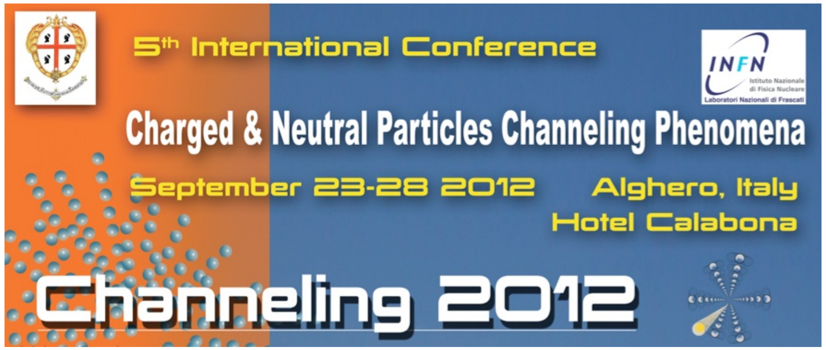
# *Coherent bremstrahlung from neutrons*

**Yu.P. Kunashenko[1,2]**

[1]*Tomsk Polytechnic University,Tomsk, Russia*

[2]*Tomsk State Pedagogical University,Tomsk, Russia*



# Channeling-2012

Neutron has an electric charge equal to zero, but it has spin (and anomalous magnetic moment) and therefore it can interact with the electromagnetic field.

Schwinger first predicted that the fast neutrons due to its magnetic moment can be scattered by electric field of an atom: J. Schwinger Phys. Rev. 73 (1948) 407.

Experiment:

Alexandrov Yu. A. Bondarenko I.I. 1956 *ZhETP*, **31** 726

Coherent neutron scattering and neutron channeled was discused in 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.
- A.N. Dyumin, V.A. Ruban, B.B. Tokarev, M.F. Vlasov, JETP Letters, 42 (1985) 61.
- Yu.P.Kunashenko, Il Nuovo Cimento (2011), v.034.
- Y.P. Kunashenko, Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques. (2012) **6** 271
- Vysotskii V. I. and Kuzmin R. N. 1992 *Usp. Fiz. Nauk* **162** 2
- Korotchenko K.B. and Kunashenko Yu.P. *IL Nuovo Cimento*, **C 34** 537
- A.N. Dyumin, V.A. Ruban, B.B. Tokarev, M.F. Vlasov, JETP Letters, 42 (1985) 61.

Another mechanism of a neutron interaction with electromagnetic field is the photon emission from neutrons.

**Radiation in magnetic field**


•I. M.Ternov, V. G. Bagrov, A. M. Khapaev, 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)


**Bremsstrahlung**

Yu.P. Kunashenko, TSPU Bulletin, 122, 49 (2012)

## The photon scattering by neutron

We use the method of virtual photons to find the coherent bremsstrahlung from neutrons. Therefore it is necessary to know the photon scattering cross-section.

$$M_{fi} = \sum_{\alpha} \int \left\{ \frac{\langle f|V|\alpha\rangle\langle\alpha|V|i\rangle}{E_i - E_\alpha} + \frac{\langle f|V|\alpha\rangle\langle\alpha|V|i\rangle}{E_i - E_\alpha} \right\} d\vec{k}_\alpha$$

$$|i\rangle = \mathrm{X}_i \exp[i\boldsymbol{k}_i\boldsymbol{r}]|1\rangle,$$

$$|f\rangle = \mathrm{X}_f \exp[i\boldsymbol{k}_f\boldsymbol{r}]|1\rangle,$$

$$|\alpha\rangle = \mathrm{X}_\alpha \exp[i\boldsymbol{k}_n\boldsymbol{r}](0)1\rangle,$$

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

If in the initial state neutron at rest, we have:

$$M_{fi} = \frac{2\pi\hbar c^2}{\sqrt{\omega\omega'}}\left(\frac{\langle \mathrm{X}_f|\,(\boldsymbol{\mu}\,[i\boldsymbol{k},\boldsymbol{e}])\,(\boldsymbol{\mu}\,[i\boldsymbol{k}',\boldsymbol{e}'])|\mathrm{X}_i\rangle}{\hbar\omega} - \frac{\langle \mathrm{X}_f|\,(\boldsymbol{\mu}[i\boldsymbol{k}',\boldsymbol{e}'])\,(\boldsymbol{\mu}\,[i\boldsymbol{k},\boldsymbol{e}])|\mathrm{X}_i\rangle}{\hbar\omega'}\right) \times \delta\left(\boldsymbol{k} - (\boldsymbol{k}_f - \boldsymbol{k}')\right)$$

Let the incident photon moves along the axis OZ

$$\boldsymbol{k} = \{0,0,k\}, \quad k = \omega / c \qquad \boldsymbol{e}_{1,1} = \boldsymbol{e}_x \,, \boldsymbol{e}_{1,2} = \boldsymbol{e}_y$$

$$\mathrm{k}' = \{k' \sin\Theta \cos\Phi, k' \sin\Theta \sin\Phi, k' \cos\Theta\}, \quad k' = \omega' / c,$$

$$\boldsymbol{e}_{2,1} = \frac{\boldsymbol{n} \times \boldsymbol{e}_z}{\sqrt{1-(\boldsymbol{n}\cdot\boldsymbol{e}_z)^2}} \,, \boldsymbol{e}_{2,2} = \frac{\boldsymbol{n}(\boldsymbol{n}\cdot\boldsymbol{e}_z) - \boldsymbol{e}_z}{\sqrt{1-(\boldsymbol{n}\cdot\boldsymbol{e}_z)^2}} \,, \quad \boldsymbol{n} = \frac{\boldsymbol{k}}{k}.$$

According to Fermi's golden rule the photon scattering-cross section by the neutron is:

$$d\sigma_{fi} = \frac{2\pi}{\hbar c} |M_{fi}|^2 \delta(\hbar\omega - T_f - \hbar\omega') \frac{\hbar\omega'^2 d\hbar\omega'}{(2\pi\hbar c)^3} d\Omega \;.$$

The analysis shows that there are two possible of photon scattering by neutrons: the orientation of the neutron spin does not change, and the photon  scattering with the neutron spin-flip.

Consider the case of the neutron spin is parallel to the initial momentum of the neutron (in the laboratory reference frame; parallel to the axis OZ). Spin wave in this case are:

$$X_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad X_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

The scattering cross-section of a photon by a neutron with spin-flip is:

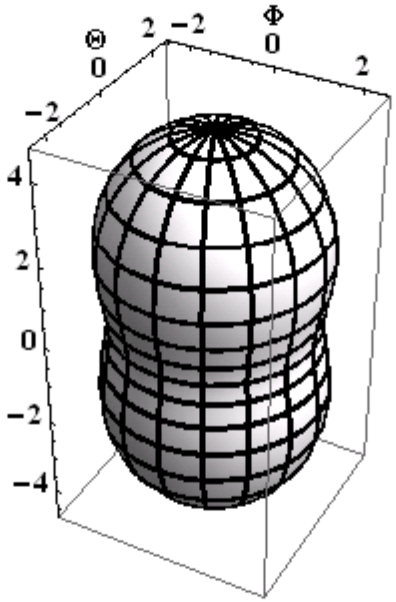
$$\frac{d\sigma_{\uparrow\downarrow}}{d\Omega} = \frac{\pi\,\mu^4}{\hbar^2 c^2}\,\frac{\hbar\omega_2\left(\hbar\omega_1 + \hbar\omega_2\right)^2}{\hbar\omega_1}\left(3 + \cos 2\Theta\right)$$

The scattering cross-section of a photon by a neutron without spin-flip is:

$$\frac{d\sigma_{\uparrow\uparrow}}{d\Omega} = \frac{\pi\,\mu^4}{\hbar^2 c^2}\,\frac{\hbar\omega_2\left(\hbar\omega_1{}^2 + \hbar\omega_2{}^2\right)}{\hbar\omega_1}\sin^2\Theta$$

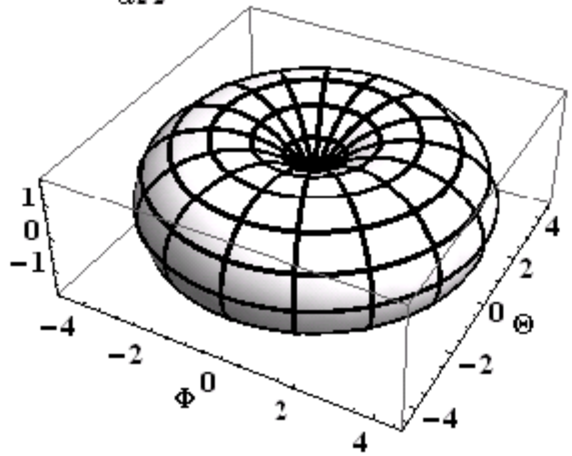
Figure shows the indecatrix of a photon scattering by a neutron without spin flip neutron (Fig. a) and with neutron spin-flip (Fig. b). Energy of the incident photon is equal 1 MeV and scattered one 0.9 MeV.

$\frac{d\sigma_{fi}}{d\Omega}\times 10^{7}\quad \mu barn/St$




**a)**

$\frac{d\sigma_{fi}}{d\Omega}\times 10^{7}\quad \mu barn/St$




**b)**

## Coherent Bremsstrahlung from Neutrons

Bremsstrahlung process can be described in terms of the scattering of a virtual photon by a neutron. Let me consider coherent bremstrahlung from neutron when neutron velosity parallel to crystal axis. Spectrum of virtual photons of crystal axis is:

$$n(\omega)d\omega = \frac{Z^2 e^2}{\pi^2} N \left\{ \left[ L - B \exp\left[ -\left( \frac{\hbar\omega}{\gamma\hbar c} \bar{u} \right)^2 \right] \right] + \frac{2\pi}{d} \sum_{g_n} B \exp\left[ -\left( \frac{\hbar\omega}{\gamma\hbar c} \bar{u} \right)^2 \right] \delta(k_1 - g_n) |S|^2 \right\} \frac{d\omega}{\omega}$$

$$L = \pi \ln\left[ \frac{a\lambda^{-2}}{(\hbar\omega / \gamma\hbar c)^2 + R^{-2}} \right], \quad a \approx 1$$

$$B(x) = \pi\left\{ -(1+x)e^x Ei(-x) - 1 \right\}, \quad x = \left[ \left( \frac{\hbar\omega}{\gamma\hbar c} \right)^2 + R^{-2} \right] \bar{u}^2$$

Transform the scattering cross-section of a photon by a neutron into the laboratory coordinate system

Lorentz transformation: $\omega = \gamma\omega_2\left(1 - \beta\cos\Theta\right)$

Frequency of the incident and scattered photons are related by the usual Compton relation (m-is neutron rest mass):

$$\frac{\hbar}{mc^2}\omega_1 = \frac{\omega_2}{mc^2/\hbar + \omega_2\left(1 - \cos\Theta\right)}$$

We obtain a common formula for the cross-section of a photon scattering by a neutron without spin flip of neutron and for spin-flip scattering in laboraratory coordinat system:

$$\sigma(\omega,\omega_1) = \frac{2\pi\mu^4}{\hbar^2 c^4}\frac{\omega}{\gamma^3\omega_1}\times$$

$$\frac{\left(\omega - \gamma\omega_1(1-\beta)\right)\left(\omega - \gamma\omega_1(1+\beta) + 2\omega_1\omega\frac{mc^2}{\hbar}\right)\left(\frac{mc^2}{\hbar}(\omega+\gamma\omega_1) - \beta\gamma\left(2 + \frac{mc^2}{\hbar}\omega_1\right)\right)}{\left(\beta\gamma - \frac{mc^2}{\hbar}\omega\right)\left(\beta - \frac{mc^2}{\hbar}\omega_1(1-\beta)\right)}.$$

Using the virtual photons methods we find the cross-section of the coherent bremsstrahlung from neutron :

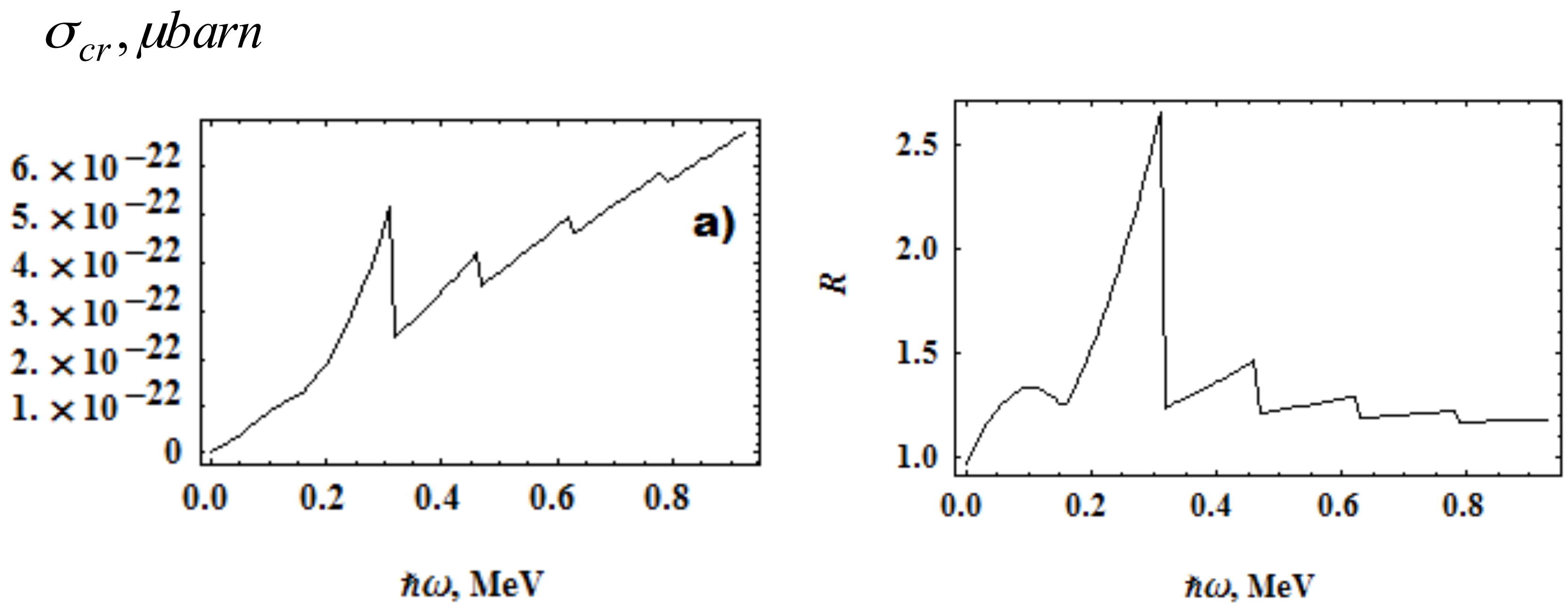
$$\sigma_{cr} = 2\int_{\omega_{MIN}}^{\omega_{MAX}} \sigma(\omega,\omega_1) n(\omega_1) d\omega_1$$

The limits of integration are determined by the condition $-1 \le \cos\Theta \le 1$

and equals

$$\omega_{MIN} = \frac{\omega}{\gamma + \beta\gamma + \frac{mc^2}{\hbar}\omega} \qquad \omega_{MAX} = \frac{\omega}{\gamma(1-\beta)}$$

Figure shows a cross-section of the coherent bremsstrahlung from neutron (Fig. a), and the ratio R of the coherent bremsstrahlung cross-section from the neutron to one of the radiation from neutron in an amorphous target containing the same number of atoms, as the axis of the crystal (Fig. b). Crystal tungsten oriented by axis <100>, the relativistic factor of the neutron $\gamma = 10$



# Conclusions

- Our calculations show that during the passage of neutrons through oriented crystals is possible the process of coherent bremsstrahlung. The value of the total cross-section of the coherent bremsstrahlung from neutron in a crystal can exceed the bremsstrahlung cross section in an amorphous target.

- More brighter coherent effects can be achieved in the study of the differential cross-section of coherent bremsstrahlung from neutron in the crystal.

# Thank you for attention