Spin effects for neutrinos and electrons moving in dense matter

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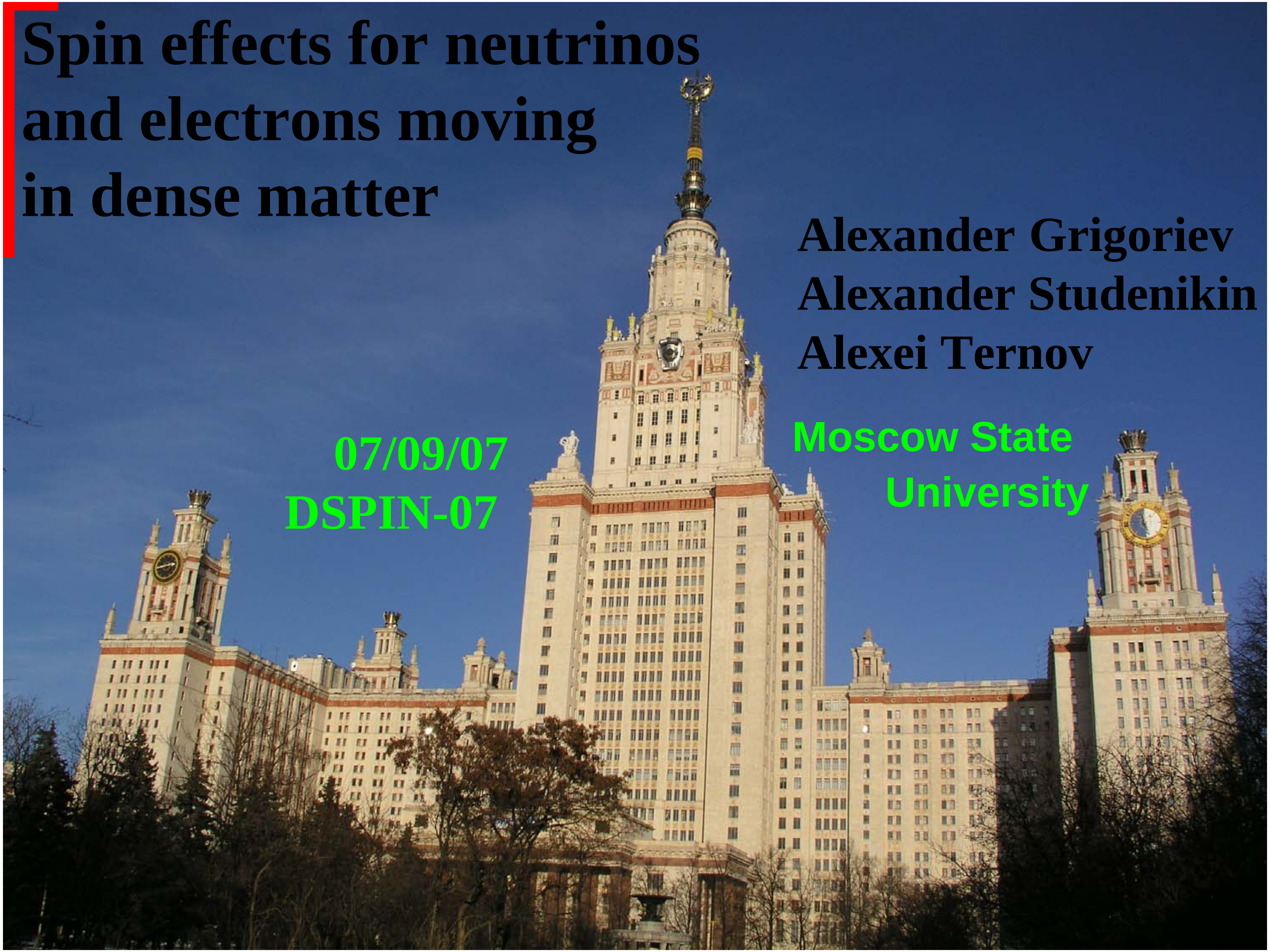
07/09/07
DSPIN-07



New mechanism of electromagnetic radiation

1. Spin light of ν in matter

Spin precession

2. Spin light of electron in matter

3. ν and e quantum states in matter

New approach to particles in matter

A.Studenikin,**J.Phys.A:Math.Gen.39**(2006)6769; **Ann.Fond. de Broglie 31** # 2-3 (2006)

A.Studenikin, **Phys.Atom.Nucl. 70** (2007) 1275; *ibid* **67** (2004)1014

A.Grigoriev, S.Shinkevich, A.Studenikin, A.Ternov, I.Trofimov, **Phys. J. 6** (2007) 66;

A.Grigoriev, A.Savochkin, A.Studenikin, **Phys. J. 8** (2007) 66;

A.Studenikin, A.Ternov, **Phys.Lett.B 608** (2005) 107

A.Grigoriev, A.Studenikin, A.Ternov, **Phys.Lett.B 622** (2005) 199;

Grav. & Cosm. 11 (2005) 132 **Phys.Atom.Nucl. 69** (2006)1940

K.Kouzakov, A.Studenikin, **Phys.Rev.C 72** (2005) 015502

M.Dvornikov, A.Grigoriev, A.Studenikin, **Int.J Mod.Phys.D 14** (2005) 309

S.Shinkevich, A.Studenikin, **Pramana 64** (2005) 124

A.Studenikin, **Nucl.Phys.B** (Proc.Suppl.) **143** (2005) 570

M.Dvornikov, A.Studenikin, **Phys.Rev.D 69** (2004) 073001

Phys.Atom.Nucl. 64 (2001) 1624

Phys.Atom.Nucl. 67 (2004) 719

JETP 99 (2004) 254 **JHEP 09** (2002) 016

A.Lobanov, A.Studenikin, **Phys.Lett.B 601** (2004) 171

Phys.Lett.B 564 (2003) 27

Phys.Lett.B 515 (2001) 94

A.Grigoriev, A.Lobanov, A.Studenikin, **Phys.Lett.B 535** (2002) 187

A.Egorov, A.Lobanov, A.Studenikin, **Phys.Lett.B 491** (2000) 137

ν **magnetic moment ?**

I.

R.N.Mohapatra, A.Y.Smirnov,

Neutrino mass and New Physics, **Ann.Rev.Nucl.Part.Phys. 56 (2006)**

“Recent discovery of
flavour conversion of
solar, atmospheric, reactor and accelerator
neutrinos have conclusively established that

neutrinos have nonzero mass

and they mix among themselves
much like quarks, providing the first evidence of
new physics beyond the standard model.”

Neutrino mass

$$m_\nu \neq 0 \; !$$

$\Longrightarrow$

Neutrino magnetic moment

$$\mu_\nu \neq 0 \; ? \; (!)$$

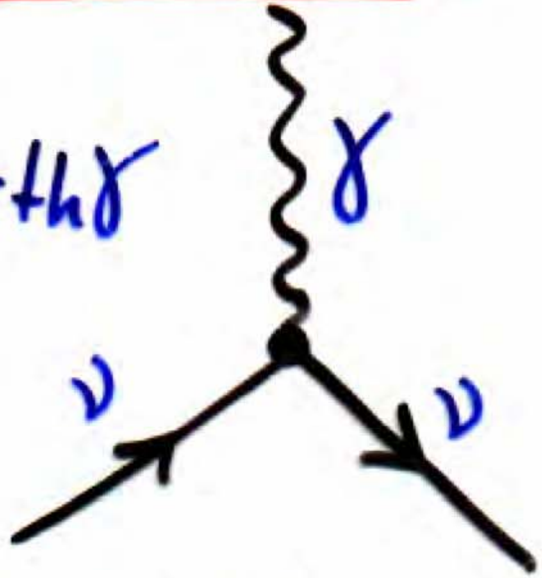
$\circledast$ Lee, Shrock 1977
Shrock, Fujikawa 1980

...Massive neutrino electromagnetic properties...

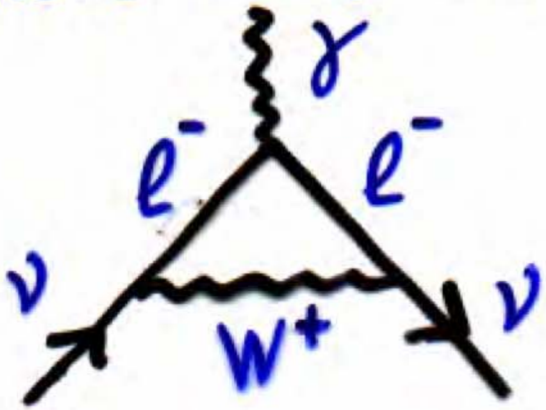
Electromagnetic

properties of ν

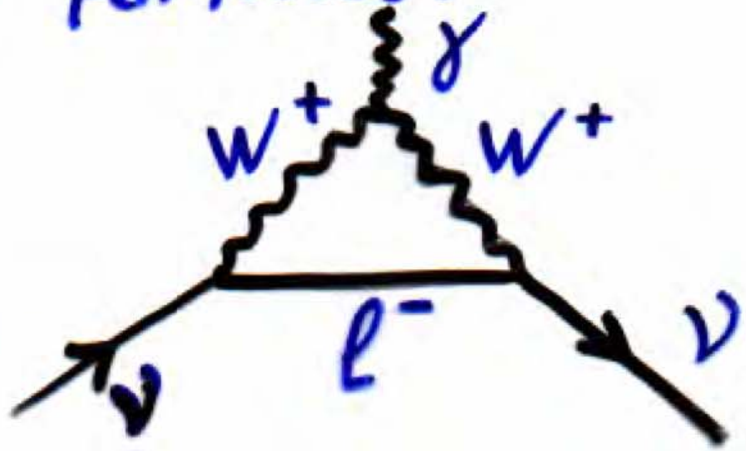
② Electromagnetic ν properties



$\underline{Q_\nu = 0}$ => interaction with γ entirely from loop effects through weak interactions with charged particles:



,



Theory (Standard Model with ν_R)

$$\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e} \sim 3\cdot 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1\,\mathrm{eV}}\right), \quad \mu_B = \frac{e}{2m_e}$$

Lee
Shrock, 1977; Fujikawa
Shrok, 1980

In the Standard Model : $m_\nu = 0$,

there is no ν_R $\Rightarrow$

ν magnetic moment $\mu_\nu = 0$.

Thus, $\mu_\nu \neq 0$ $\leftarrow$ beyond the SM .

The most general study of the

massive neutrino vertex function

(including electric and magnetic

form factors) in arbitrary R_ξ gauge

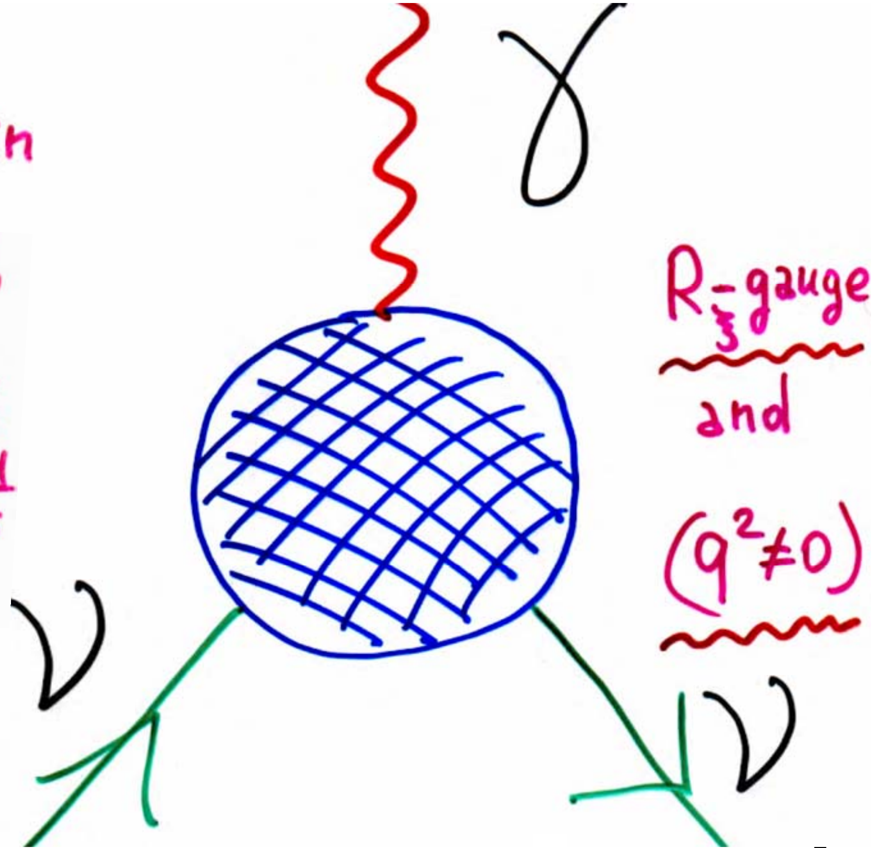
in the context of the SM + SU(2)-singlet

ν_R accounting for masses of particles

in polarization loops

M. Dvornikov, A. Studenikin

- Phys. Rev. D 63, 073001, 2004, "Electric charge and magnetic moment of massive neutrino";
- JETP 126 (2004), N8, 1 "Electromagnetic form factors of a massiv neutrino."



R_ξ-gauge and $(q^2 \neq 0)$

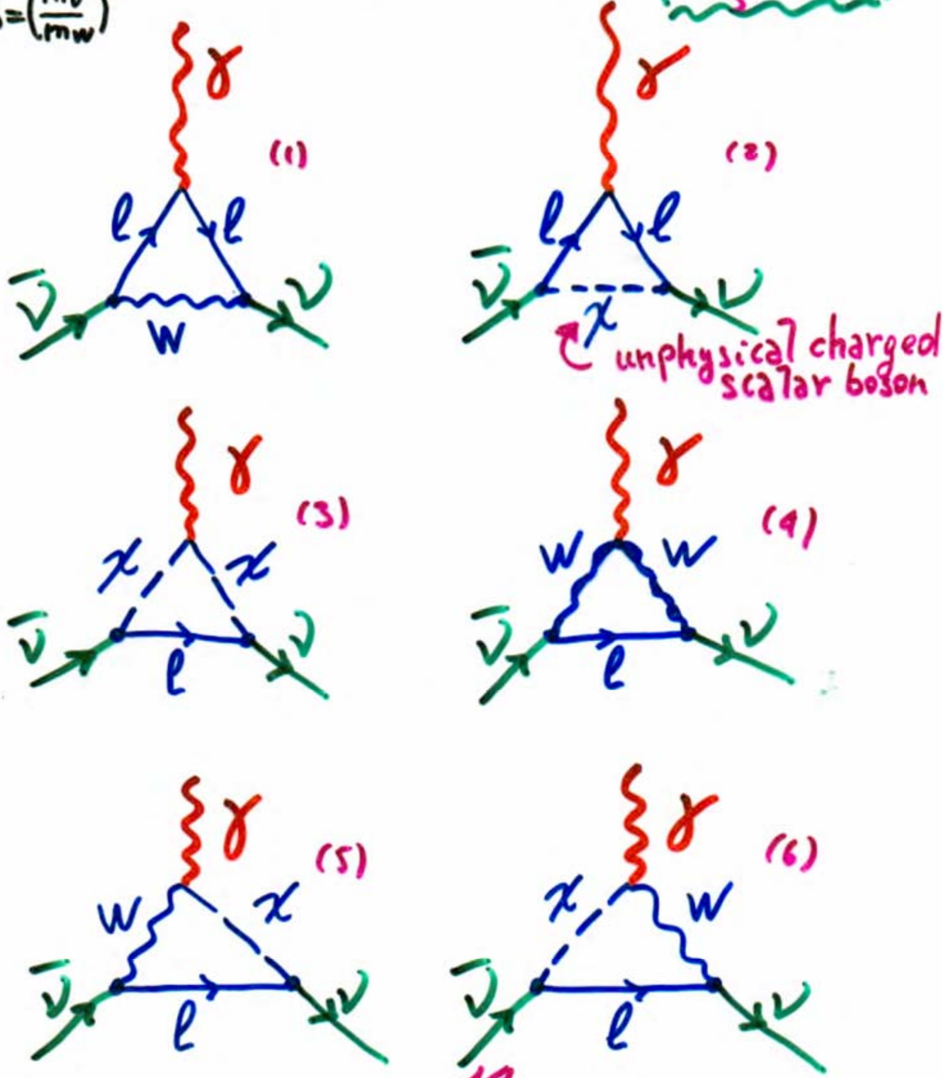
$$\Delta_\mu(q) = \underbrace{f_Q}_{\text{charge}}(q^2)\gamma_\mu + \underbrace{f_M}_{\text{magnetic moment}}(q^2)\, i\sigma_{\mu\nu} q^\nu - \underbrace{f_E}_{\text{electric moment}}(q^2)\, i\sigma_{\mu\nu} q^\nu \gamma_5 - \underbrace{f_A}_{\text{anapole moment}}(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

$a=\left(\frac{m_\ell}{m_W}\right)^2,$

$b=\left(\frac{m_\nu}{m_W}\right)^2$

Proper vertices

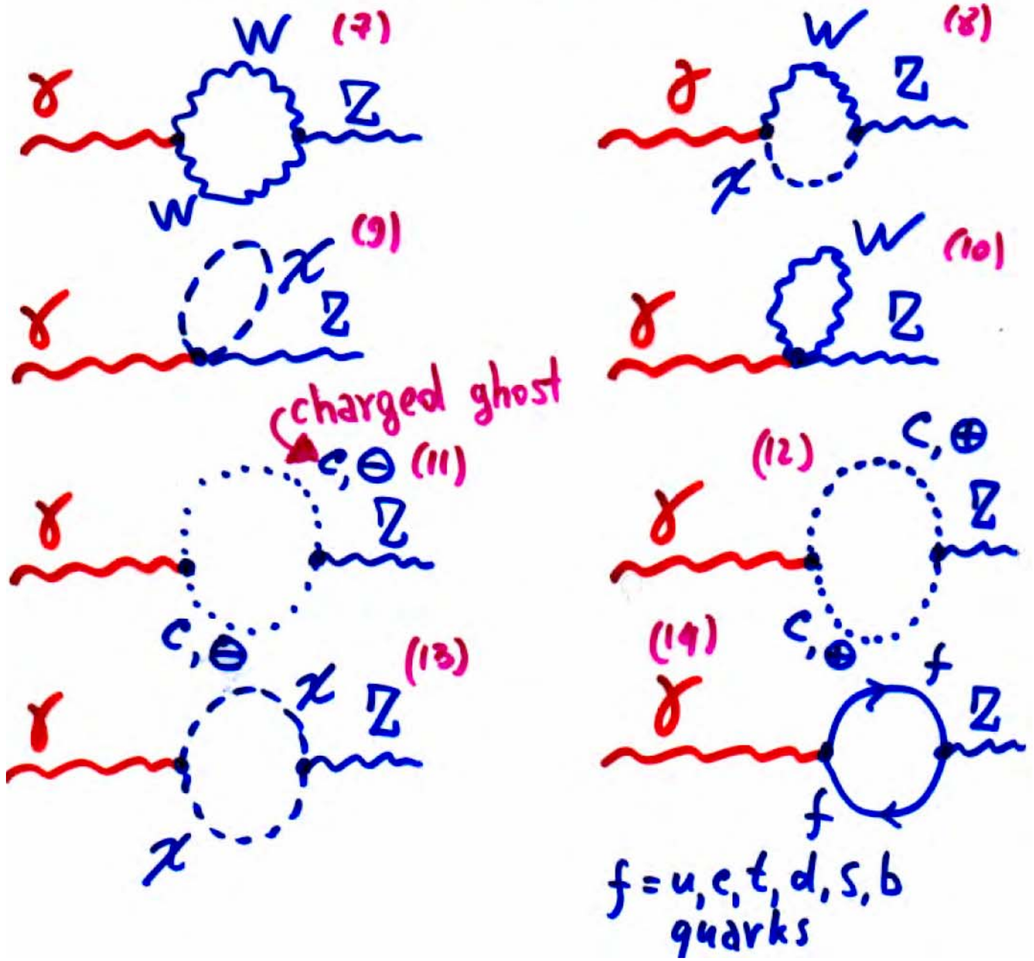
R_ξ-gauge



$$\Lambda_\mu(q) = \sum_{i=1}^{14} \Lambda^i_\mu(q)$$

$$\Lambda^{j}_{\mu}(q) = \frac{g}{2\cos\theta_W}\,\Pi^{(j)}_{\mu\nu}(q)\,\frac{1}{q^2 - M_Z^2}$$
$$\times\left\{ g^{\nu\alpha} - (1-\alpha_Z)\frac{q^\nu q^\alpha}{q^2 - \alpha_Z M_Z^2}\right\}\gamma_\alpha\,,\quad j = 7,\dots,14$$

γ-Z self-energy diagrams



$m_\nu \ll m_e \ll M_W$ **light** ν

$\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e}$

$$\boxed{\mu_\nu = \frac{eG_F}{4\pi^2\sqrt{2}} m_\nu \frac{3}{4(1-a)^3}(2 - 7a + 6a^2 - 2a^2 \ln a - a^3)}, \quad a = \left(\frac{m_e}{M_W}\right)^2$$

$m_e \ll m_\nu \ll M_W$ **intermediate** ν

$$\boxed{\mu_\nu = \frac{3eG_F}{8\pi^2\sqrt{2}} m_\nu \left\{1 + \frac{5}{18}b\right\}}, \quad b = \left(\frac{m_\nu}{M_W}\right)^2$$

M.Dvornikov,
A.Studenikin,
*Phys.Rev.**D*** **69** (2004)
073001;
JETP ***99*** (2004) 254

$m_e \ll M_W \ll m_\nu$ **heavy** ν

$$\boxed{\mu_\nu = \frac{eG_F}{8\pi^2\sqrt{2}} m_\nu}$$

Status of Experiments on the Neutrino Magnetic Moment Measurement

…stolen from the talk of
Alexander Starostin (*ITEP*)

given at the
13th Lomonosov Conference on
Elementary Particle Physics
(Moscow, August 23-29, 2007)

MUNU experiment at Bugey reactor (2005)

$$\boxed{\mu_\nu \leq 9 \times 10^{-11} \mu_B}$$

TEXONO collaboration at Kuo-Sheng power plante (2006)

$$\boxed{\mu_\nu \leq 7 \times 10^{-11} \mu_B}$$

μ_ν is presently known to be in the range

$$\boxed{10^{-20} \mu_B \leq \mu_\nu \leq 10^{-10} \mu_B}$$

μ_ν provides a tool for exploration possible physics beyond the Standard Model.

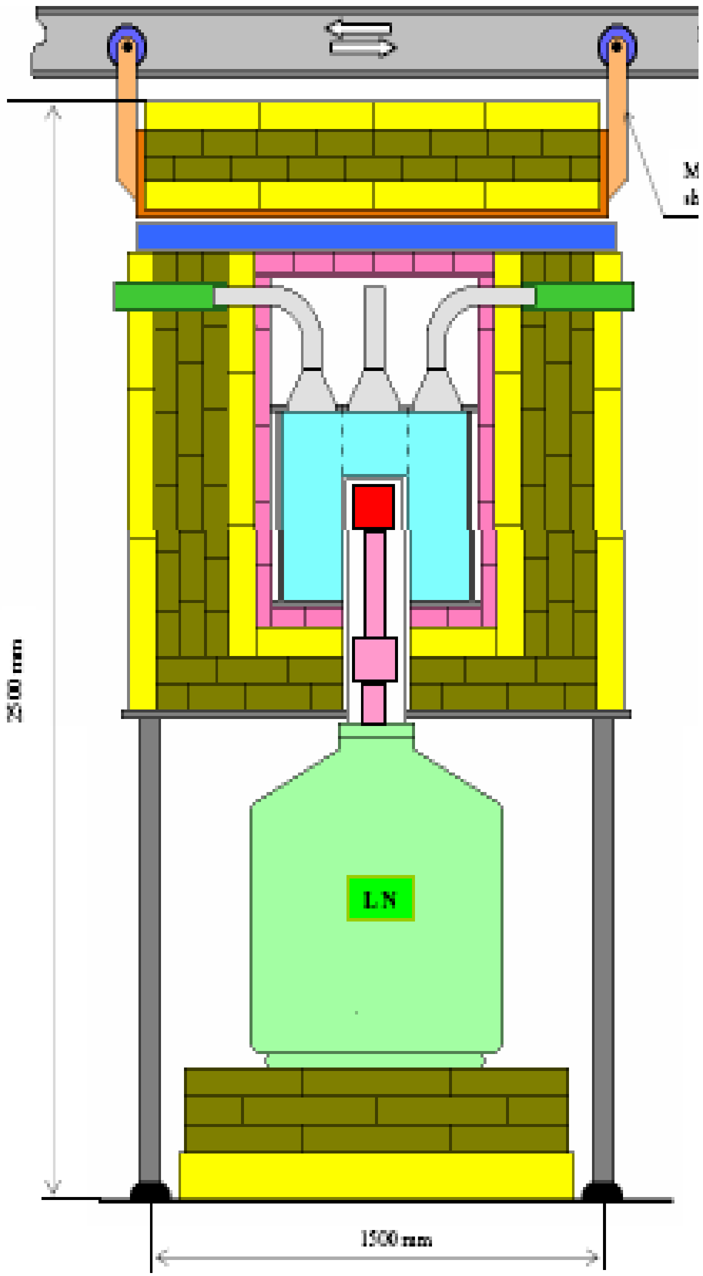
Experiment GEMMA

(**G**ermanium **E**xperiment for measurement of **M**agnetic **M**oment of **A**ntineutrino)

ITEP – LNP JINR Dubna

[Phys. of At.Nucl.,67,№11(2004)1948]

- Spectrometer includes a HPGe detector of 1.5 kg installed within NaI active shielding.
- HPGe + NaI are surrounded with multi-layer passive shielding – electrolytic copper, borated polyethylene and lead.
- Circuit noises were discriminated by means method of frequency analysis of signals.



Preliminary result of the 1st year

- (anti)neutrino magnetic moment:

  ! $\mu_\nu \leq 5.8 \cdot 10^{-11}\ \mu_B$ *(90% CL)* !

- *Available as* *hep-ex/0705.4576*

- Compared with the TEXONO experiment

  $\mu_\nu \leq 7.2 \cdot 10^{-11}\ \mu_B$ *(90% CL)*

Alexander Starostin, **talk given at**
13th Lomonosov Conference on Elementary Particle Physics,
Moscow State University, August 24, 2007

Main results of our previous studies

Spin oscillations

1994-1997 • $\nu_L \leftrightarrow \nu_R$ in $B_\perp$, $(B_{cr}=B_{cr}(\Delta m^2,\theta,\rho))$

1998-2000 $\nu_L \leftrightarrow \nu_R$ in arbitrary e.m. fields,

2000-2002 $\nu_L \leftrightarrow \nu_R$ in moving matter,

1995-2002 $\nu_e \leftrightarrow \nu_\mu$ in moving matter,

2003-2005 "spin light of neutrino" in matter and e.m. fields and gravitational fields

2004-2006… **quantum theory of neutrino motion in background matter**

NB !

These studies are performed within the Standard Model of interaction

ν *magnetic moment evolution in matter and external fields*

New effects: #1, #2, #3, #4

hep-ph/0407010,
A. Studenikin: Neutrino in electromagnetic fields and moving matter,
Phys. Atom. Nucl. 67 (N5) 1024, 2004.

The four new effects in neutrino oscillations,
Nucl.Phys.B (Proc.Suppl.) **143** (2005) 570

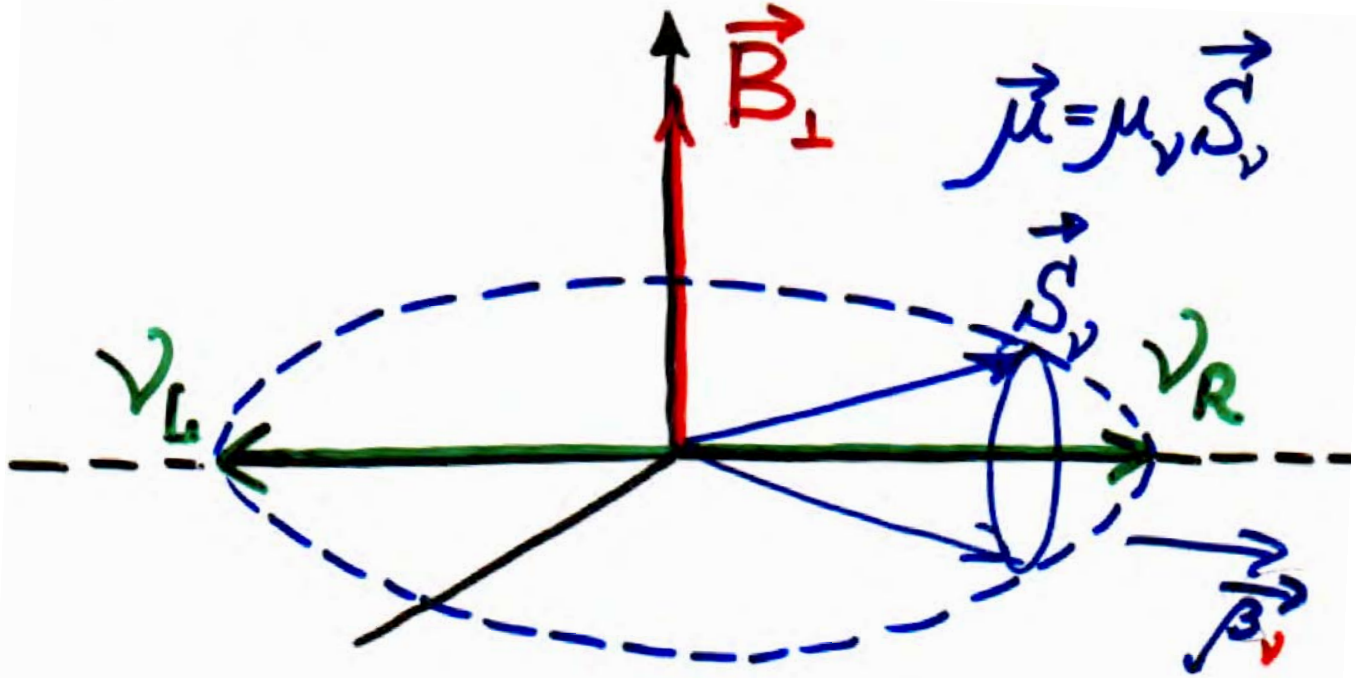
#1 Lorentz invariant approach to ν spin evolution in arbitrary e.m. field $F_{\mu\nu}$

(only $B_\perp$ was considered before) (*)

$\Longrightarrow$ predictions for new resonances in $\nu_L \leftrightarrow \nu_R$ in various configurations of e.m. fields (e.m. wave etc ...)

#2 ... matter effect included ...

ν spin precession can be stimulated not only by e.m. interactions with e.m. field $F_{\mu\nu}$ but also by ν weak interactions with matter!



$$\frac{d\vec{S}_\nu}{dt} = 2\mu_\nu[\vec{S}_\nu \times \underline{\underline{\vec{B}}}] + 2\mu_\nu[\vec{S}_\nu \times \vec{G}]$$

electromagnetic interacton with e.m. field

weak interaction with matter

ν spin evolution in presence of general external fields

M.Dvornikov, A.Studenikin,
JHEP 09 (2002) 016

General types non-derivative interaction with external fields

$$\boxed{\begin{aligned}-\mathcal{L} = g_s s(x)\bar{\nu}\nu + g_p \pi(x)\bar{\nu}\gamma^5\nu + g_v V^{\mu}(x)\bar{\nu}\gamma_{\mu}\nu + g_a A^{\mu}(x)\bar{\nu}\gamma_{\mu}\gamma^5\nu + \\ + \frac{g_t}{2}T^{\mu\nu}\bar{\nu}\sigma_{\mu\nu}\nu + \frac{g_t'}{2}\Pi^{\mu\nu}\bar{\nu}\sigma_{\mu\nu}\gamma_5\nu,\end{aligned}}$$

scalar, pseudoscalar, vector, axial-vector, tensor and pseudotensor fields:

$$s, \pi, V^{\mu} = (V^0, \vec{V}), A^{\mu} = (A^0, \vec{A}),$$
$$T_{\mu\nu} = (\vec{a}, \vec{b}), \Pi_{\mu\nu} = (\vec{c}, \vec{d})$$

Relativistic equation (quasiclassical) for ν spin vector:

$$\begin{aligned}\dot{\vec{\zeta}}_{\nu} = 2g_a \Big\{ A^0[\vec{\zeta}_{\nu} \times \vec{\beta}] - \frac{m_{\nu}}{E_{\nu}}[\vec{\zeta}_{\nu} \times \vec{A}] - \frac{E_{\nu}}{E_{\nu}+m_{\nu}}(\vec{A}\vec{\beta})[\vec{\zeta}_{\nu} \times \vec{\beta}] \Big\} \\ +2g_t \Big\{ [\vec{\zeta}_{\nu} \times \vec{b}] - \frac{E_{\nu}}{E_{\nu}+m_{\nu}}(\vec{\beta}\vec{b})[\vec{\zeta}_{\nu} \times \vec{\beta}] + [\vec{\zeta}_{\nu} \times [\vec{a} \times \vec{\beta}]] \Big\} + \\ +2ig_t' \Big\{ [\vec{\zeta}_{\nu} \times \vec{c}] - \frac{E_{\nu}}{E_{\nu}+m_{\nu}}(\vec{\beta}\vec{c})[\vec{\zeta}_{\nu} \times \vec{\beta}] - [\vec{\zeta}_{\nu} \times [\vec{d} \times \vec{\beta}]] \Big\}.\end{aligned}$$

- *Neither* s *nor* π *nor* V *contributes to spin evolution*

- **Electromagnetic interaction**

$$T_{\mu\nu} = F_{\mu\nu} = (\vec{E}, \vec{B})$$

- **SM weak interaction**

$$G_{\mu\nu} = (-\vec{P}, \vec{M}) \qquad \begin{aligned}\vec{M} &= \gamma(A^0\vec{\beta} - \vec{A}) \\ \vec{P} &= -\gamma[\vec{\beta} \times \vec{A}],\end{aligned}$$

#3 $\nu_L \leftrightarrow \nu_R$ and $\nu_\ell \leftrightarrow \nu_{\ell'}$, $\ell \neq \ell'$

(neutrino spin and flavour oscillations)

in moving and polarized matter

$\Longrightarrow$

matter motion can significantly change the neutrino oscillation pattern

#4

New mechanism of

e.m. radiation by ν in matter and e.m. fields, and gravitational fields

$$\boxed{\nu \xrightarrow[\text{environment}]{\text{background}} \nu + \gamma,}$$

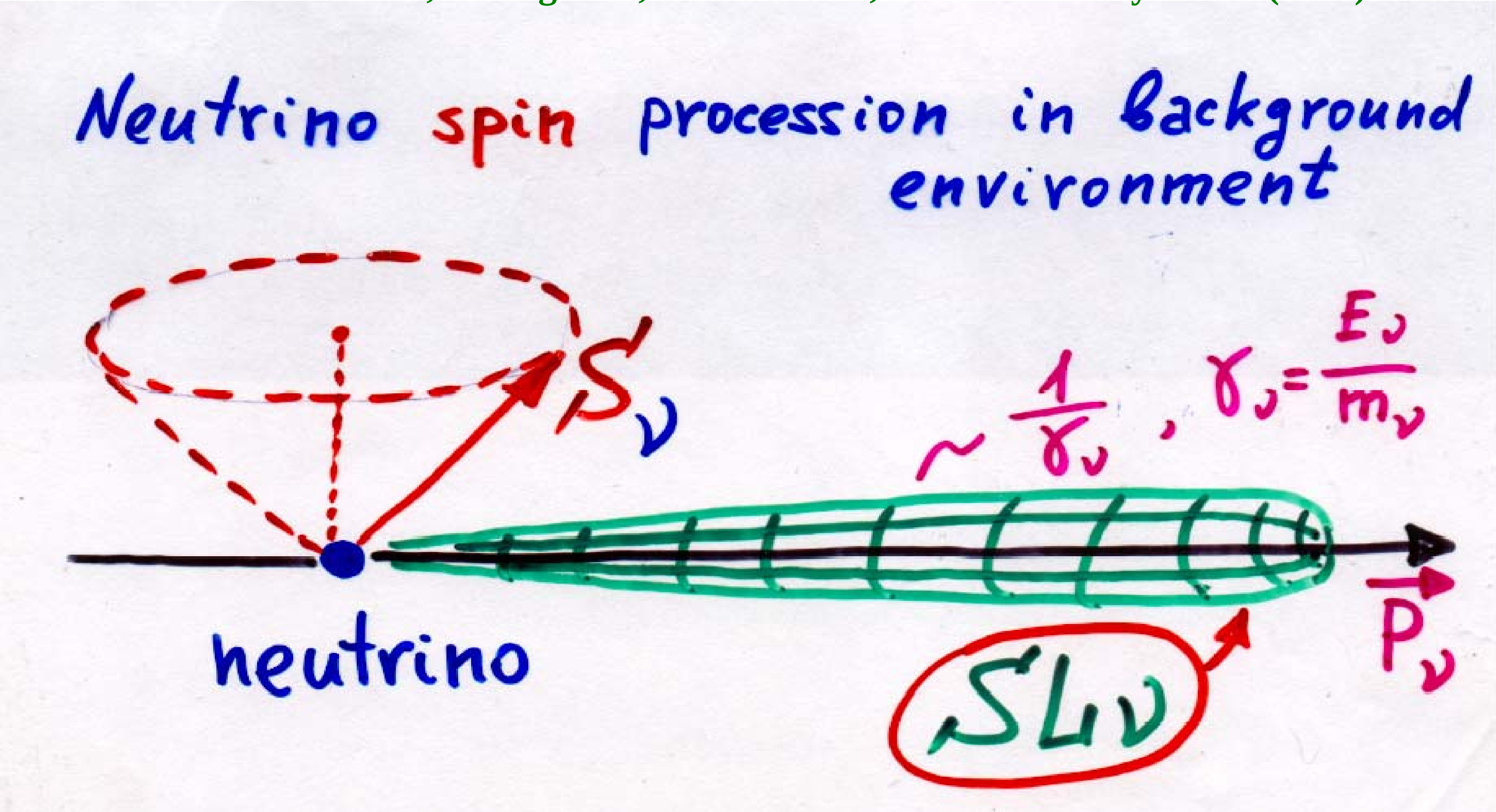
$\parallel$ "Spin Light of Neutrino": "$SL\nu$"

A.Lobanov, A.S., Phys.Lett.B 564 (2003) 27

Quasi-classical theory of spin light of neutrino in matter and gravitational field

$SL\nu$

A.Lobanov, A.Studenikin, Phys.Lett. B 564 (2003) 27,
Phys.Lett. B 601 (2004) 171;
M.Dvornikov, A.Grigoriev, A.Studenikin, Int.J.Mod.Phys. D 14 (2005) 309



Now we know:

#4 new mechanism of e.m. radiation by ν in matter (with or without e.m. field being superimposed)

– spin light of neutrino –

that must be important for

dense astrophysical (gamma-ray bursts) (SN,...)

cosmological (the early Universe)

environments.

…however !!!

… **Consistent approach to** $\boxed{SL\nu}$

A.S., "Neutrinos and electrons in background matter: a new approach", **Ann.Fond. de Broglie 31** (2006) no. 2-3

- We present a rather **powerful method** for description of **neutrinos** (and **electrons**) motion in **background matter** which implies the use of **modified Dirac equations** with effective matter potentials being included.

ν and e in matter being treated within the method of exact solutions of quantum wave equations -

«method of exact solutions »

A.Studenikin, A.Ternov,
Phys.Lett.B 608 (2005) 107;

hep-ph/0410297,
"Neutrino quantum states in matter";

hep-ph/0410296,
"Generalized Dirac-Pauli equation and neutrino quantum states in matter"

A.Grigoriev, A.Studenikin, A.Ternov,
Phys.Lett.B 608 622 (2005) 199

A.Studenikin,

J.Phys.A: Math.Gen.39 (2006) 6769;

Ann. Fond. de Broglie 31 (2006) no. 2-3,
"Neutrinos and electrons in background matter: a new approach"

Interaction of particles in external electromagnetic fields

(**Furry representation** in quantum electrodynamics)

$$e \xrightarrow{B_\perp} e + \gamma$$

synchrotron radiation

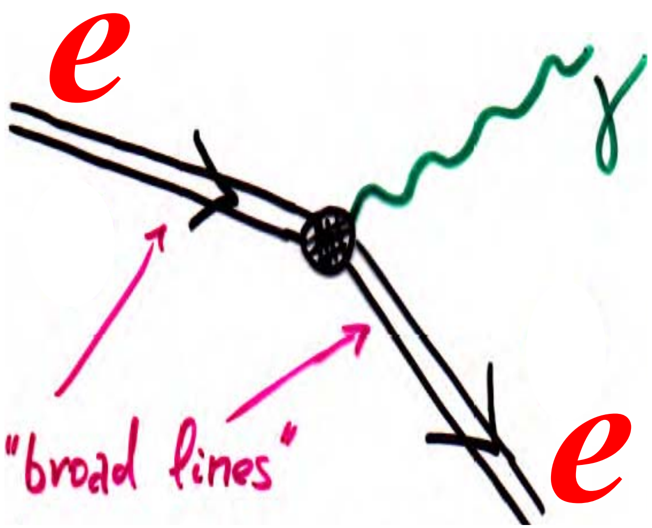
Potential of electromagnetic field

$$\boxed{A_\mu(x) = A^q_\mu(x) + A^{ext}_\mu(x)},$$

quantized part of potential

evolution **operator**

$$\boxed{U_F(t_1,t_2) = Texp\Big[-i\int_{t_1}^{t_2} j^\mu(x)A^q_\mu(x)dx\Big]},$$



charged particles **current** $\boxed{j_\mu(x) = \frac{e}{2}[\overline{\Psi}_F\gamma_\mu, \Psi_F]}$,

Dirac equation in **external classical (non-quantized) field** $A^{ext}_\mu(x)$

$$\boxed{\Big\{\gamma^\mu\Big(i\partial_\mu - eA^{ext}_\mu(x)\Big) - m_e\Big\}\Psi_F(x) = 0}$$

Modified **Dirac equations** for e and ν

(containing the correspondent effective matter potentials)

$$+$$

exact solutions (particles wave functions)

$$\Downarrow$$

a basis for investigation of different phenomena which can proceed when **neutrinos** and **electrons** move in dense media

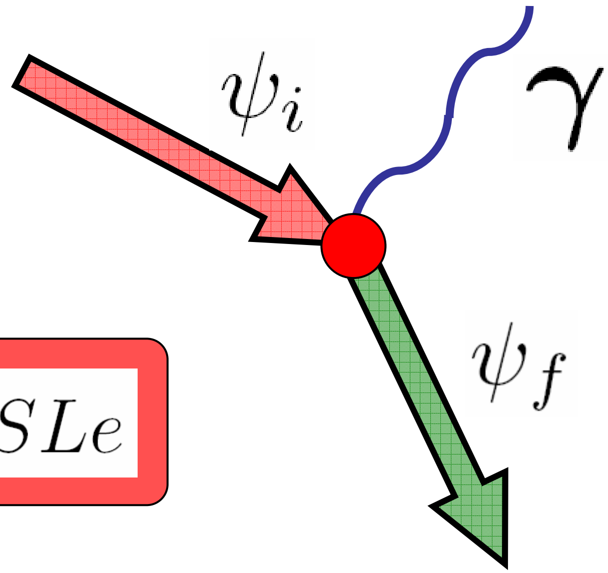
(**astrophysical** and **cosmological** **environments**).

2003-2004-2005

Spin light of neutrino in matter $\boxed{SL\nu}$

2005-2006

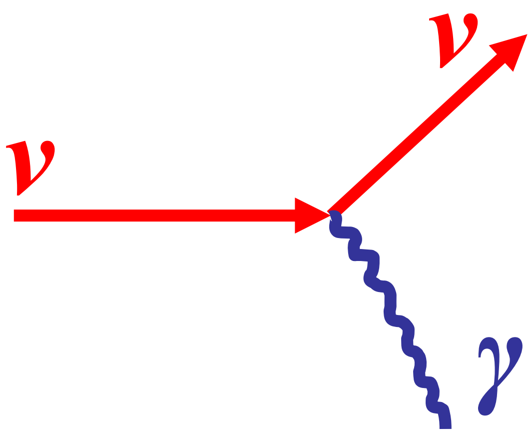
Spin light of electron in matter $\boxed{SLe}$



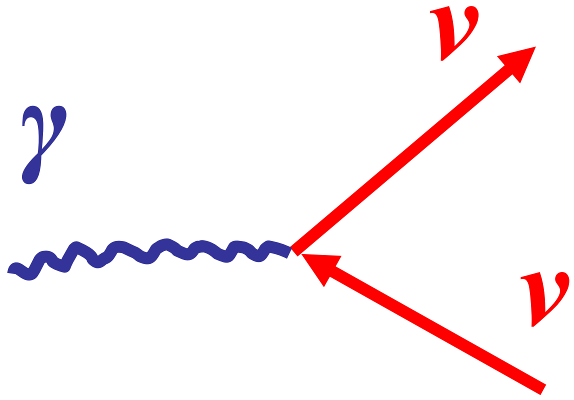
- We predict the existence of a **new mechanism** of the electromagnetic process stimulated by the presence of matter, in which a neutrino or electron due to spin precession can emit light.

New mechanism of electromagnetic radiation

Neutrino – photon couplings (I)

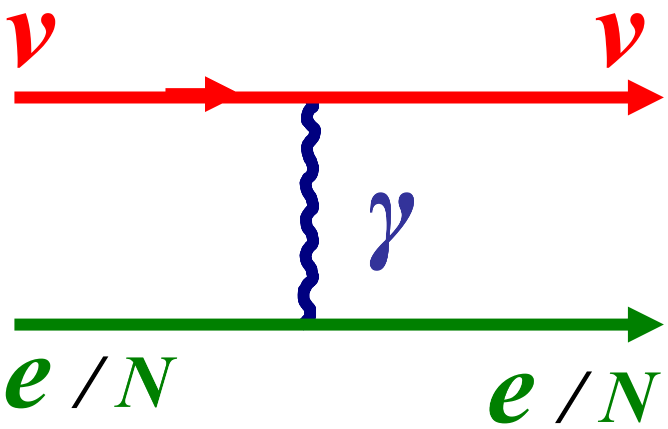


ν decay, Cherenkov radiation

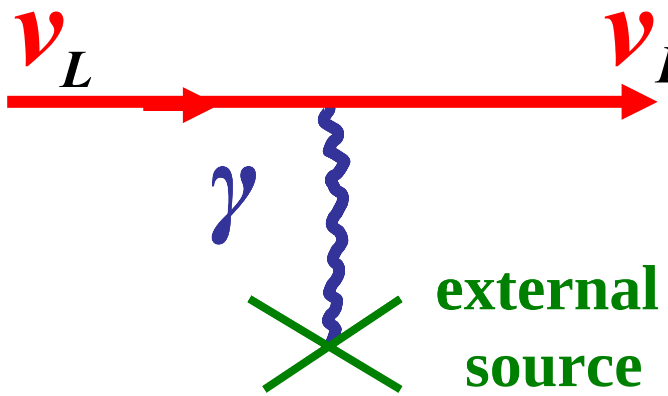


γ decay in plasma

!!!

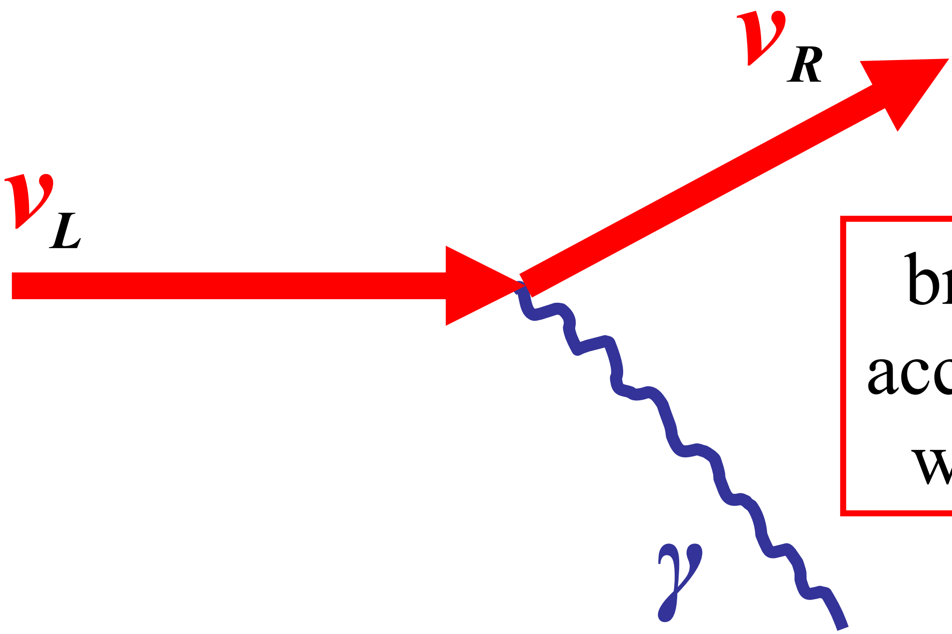


Scattering



Spin precession

Neutrino – photon couplings (II)



broad neutrino lines account for interaction with environment

"Spin light of neutrino in matter"

…within the quantum treatment…

Quantum treatment of neutrino in matter

A.Studenikin, J.Phys.A: Math.Gen 39 (2006) 6769

A.Grigoriev, A.Studenikin, A.Ternov, Phys.Atom.Nucl. 69 (2006) 1940

A.Studenikin, A.Ternov, Phys.Lett.B 608 (2005) 107

A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 622 (2005) 199

Grav. & Cosm. 11 (2005) 132

I.Pivovarov, A.Studenikin, PoS (HEP2005) 191

Standard model electroweak interaction of a flavour neutrino in matter ($f = e$)

Interaction Lagrangian (it is supposed that **matter contains only electrons**)

$$L_{int} = -\frac{g}{4\cos\theta_W}\left[\bar{\nu}_e\gamma^\mu(1+\gamma_5)\nu_e - \bar{e}\gamma^\mu(1-4\sin^2\theta_W+\gamma_5)e\right]Z_\mu$$

$$-\frac{g}{2\sqrt{2}}\bar{\nu}_e\gamma^\mu(1+\gamma_5)eW_\mu^+ - \frac{g}{2\sqrt{2}}\bar{e}\gamma^\mu(1+\gamma_5)\nu_e W_\mu^-$$

Charged current interactions contribution to neutrino potential in matter

$$\Delta L_{eff}^{CC} = \sqrt{2}\,G_F\left\langle \bar{e}\gamma^\mu(1+\gamma_5)e\right\rangle\left(\bar{\nu}_e\gamma^\mu\frac{1+\gamma_5}{2}\nu_e\right)$$

Neutral current interactions contribution to neutrino potential in matter

$$\Delta L_{eff}^{NC} = -\frac{G_F}{\sqrt{2}}\left\langle \bar{e}\gamma^\mu\left[(1-4\sin\theta_W^2)+\gamma_5\right]e\right\rangle\left(\bar{\nu}_e\gamma^\mu\frac{1+\gamma_5}{2}\nu_e\right)$$

Modified Dirac equation for neutrino in matter

Addition to the vacuum neutrino Lagrangian

$$\Delta L_{eff} = \Delta L_{eff}^{CC} + \Delta L_{eff}^{NC} = -f^{\mu}\Big(\bar{\nu}\gamma_{\mu}\frac{1+\gamma^5}{2}\nu\Big)$$

matter current

where $$f^{\mu} = \frac{G_F}{\sqrt{2}}\Big((1+4\sin^2\theta_W)j^{\mu} - \lambda^{\mu}\Big)$$

matter polarization

$$\boxed{\Big\{i\gamma_{\mu}\partial^{\mu} - \frac{1}{2}\gamma_{\mu}(1+\gamma_5)f^{\mu} - m\Big\}\Psi(x) = 0}$$

It is supposed that there is a macroscopic amount of electrons in the scale of a neutrino de Broglie wave length. Therefore, **the interaction of a neutrino with the matter (electrons) is coherent.**

L.Chang, R.Zia,'88; J.Panteleone,'91; K.Kiers, N.Weiss, M.Tytgat,'97-'98; P.Manheim,'88; D.Nötzold, G.Raffelt,'88; J.Nieves,'89; V.Oraevsky, V.Semikoz, Ya.Smorodinsky,89; W.Naxton, W-M.Zhang'91; M.Kachelriess,'98; A.Kusenko, M.Postma,'02.

A.Studenikin, A.Ternov, hep-ph/0410297;
***Phys.Lett.B* 608 (2005) 107**

This is the most general equation of motion of a neutrino in which the effective potential accounts for both the **charged** and **neutral-current** interactions with the background matter and also for the possible effects of the matter **motion** and **polarization**.

Stationary states

$$\Psi(\mathbf{r},t) = e^{-i(E_\varepsilon t - \mathbf{pr})}u(\mathbf{p},E_\varepsilon),$$

neutrino wave function in matter

and

$$E_\varepsilon = \varepsilon\sqrt{\mathbf{p}^2\Big(1 - s\alpha\frac{m}{p}\Big)^2 + m^2} + \alpha m$$

neutrino energy spectrum in matter

$s = \pm 1$ for two **helicity** states ,

where the **matter density parameter** $\alpha = \dfrac{1}{2\sqrt{2}}\tilde{G}_F\dfrac{n}{m}$,

J.Panteleone, 1991 (if NC interaction were left out)

$\dfrac{1}{2\sqrt{2}}\tilde{G}_F n \sim 1\ eV$ for $n = 10^{37}\ cm^{-3}$

density of matter in a neutron star

Neutrino energy in the background matter depends on the state of the neutrino longitudinal polarization (helicity), i.e. in the relativistic case the left-handed and right-handed neutrinos with equal momenta have different energies.

Neutrino wave function in matter (II)

$$\boxed{\Psi_{\varepsilon,\mathbf{p},s}(\mathbf{r},t)=\frac{e^{-i(E_\varepsilon t-\mathbf{pr})}}{2L^{\frac{3}{2}}}\begin{pmatrix}\sqrt{1+\frac{m}{E_\varepsilon-\alpha m}}\sqrt{1+s\frac{p_3}{p}}\\ s\sqrt{1+\frac{m}{E_\varepsilon-\alpha m}}\sqrt{1-s\frac{p_3}{p}}\;\;e^{i\delta}\\ s\varepsilon\eta\sqrt{1-\frac{m}{E_\varepsilon-\alpha m}}\sqrt{1+s\frac{p_3}{p}}\\ \varepsilon\eta\sqrt{1-\frac{m}{E_\varepsilon-\alpha m}}\sqrt{1-s\frac{p_3}{p}}\;\;e^{i\delta}\end{pmatrix}}$$

A.Studenikin, A.Ternov, hep-ph/0410297;
***Phys.Lett.B* 608 (2005) 107;**

$$\eta=\mathrm{sign}\left(1-s\alpha\frac{m}{p}\right),\;\delta=\arctan\left(p_2/p_1\right)$$

A.Grigoriev, A.Studenikin, A.Ternov,
***Phys.Lett.B* 622 (2005) 199**

$$\boxed{E_\varepsilon-\alpha m=\varepsilon\sqrt{\mathbf{p}^2\left(1-s\alpha\frac{m}{p}\right)^2+m^2}}$$

The quantity $\boxed{\varepsilon=\pm1}$ splits the solutions into the two branches that in the limit of **vanishing matter density,** $\boxed{\alpha\rightarrow0,}$ reproduce the **positive** and **negative-frequency** solutions, respectively.

Spin ***L***ight

of ***N***eutrino in matter

Quantum theory of $\boxed{SL\nu}$

- A.Studenikin, A.Ternov, *Phys. Lett.**B*** **608** (2005) 107;
- A.Grigoriev, A.Studenikin, A.Ternov, *Phys. Lett.**B*** **622** (2005) 199,
  hep-ph/0502231, hep-ph/0507200;
- A.Grigoriev, A.Studenikin, A.Ternov, *Grav. & Cosm.* **11** (2005) 132;

A.Grigoriev, A.Studenikin, A.Ternov, Phys.Atom.Nucl. 69 (2006) 1940,
hep-ph/0502210, hep-ph/0511311,
hep-ph/0511330;

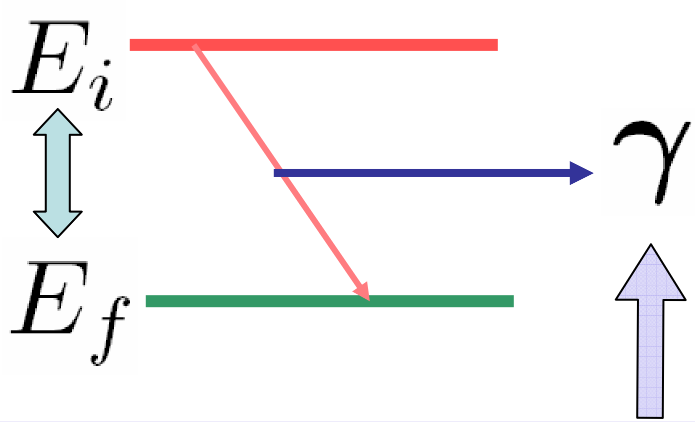
A.Studenikin, A.Ternov, hep-ph/0410296, hep-ph/0410297

Quantum theory of spin light of neutrino (I)

Quantum treatment of *spin light of neutrino* in matter shows that this process originates from the **two subdivided phenomena:**

$SL\nu$

- the **shift** of the neutrino **energy levels** in the presence of the background matter, which is different for the two opposite **neutrino helicity states**,



$$E = \sqrt{\mathbf{p}^2\left(1 - s\alpha\frac{m}{p}\right)^2 + m^2} + \alpha m$$

$$s = \pm 1$$

- the radiation of the photon in the process of the neutrino transition from the **"excited" helicity state** to the **low-lying helicity state** in matter

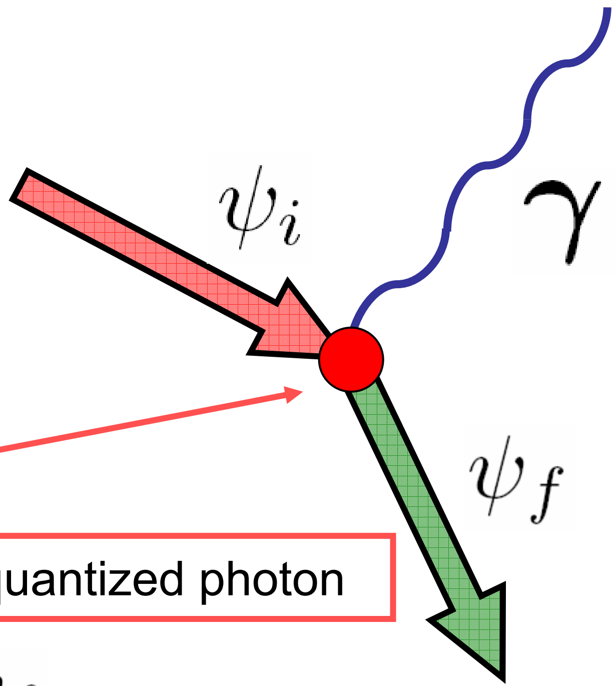
A.Studenikin, A.Ternov, Phys.Lett.B 608 (2005) 107;
A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 622 (2005) 199;
Grav. & Cosm. 14 (2005) 132;

hep-ph/0507200, hep-ph/0502210,
hep-ph/0502231

neutrino-spin self-polarization effect in the matter

A.Lobanov, A.Studenikin, Phys.Lett.B 564 (2003) 27;
Phys.Lett.B 601 (2004) 171

Quantum theory of spin light of neutrino $SL\nu$



Within the **quantum approach**, the corresponding Feynman diagram is the one-photon emission diagram with the initial and final neutrino states described by the **“broad lines”** that account for the neutrino interaction with matter.

Neutrino magnetic moment interaction with quantized photon

the amplitude of the transition $\psi_i \longrightarrow \psi_f$

$$\boxed{S_{fi} = -\mu\sqrt{4\pi}\int d^4x\bar{\psi}_f(x)(\hat{\mathbf{\Gamma}}\mathbf{e}^*)\frac{e^{ikx}}{\sqrt{2\omega L^3}}\psi_i(x)},$$

$$\boxed{\hat{\mathbf{\Gamma}} = i\omega\{[\mathbf{\Sigma}\times\boldsymbol{\varkappa}] + i\gamma^5\mathbf{\Sigma}\}},\qquad k^\mu = (\omega,\mathbf{k}),\ \boldsymbol{\varkappa} = \mathbf{k}/\omega \text{ momentum}$$

$\mathbf{e}^*$ polarization of photon

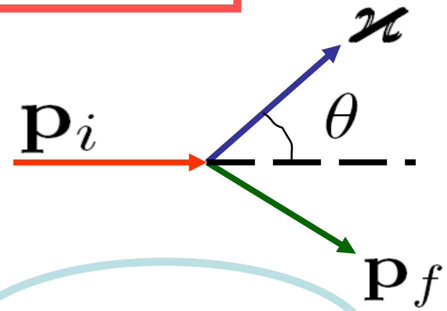
Spin light of neutrino photon's energy

$SL\nu$ transition amplitude after integration :

$$S_{fi} = -\mu\sqrt{\frac{2\pi}{\omega L^3}}\; 2\pi\delta(E_f - E_i + \omega) \int d^3x \bar{\psi}_f(\mathbf{r})(\hat{\mathbf{\Gamma}}\mathbf{e}^*)e^{i\mathbf{kr}}\psi_i(\mathbf{r})$$

Energy-momentum conservation

$$E_i = E_f + \omega, \qquad \mathbf{p}_i = \mathbf{p}_f + \boldsymbol{\varkappa}$$



For **electron neutrino** moving in matter composed of **electrons**

$$\alpha = \frac{1}{2\sqrt{2}}\tilde{G}_F \frac{n}{m} > 0$$

$$\omega = \frac{2\alpha m p_i\left[(E_i - \alpha m) - (p_i + \alpha m)\cos\theta\right]}{(E_i - \alpha m - p_i\cos\theta)^2 - (\alpha m)^2}$$

photon energy

- In the radiation process: $s_i = -1 \Rightarrow s_f = +1$ **neutrino self-polarization**
- For not very high densities of matter , $\tilde{G}_F n/m \ll 1$, in the linear approximation over α

$$\omega = \frac{\beta}{1 - \beta\cos\theta}\omega_0 \quad , \quad \omega_0 = \frac{\tilde{G}_F}{\sqrt{2}} n\beta$$

neutrino speed in vacuum

Spin light transition rate (III)

$SL\nu$

transition rate for different neutrino momentum p

and **matter density parameter** $\alpha = \frac{1}{2\sqrt{2}}\tilde{G}_F \frac{n}{m} > 0$

"relativistic" case

$\boxed{p \gg m}$

$$\Gamma = \begin{cases} \frac{64}{3}\mu^2\alpha^3 p^2 m, & \text{for } \alpha \ll \frac{m}{p}, \\ 4\mu^2\alpha^2 m^2 p, & \text{for } \frac{m}{p} \ll \alpha \ll \frac{p}{m}, \\ 4\mu^2\alpha^3 m^3, & \text{for } \alpha \gg \frac{p}{m}. \end{cases}$$

"non-relativistic" case

$\boxed{p \ll m}$

neutrino momentum

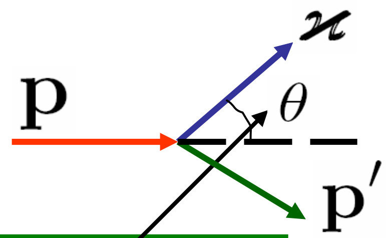
mass

$$\Gamma = \begin{cases} \frac{64}{3}\mu^2\alpha^3 p^3, & \text{for } \alpha \ll 1, \\ \frac{512}{5}\mu^2\alpha^6 p^3, & \text{for } 1 \ll \alpha \ll \frac{m}{p}, \\ 4\mu^2\alpha^3 m^3, & \text{for } \alpha \gg \frac{m}{p}. \end{cases}$$

neutrino magnetic moment

Spin light radiation power

$\boxed{SL\nu}$ radiation power angular distribution :



$$I = \mu^2 \int_0^{\pi} \omega^4 \left[(\tilde{\beta}\tilde{\beta}' + 1)(1 - y\cos\theta) - (\tilde{\beta} + \tilde{\beta}')(\cos\theta - y) \right] \frac{\sin\theta}{1 + \tilde{\beta}' y} d\theta$$

$$\tilde{\beta} = \frac{p + \alpha m}{E - \alpha m}, \quad \tilde{\beta}' = \frac{p' - \alpha m}{E' - \alpha m}, \quad y = \frac{\omega - p\cos\theta}{p'}, \quad K = \frac{E - \alpha m - p\cos\theta}{\alpha m}, \quad \omega = \frac{2\alpha m p\left[(E - \alpha m) - (p + \alpha m)\cos\theta\right]}{(E - \alpha m - p\cos\theta)^2 - (\alpha m)^2}$$

“relativistic” case

$\boxed{p \gg m}$

$$I = \begin{cases} \frac{128}{3}\mu^2\alpha^4 p^4, & \text{for } \alpha \ll \frac{m}{p}, \\ \frac{4}{3}\mu^2\alpha^2 m^2 p^2, & \text{for } \frac{m}{p} \ll \alpha \ll \frac{p}{m}, \\ 4\mu^2\alpha^4 m^4, & \text{for } \alpha \gg \frac{p}{m}. \end{cases}$$

“non-relativistic” case

$\boxed{p \ll m}$

$$I = \begin{cases} \frac{128}{3}\mu^2\alpha^4 p^4, & \text{for } \alpha \ll 1, \\ \frac{1024}{3}\mu^2\alpha^8 p^4, & \text{for } 1 \ll \alpha \ll \frac{m}{p}, \\ 4\mu^2\alpha^4 m^4, & \text{for } \alpha \gg \frac{m}{p}. \end{cases}$$

Spin light photon average energy

$$\langle\omega\rangle = \frac{\text{radiation power}}{\text{transition rate}} = \frac{I}{\Gamma}$$

See also:
A.Lobanov,
Phys.Lett.B 619
(2005) 136

"**relativistic**" case

$\boxed{p \gg m}$

$$\langle\omega\rangle \simeq \begin{cases} 2\alpha\frac{p^2}{m}, & \text{for } \alpha \ll \frac{m}{p}, \\ \frac{1}{3}p, & \text{for } \frac{m}{p} \ll \alpha \ll \frac{p}{m}, \\ \alpha m, & \text{for } \alpha \gg \frac{p}{m}. \end{cases}$$

"**non-relativistic**" case

$\boxed{p \ll m}$

$$\langle\omega\rangle \simeq \begin{cases} 2p\alpha, & \text{for } \alpha \ll 1, \\ \frac{10}{3}p\alpha^2, & \text{for } 1 \ll \alpha \ll \frac{m}{p}, \\ \alpha m, & \text{for } \alpha \gg \frac{m}{p}. \end{cases}$$

$\alpha \ll \frac{m}{p}$

$$\omega = 2.37 \times 10^{-7}\left(\frac{n}{10^{30}cm^{-3}}\right)\left(\frac{E}{m_\nu}\right)^2 eV.$$

energy range of $\boxed{SL\nu}$

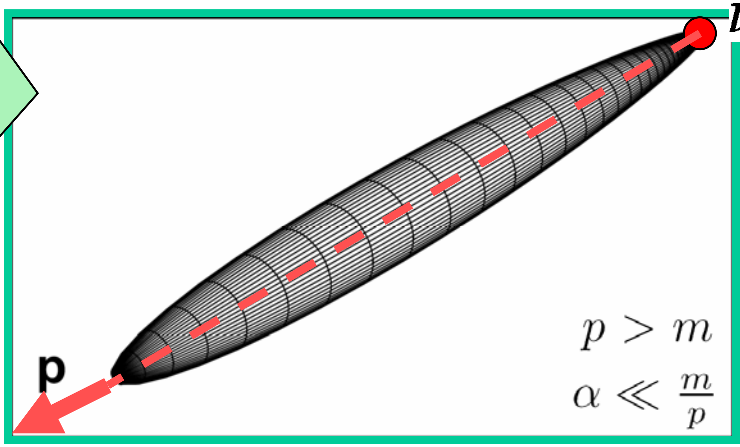
span up to

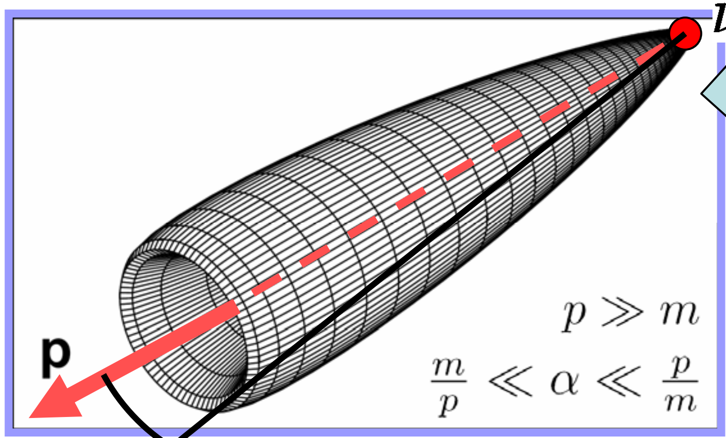
gamma-rays

Spatial distribution of radiation power

From the **angular distribution** of $SL\nu$

$$I = \mu^2 \int_0^\pi \omega^4 \left[(\tilde{\beta}\tilde{\beta}' + 1)(1 - y\cos\theta) - (\tilde{\beta} + \tilde{\beta}')(\cos\theta - y)\right] \frac{\sin\theta}{1 + \tilde{\beta}' y} d\theta$$





for $p/m = 5$ **and** $\alpha = 0.01$

$\boxed{n \approx 10^{35} cm^{-3}}$

neutrino momentum

mass

matter density

$$\cos\theta_{max} \simeq 1 - \frac{2}{3}\alpha\frac{m}{p}$$

maximum in radiation power distribution

for $p/m = 10^3$ **and** $\alpha = 100$

$\boxed{n \approx 10^{39} cm^{-3}}$

increase of matter density

projector-like distribution → **cap-like distribution**

Propagation of spin light photon in plasma

A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 622 (2005) 199; Grav. & Cosm. 14 (2005) 132

Only **photons** **with energy that exceeds** **plasmon frequency** can propagate in electron plasma.

$$\omega_{pl} = \sqrt{\frac{4\pi e^2}{m_e} n}$$

$e^2 = \alpha_{QED}$ **fine-structure constant**

The case of relativistic **neutrino** $p \gg m$
and rather dense **plasma** $\frac{m}{p} \ll \alpha \ll \frac{p}{m}$:

$$\omega_{max} \simeq p \quad \Longleftrightarrow \quad \omega(\theta_{max}) \simeq \frac{3}{4} p$$

maximal value of photon's energy

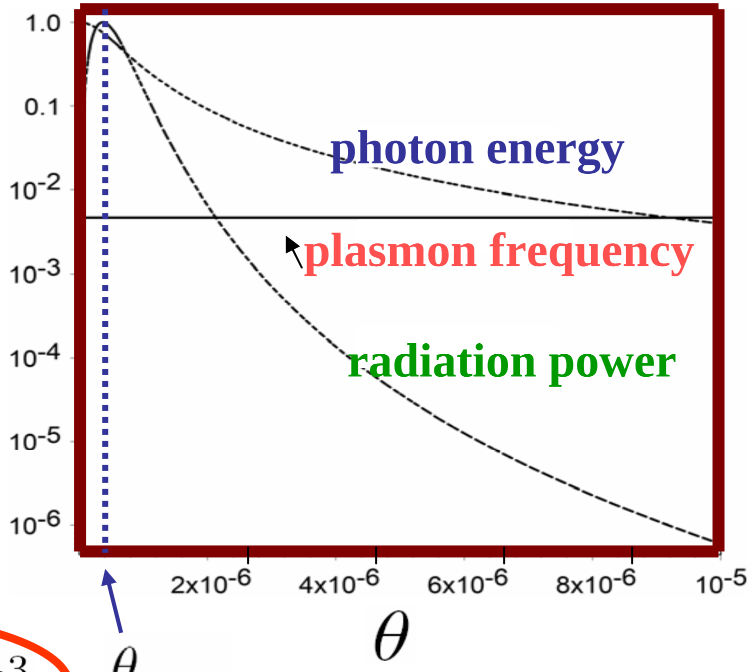
photon's energy in direction of radiation power maximum

$$\cos\theta_{\omega_{max}} = 1 \quad \Longleftrightarrow \quad \cos\theta_{max} \simeq 1 - \frac{2}{3}\alpha\frac{m}{p}$$

$$p \gg p_{min} = 3.5 \times 10^4 \left(\frac{n}{10^{30} cm^{-3}}\right)^{1/2} eV$$

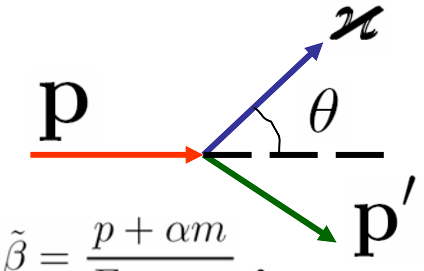
$p_{min} \sim 1\ MeV$ for $n \sim 10^{33}\ cm^{-3}$

Angular distributions of **photon energy** and **radiation power**



θ_{max}

Polarization properties of $SL\nu$ photons (II)



Radiation power of **circularly polarized** photons:

$$\boxed{I^{(l)} = \mu^2 \int_0^{\pi} \frac{\omega^4}{1+\beta' y} S_l \sin\theta d\theta}$$, $\tilde{\beta}' = \frac{p' - \alpha m}{E' - \alpha m}$, $\tilde{\beta} = \frac{p + \alpha m}{E - \alpha m}$,

$$y = \frac{\omega - p\cos\theta}{p'}, \quad K = \frac{E - \alpha m - p\cos\theta}{\alpha m},$$

$$\omega = \frac{2(E-\alpha m)(K\beta - 1)}{K^2 - 1}$$

where

$$\boxed{S_l = \frac{1}{2}(1 + l\beta')(1 + l\beta)(1 - l\cos\theta)(1 + ly)}$$

$l = \pm 1$ correspond to the photon **right** and **left circular polarizations** .

In the limit of **low matter density** $\alpha \ll 1$: $E_0 = \sqrt{p^2 + m^2}$

$$\boxed{I^{(l)} \simeq \frac{64}{3}\mu^2 \alpha^4 p^4 \left(1 - l\frac{p}{2E_0}\right)}, \quad I^{(+1)} > I^{(-1)}, \text{ however } I^{(+1)} \sim I^{(-1)} .$$

In **dense matter** $(\alpha \gg \frac{m}{p}$ for $p \gg m$, and $\alpha \gg 1$ for $p \ll m)$:

$$\boxed{\begin{array}{ccc} I^{(+1)} & \simeq & I \\ I^{(-1)} & \simeq & 0 \end{array}}$$

In a dense matter $SL\nu$ is right-circular polarized.

Experimental identification of $SL\nu$ from astrophysical and cosmological sources

A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 622 (2005) 199, **hep-ph/0507200**

- **Fireball model of GRBs** — **B.Zhang, P.Meszaros,** Int.J.Mod.Phys. **A19** (2004) 2385; **T.Piran,** Rev.Mod.Phys. **76** (2004) 1143.

- **Gamma-rays** can be expected to be produced during **collapses** or **coalescence** processes of neutron stars, owing to $\boxed{SL\nu}$ in dense matter.

- Another favorable situation for effective $\boxed{SL\nu}$ production can be realized during a **neutron star** being **"eaten up"** by the **black hole** at the center of our Galaxy .

For estimation, consider a neutron star with mass $M_{NS} \sim 3M_{\odot}$, $M_{\odot} = 2 \cdot 10^{33} g$

$\Rightarrow$ $n \sim 8 \cdot 10^{38}\ cm^{-3}$, matter density parameter $\alpha \sim 23$,

if $m_\nu \sim 0.1\ eV$.

Then for **relativistic neutrinos** $(p \gg m)$

the $\boxed{SL\nu}$ **photon energy** $\langle \omega \rangle \sim \frac{1}{3} p$ $\Leftarrow$ **totally polarized** **gamma-rays.**

It is possible to have $\tau = \dfrac{1}{\Gamma_{SL\nu}} <<$ age of the Universe ?

For ultra-relativistic ν

with momentum $p \sim 10^{20} eV$

and magnetic moment $\mu \sim 10^{-10}\mu_B$

in very dense matter $n \sim 10^{40} cm^{-3}$

from $\Gamma_{SL\nu} = 4\mu^2\alpha^2 m_\nu^2 p$

$p \gg m_{plasmon}$

recently also discussed by A.Kuznetsov, N.Mikheev, 2006

A.Lobanov, A.S., PLB 2003; PLB 2004
A.Grigoriev, A.S., PLB 2005
A.Grigoriev, A.S., A.Ternov, PLB 2005

$$\alpha m_\nu = \frac{1}{2\sqrt{2}} G_F n (1 + sin^2\theta_W)$$

it follows that

$$\tau = \frac{1}{\Gamma_{SL\nu}} = 1.5 \times 10^{-8} s$$

Spin Light

of Electron in matter

SLe

… a method of studying charged particles interaction in matter…

A.S.,
J.Phys.A: Math. Gen. 39 (2006) 6769

Grigoriev, Shinkevich, Studenikin, Ternov, Trofimov, hep-ph/0611128, Izv.Vuz.Fiz. # 6 (2007) 66.

Standard model electroweak interaction of an electron in matter (*e, p, n*)

Interaction Lagrangian (for **matter composed of electrons, protons and neutrons**)

$$L_{int} = -\frac{g}{4\cos\theta_W}\left[\bar{\nu}_e\gamma^\mu(1+\gamma_5)\nu_e - \bar{e}\gamma^\mu(1-4\sin^2\theta_W+\gamma_5)e\right]Z_\mu$$

Neutral current interactions contribution to electron potential in electrically neutral matter ($n_e = n_p$)

$$\Delta L^{(e)}_{eff} = -f^\mu\left(\bar{e}\gamma_\mu\frac{1-4\sin^2\theta_W+\gamma^5}{2}e\right),$$

where $$f^\mu = \frac{G_F}{\sqrt{2}}(-j_n^\mu + \lambda_n^\mu).$$

matter current

matter polarization

A.Studenikin, J.Phys.A: Math. Gen. 39 (2006) 6769

Modified Dirac equation for electron in matter

$$\left\{ i\gamma_\mu \partial^\mu - \frac{1}{2}\gamma_\mu (1 - 4\sin^2\theta_W + \gamma_5)\tilde{f}^\mu - m_e \right\} \Psi_e(x) = 0,$$

where $$\tilde{f}^\mu = -f^\mu = \frac{G_F}{\sqrt{2}}(j_n^\mu - \lambda_n^\mu)$$

matter polarization

matter current

It is suppose that there is a macroscopic amount of neutrons in the scale of an electron de Broglie wave length. Therefore, **the interaction of electron with the matter (neutrons) is coherent.**

This is the most general equation of motion of an neutrino in which the effective potential accounts for **neutral-current** interactions with the background electrically neutral matter and also for the possible effects of matter **motion** and **polarization**.

Quantum theory of spin light of electron (I)

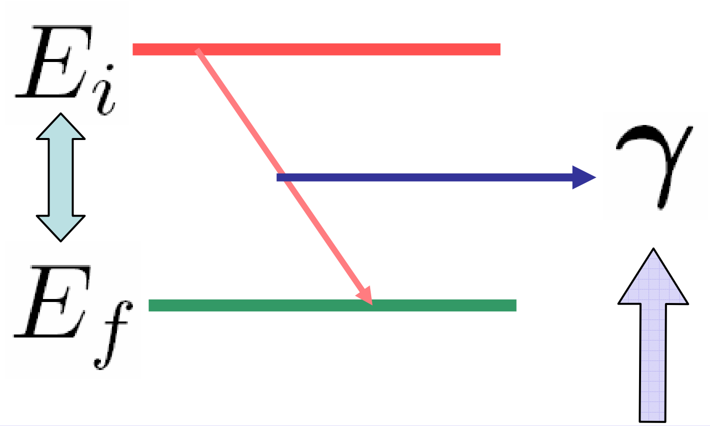
SLe

Spin light of electron in matter
originates from the **two subdivided phenomena:**

- the **shift** of the electron **energy levels** in the presence of the background matter, which is different for the two opposite electron helicity states,

$$E^{(e)}_{\varepsilon} = \varepsilon\sqrt{\mathbf{p}^2\left(1 - s\alpha_n\frac{m_e}{p}\right)^2 + m_e^2} + c\alpha_n m_e$$

$$s = \pm 1$$



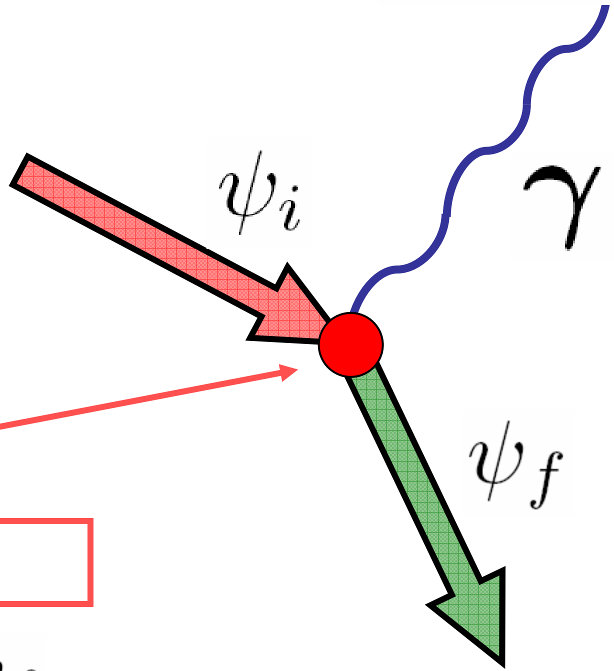
- the radiation of the photon in the process of the electron transition from the **"excited" helicity state** to the **low-lying helicity state** in matter

electron-spin self-polarization effect in the matter

A.S., J.Phys.A: Math. Gen. 39 (2006) 6769

Theory of spin light of electron SLe

The corresponding Feynman diagram is the one-photon emission diagram with the **initial** and **final** electron states described by the **“broad lines”** that account for the electron interaction with matter.



Electron interaction with quantized photon

the amplitude of the transition $\psi_i \longrightarrow \psi_f$

$$\boxed{S_{fi} = -ie\sqrt{4\pi}\int d^4x\bar{\psi}_f(x)\gamma^{\mu}e_{\mu}{}^{*}\frac{e^{ikx}}{\sqrt{2\omega L^3}}\psi_i(x)},$$

$k^{\mu} = (\omega, \mathbf{k})$, $\boldsymbol{\varkappa} = \mathbf{k}/\omega$ momentum

$\mathbf{e}^*$ polarization of photon

Order-of-magnitude estimation :

$$\boxed{R = \frac{\Gamma_{SLe}}{\Gamma_{SL\nu}} \sim \frac{e^2}{\omega^2\mu^2}} \quad ,$$

then for $\mu \sim 10^{-10}\mu_0$ **and** $\omega \sim 5\ MeV$

$$\boxed{R \sim 10^{18}} \quad ,$$

**A.S.,
J.Phys.A: Math. Gen.
39 (2006) 6769**

under these conditions $\boxed{SLe}$

is more effective than $\boxed{SL\nu}$

From exact calculations of $\boxed{SLe}$

$$n \sim 10^{37} \div 10^{40} \ \mathrm{cm}^{-3}$$
$$p \sim 1 \div 10^{3} \ \mathrm{MeV}$$
$$m_\nu = 1 \ \mathrm{eV}$$
$$\mu = 10^{-10}\mu_0$$

$$\Rightarrow$$

$$R_\Gamma = \frac{\Gamma_{SLe}}{\Gamma_{SL\nu}} \sim 10^{16} \div 10^{19}$$
$$R_\mathrm{I} = \frac{\mathrm{I}_{SLe}}{\mathrm{I}_{SL\nu}} \sim 10^{15} \div 10^{19}$$

Grigoriev, Shinkevich, Studenikin, Ternov, Trofimov, hep-ph/0611128, Izv.Vuz.Fiz. # 6 (2007) 66.

The developed approach to ν and e :

- **Modified Dirac equations** for neutrino and electron in **matter** (**background environment)**
- Exact solutions of **modified Dirac equations** in matter
  - **wave functions** and **energy spectra** in matter
- ***Spin light of neutrino*** in matter $\boxed{SL\boldsymbol{\nu}}$
  - transition **rate,** radiation **power,** photon **energy**
  - spatial angular **distribution** and **polarization**
- ***Spin light of electron*** in matter $\boxed{SLe}$

. . . Applications to astrophysics and cosmology ?

New mechanism of electromagnetic radiation

? Why **Spin Light** of neutrino $SL\nu$ / of electron SLe in matter.

Analogies with:

* classical electrodynamics

an object with charge $Q=0$ and magnetic moment $\vec{m} = \frac{1}{2}\sum_i e_i [\vec{r}_i \times \vec{v}_i] \neq 0$

$$\boxed{I^{cl.el.} = \frac{2}{3}\ddot{\vec{m}}^{\,2}}$$

magnetic dipole radiation power