrow COH}=\frac{Z^2\alpha^3\mu^4\omega\hbar^5}{4m^5\pi^2c^5}\frac{1}{k_f}\frac{k_f k_i R^4 Sin\Theta^2}{\hbar^2c^2}\times$$

$$\sum_n\frac{1-x_n^{\;2}}{\left[\left(1+k_i^{\;2}+k_f^{\;2}\right)R^2-2k_fk_iR^2x_n^{\;2}\right]}\exp\left[\overline{u^2}\left(-k_fk_ix_n^{\;2}+k_i^{\;2}+k_f^{\;2}\right)\right]$$

$$d\sigma_{\uparrow\uparrow COH}=\frac{Z^2\alpha^3\mu^4\omega\hbar^5}{4m^5\pi^2c^5}\frac{1}{k_f}\frac{k_f k_i R^4\left[Cos\Theta^2+Cos\Phi^2Sin\Theta^2\right]}{\hbar^2c^2}\times$$

$$\sum_n\frac{1-x_n^{\;2}}{\left[\left(1+k_i^{\;2}+k_f^{\;2}\right)R^2-2k_fk_iR^2x_n^{\;2}\right]}\exp\left[\overline{u^2}\left(-k_fk_ix_n^{\;2}+k_i^{\;2}+k_f^{\;2}\right)\right]$$

$$x_n=\frac{\hbar c\left(k_i-k_f\right)-\omega Cos\Theta}{\hbar c\, g_0\, n}\qquad\qquad -1\le\cos\Theta_n\le 1$$

$$d\sigma_{coh}>>d\sigma_{incoh}\,,$$

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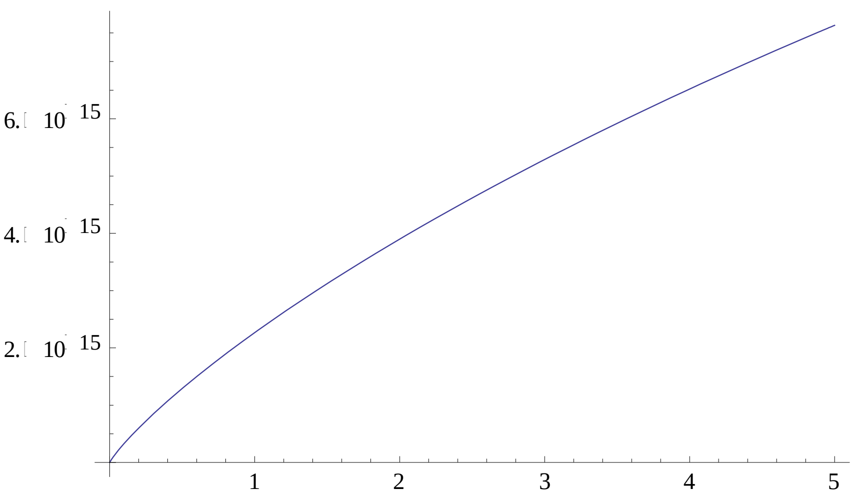
Coherent Bremsstrahlung from Fast Neutrons

Dependence of the differential cross-section from emitted Photon energy ω for fixed photon emission angles

$$\Theta = \pi/10, \quad \Phi = 0, E_i = 100 \ \text{MeV}$$

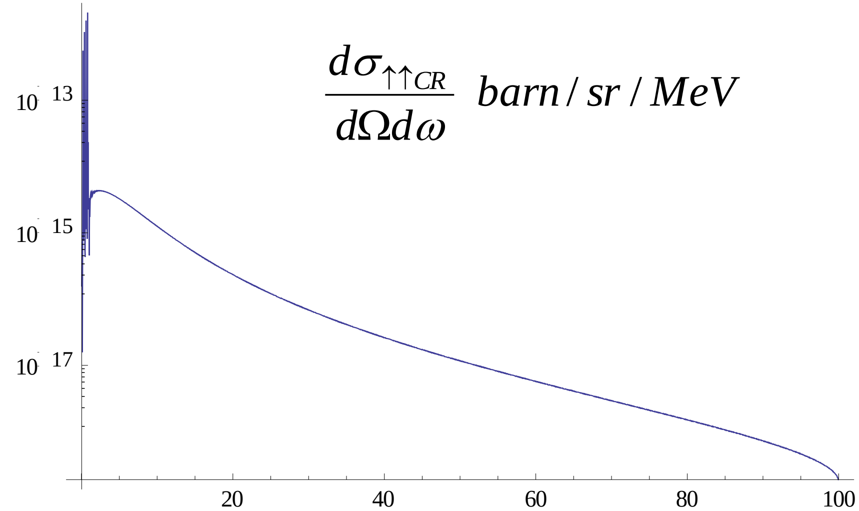
$W < 100 >, N = 1000$

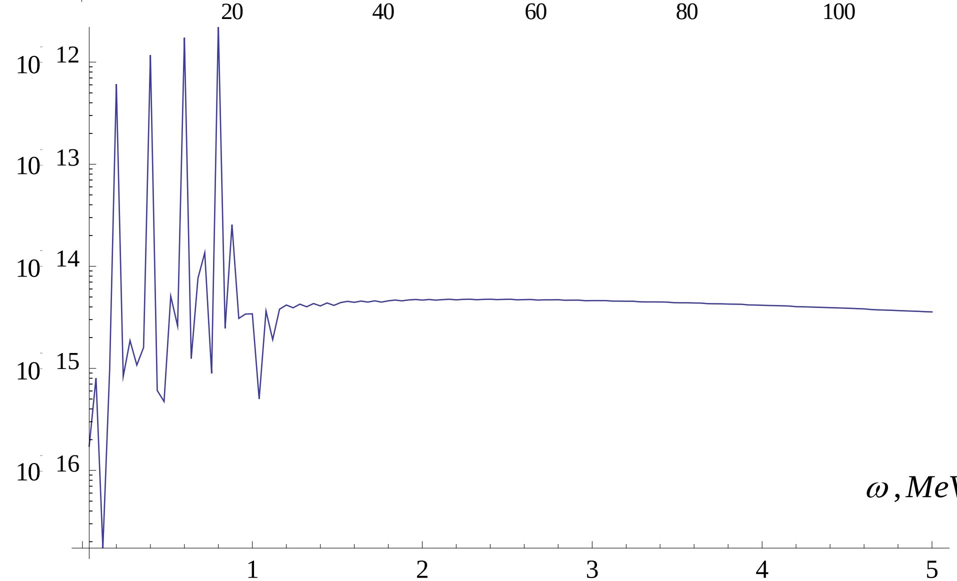
$\frac{d\sigma_{\uparrow\uparrow}}{d\Omega d\omega}$ $barn/sr/MeV$



ω, MeV

$\frac{d\sigma_{\uparrow\uparrow CR}}{d\Omega d\omega}$ $barn/sr/MeV$





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Coherent Bremsstrahlung from Fast Neutrons

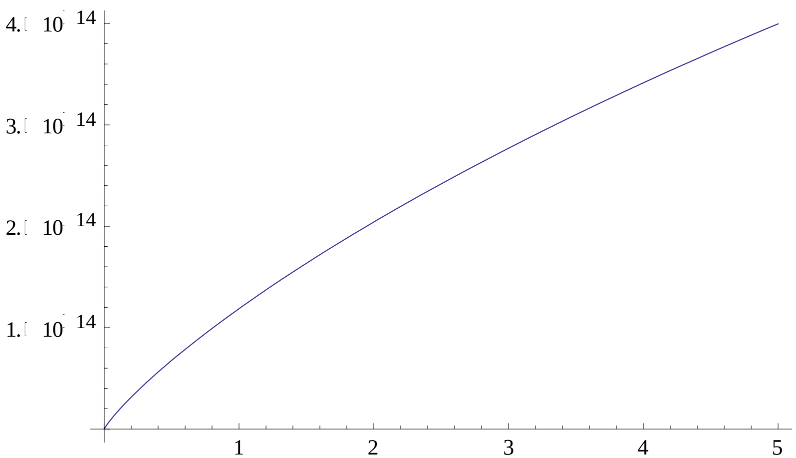
Dependence of the differential cross-section from emitted Photon energy ω for fixed photon emission angles

$$\Theta = \pi/4 \ \text{rad}, \quad \Phi = 0 \ \text{rad}, \quad E_i = 100 \ \text{MeV}$$

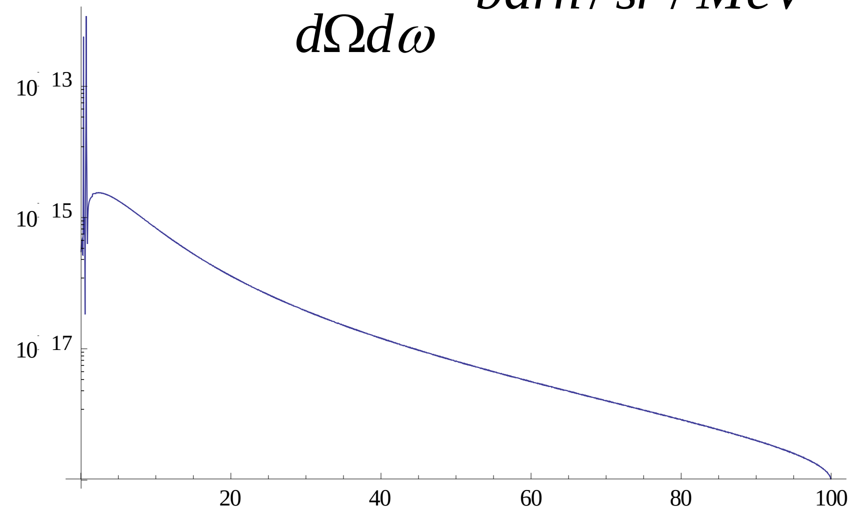
$$W < 100 >, N = 1000$$

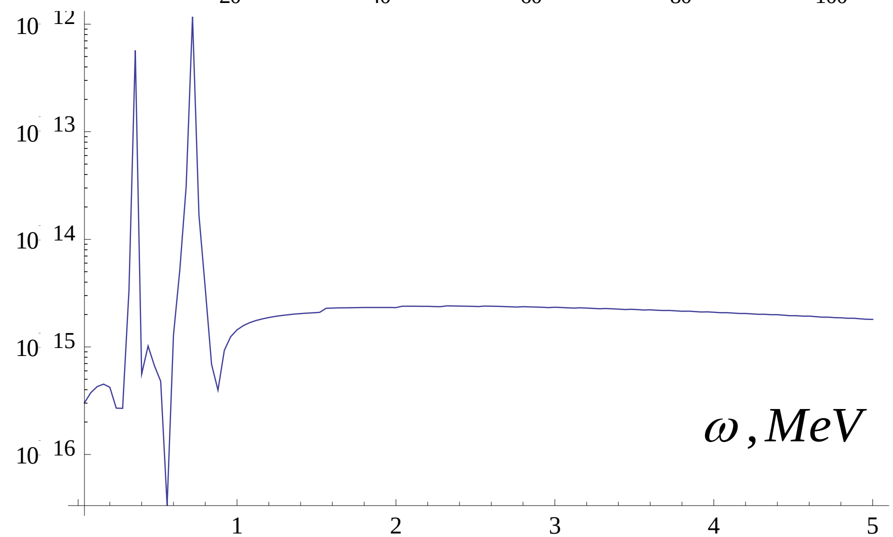
$$\frac{d\sigma_{\uparrow\uparrow CR}}{d\Omega d\omega} \ barn/sr/MeV$$

$$\frac{d\sigma_{\uparrow\uparrow}}{d\Omega d\omega} \ barn/sr/MeV$$



ω, MeV





ω, MeV

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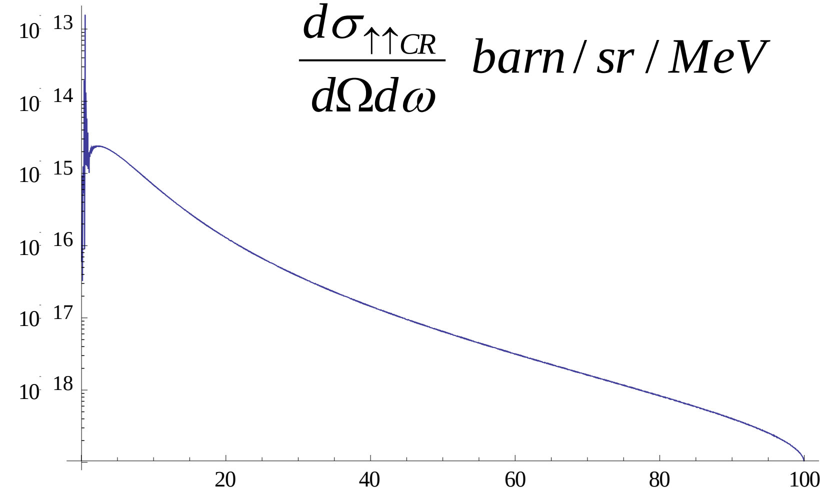
Coherent Bremsstrahlung from Fast Neutrons

Dependence of the differential cross-section from emitted Photon energy ω for fixed photon emission angles

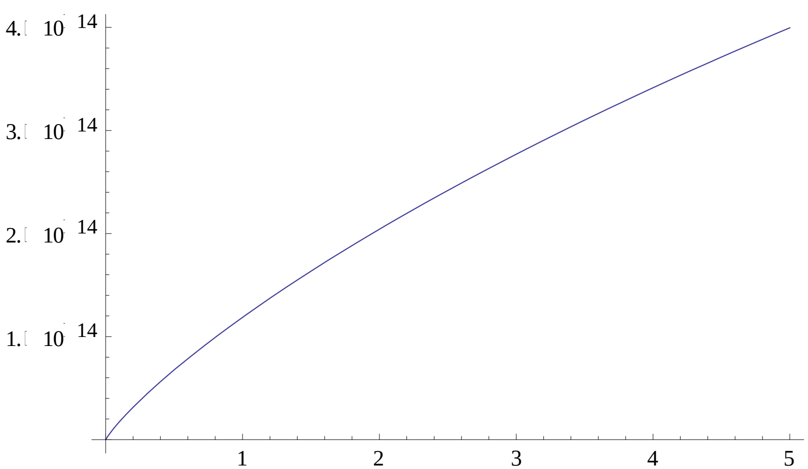
$$\Theta = 3\pi/4 \ \text{rad}, \quad \Phi = 0, \ E_i = 100 \ \text{MeV}$$

$$W<100>, N = 1000$$

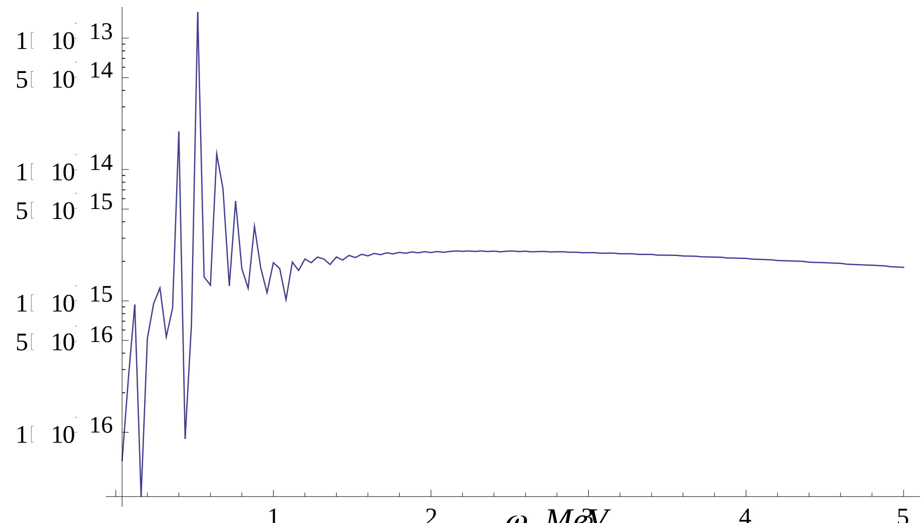
$$\frac{d\sigma_{\uparrow\uparrow CR}}{d\Omega d\omega} \ barn/sr/MeV$$



$$\frac{d\sigma_{\uparrow\uparrow}}{d\Omega d\omega} \ barn/sr/MeV$$



ω, MeV



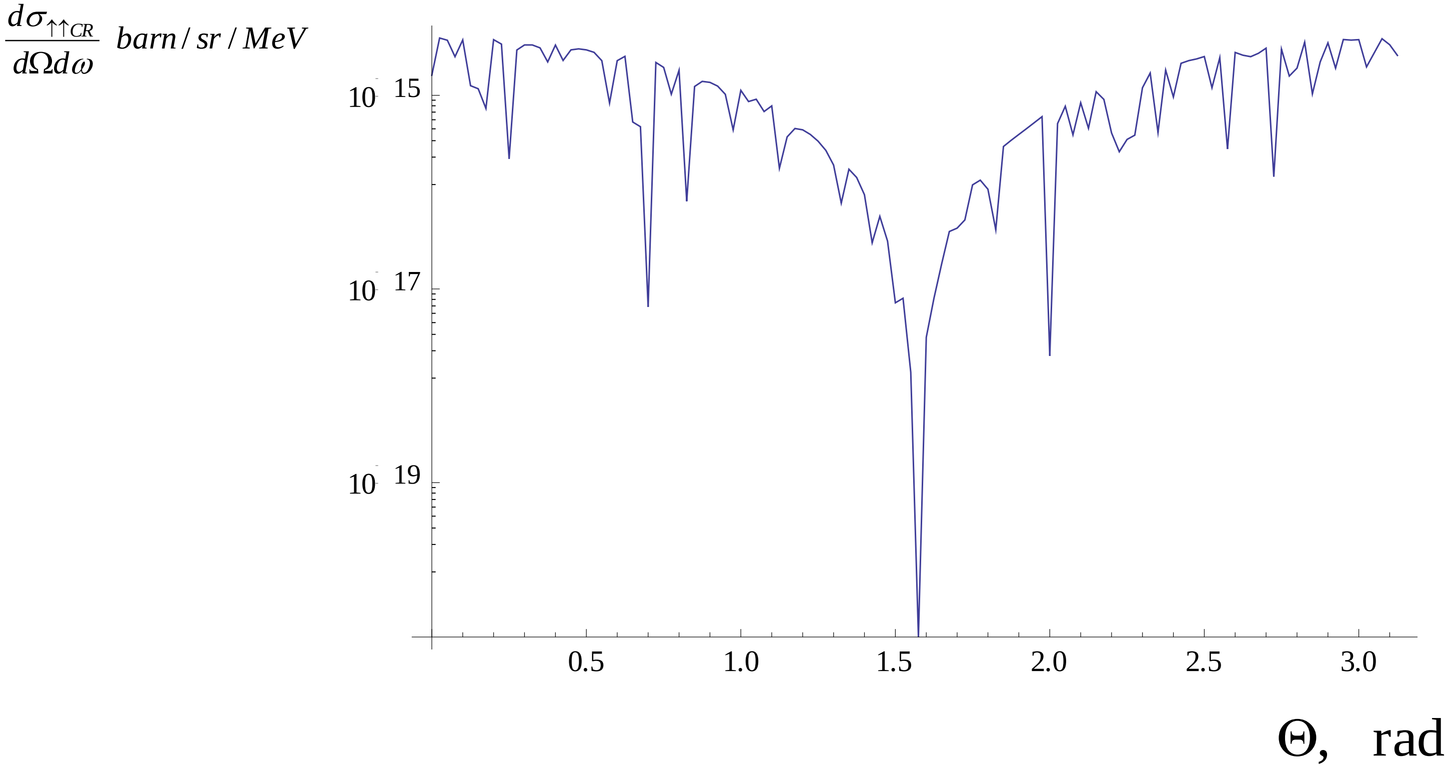
ω, MeV

Coherent Bremsstrahlung from Fast Neutrons

Angular distribution

$$\Phi = \pi/2 \ \text{rad}, \quad \omega = 1\,\text{MeV},\ E_i = 100 \ \text{MeV}$$

$$W < 100 >,\ N = 1000$$

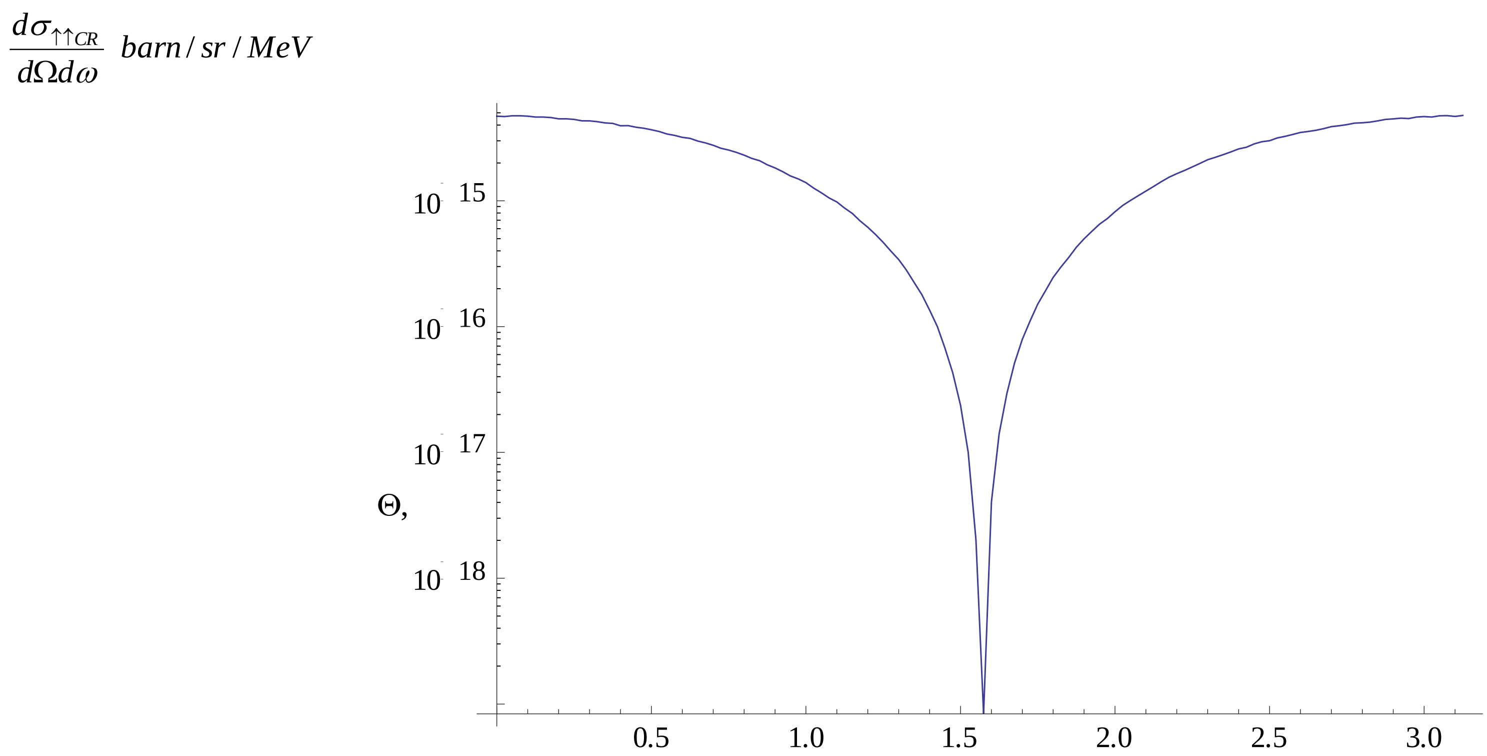


Coherent Bremsstrahlung from Fast Neutrons

Angular distribution

$$\Phi = 0 \ \text{rad}, \quad \omega = 2\ \text{MeV}, \ E_i = 100 \ \text{MeV}$$

$$W<100>, N = 1000$$



Conclusion

There are two way of **Bremsstrahlung from Fast Neutrons** **transition with spin flip** and **transition without spin flip**

This two type of radiation differ in angular distribution of emitted photon

It is possible coherent effect in **Bremsstrahlung from Fast Neutrons in spectral and angular dependence of the cross-section**

The coherent effect appears for photon energies ω ~ 1 MeV

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Thank you for your attention