The 9th APCTP-BLTP JINR Joint Workshop in Kazakhstan
Modern Problems in Nuclear and Elementary Particle Physics
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Collaborators

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Jaewon Shin, Gil-Seok Yang, C-Y. Ryu (Soongsil U y) ....

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Origin of Matter

K. Tsushima (IIP, Brazil), K. Saito (TSU)
G. Mathews (Notre Dame), Baha Ballantekin (Wisconsin),
Alex Brown (MSU)
T. Kajino (NAOJ), Ko Nakamura (Waseda)
T. Maruyama (Nihon Univ.), T. Hayakawa (JAEA), S. Chiba
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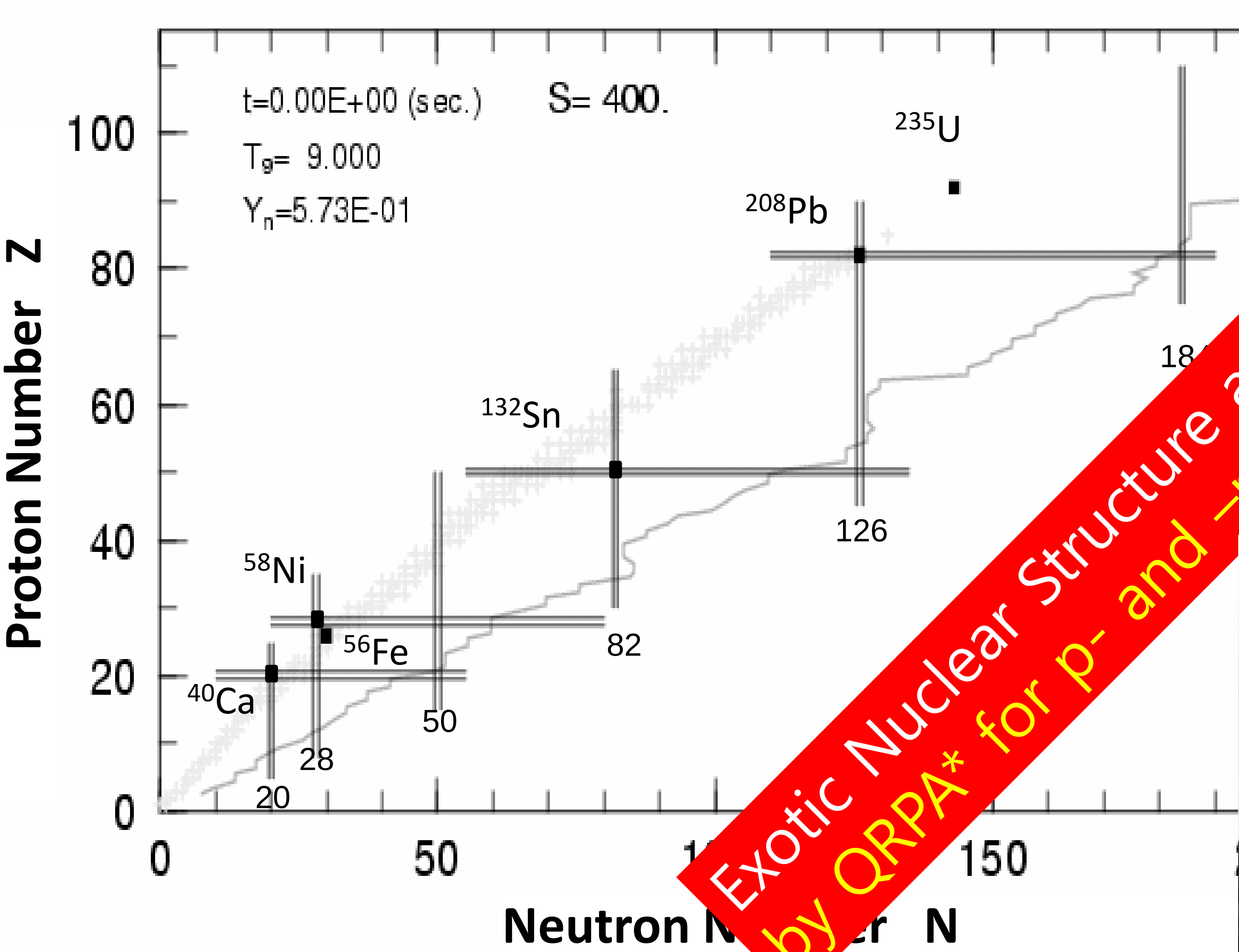
Supernova Nucleosynthesis in Neutrino-Driven Winds

Movie by Chiba, Koura & Kajino



Exotic Nuclear Structure and Reactions
by QRPA* for p- and –nu processes

HFB

Collaborators

Eunja Ha, **Y. S. Kw**...ai, **T. Miyatsu**, M. Kusakabe,
Jaewon Shin, Gil-... (Soongsil University)
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T. Miyatsu, MKC, K. Saito, PRC 88, 015802

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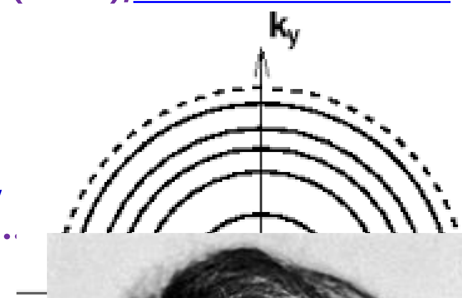
C. Deliduman...
A. Faessler (Tu... ...

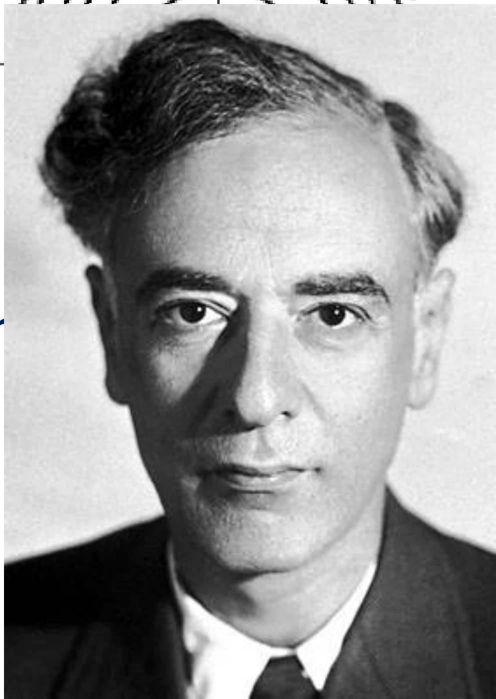
Dense Matter Physics
by RMF* (CQMC + Fock + pairing)

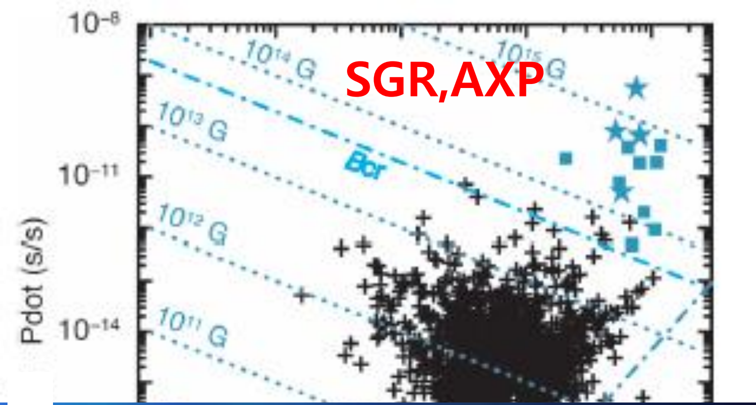
Strong Magnetic Field Physics : SMaF Physics

...rsity

Contents







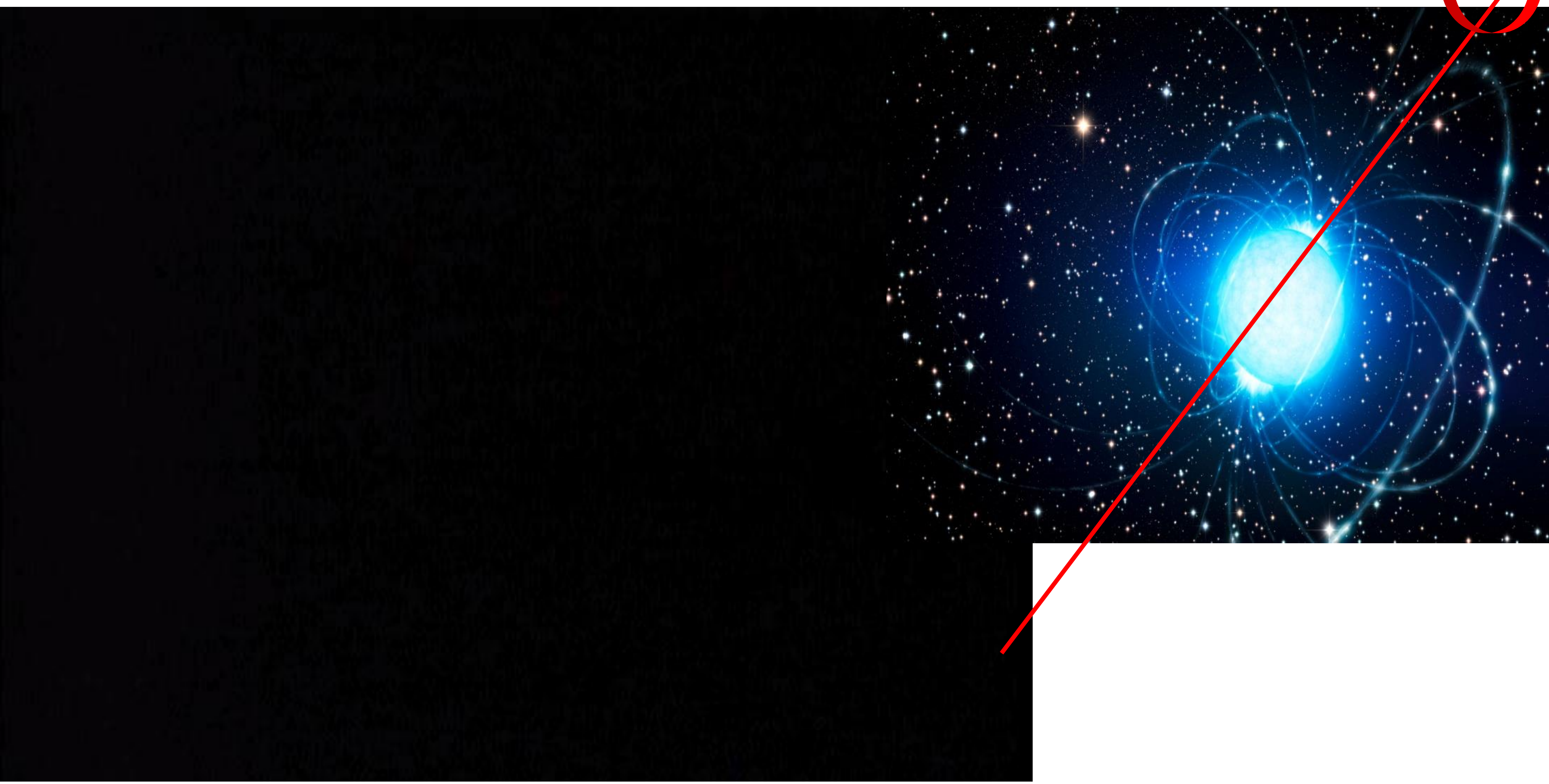
High Density Matter Study

⇒ Exotic Phases : Strange Matter, Ferromag

Meson Condensation, Quar

Courtesy by T. Maruyama

Pulsar Kick and Spin Deceleration of Neutron Stars **(Magnetar)** in Supernovae Explosion



Contents

Lagrangian with SmaF

Magnetic Field : $\vec{B} = B\hat{z}.$

$$\text{Lagrangian}: \mathcal{L} = \mathcal{L}_{RMF} + \mathcal{L}_{lep.} + \mathcal{L}_{mag}$$

Baryon | **Lepton** | B & L – Mag.

Dirac Equation under SmaF

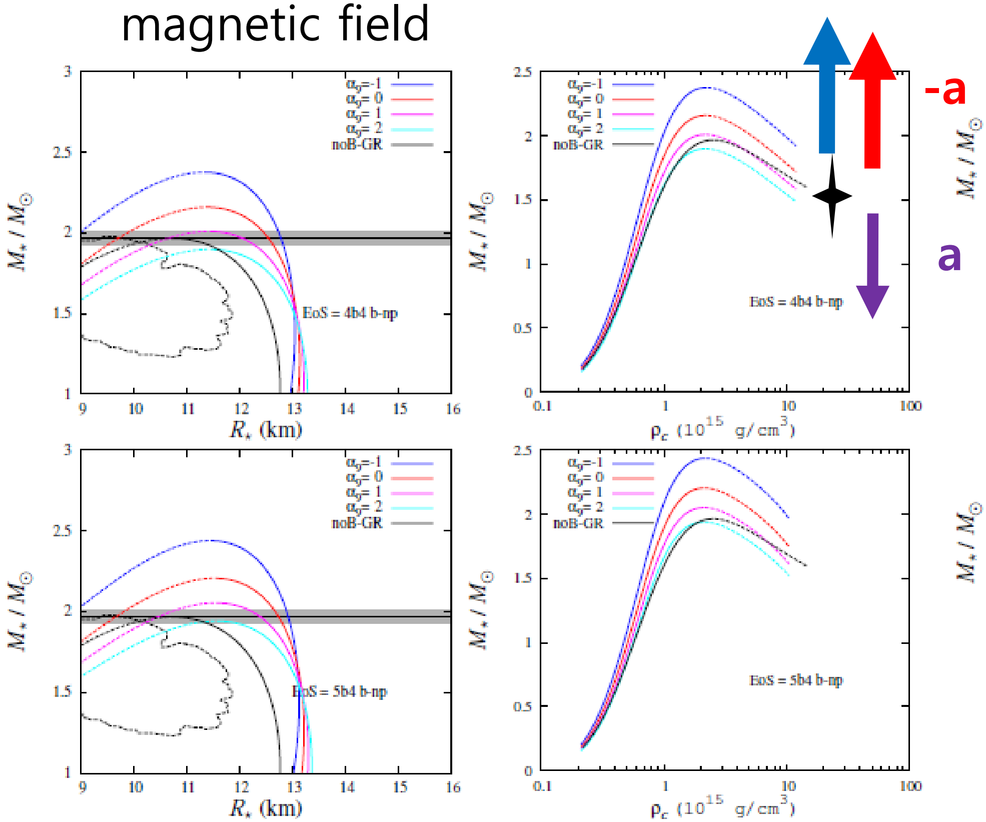
$\mu_N B \ll \varepsilon_N$ (Chem. Pot) $\rightarrow$ *B* can be treated perturbatively

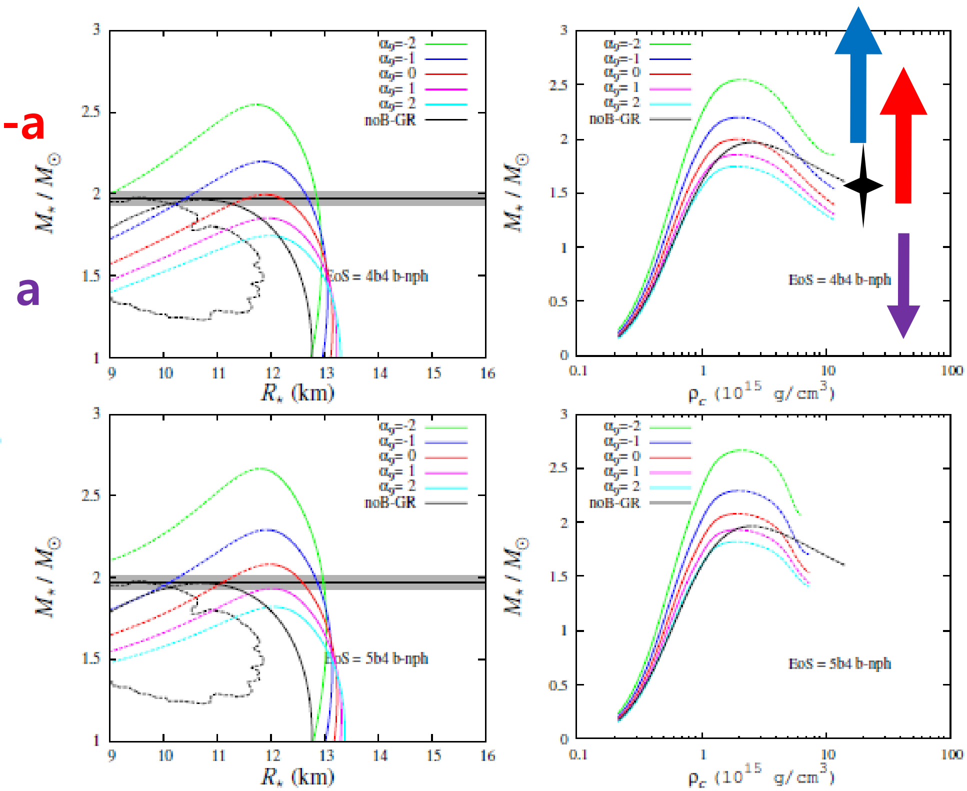
$B \sim 10^{17}$ G Landau Level can be ignored

Eq. of State Results by MTOV and Strong Magnetic fields

MKC et.al, JCAP (2013)

In np and nph phase with stronger magnetic field





$$B(\rho/\rho_0) = B^{surf} + B_0\left[1 - \exp\{-\alpha(\rho/\rho_0)^\beta\}\right]$$

the Kaluza–Klein action expands into:

$$\mathcal{R} \to f(R) = R - \alpha|F|^2 \ ,$$

$\alpha_9 \equiv \alpha/10^9\,\mathrm{cm}^2 = -2, -1, 0, 1, 2$ in the $f(R) = R + \alpha R^2$ gravity.

PRD 91, 104923 (2015)

For stronger m. field, we obtain more stiffer EOS and more massive Masses !! May **compensate modified gravity (alpha >0).**

Lagrangian with SmaF + Neutrinos

Magnetic Field : $\vec{B} = B\hat{z}.$

$$\text{Lagrangian} : \mathcal{L} = \mathcal{L}_{RMF} + \mathcal{L}_{lep.} + \mathcal{L}_{mag} + \mathcal{L}_{int}$$

Baryon

Lepton

B & L – Mag.

$$
\begin{aligned}
\hat{K}(p) &= \not{p} - M^* - \mu B \sigma_z \\
&= \begin{pmatrix}
p_0 - M^* - \mu B & 0 & -p_z & -p_x \\
0 & p_0 - M^* + \mu B & -p_x & p_z \\
p_z & p_x & -p_0 - M^* - \mu B & 0 \\
p_x & -p_z & 0 & -p_0 - M^* + \mu B
\end{pmatrix}
\end{aligned}
$$

When $\mu B << 1$,

$$
S(p) = \sum_{s=\pm 1} \left\{ \frac{u(\boldsymbol{p}, s)\bar{u}(\boldsymbol{p}, s)}{p_0 - e(\boldsymbol{p}, s) + i\delta} + \frac{v(-\boldsymbol{p}, s)\bar{v}(-\boldsymbol{p}, s)}{p_0 + e(\boldsymbol{p}, s) - i\delta} \right\} = \left[\hat{K}(p)\right]^{-1}
$$

$$
\begin{aligned}
u(\boldsymbol{p}, s)\bar{u}(\boldsymbol{p}, s) &= \left[(p_0 - e(\boldsymbol{p}, s))S(p))\right](p_0 = e(\boldsymbol{p}, s)) \\
&\approx \frac{(\not{p} + M)(1 + \gamma_5 \not{a}(p) s)}{4E_p^*} + \frac{\mu B p_z}{4E_p^*}(\sigma \cdot \boldsymbol{p} - M^* \gamma_5 \gamma_0) .
\end{aligned}
$$

negligibly small

Dirac Spinor

$$
a_z = \frac{E_p^*}{\sqrt{p_T^2 + M^{*2}}} \qquad \boldsymbol{a}_T = 0 \qquad a_0 = \frac{p_z}{\sqrt{p_T^2 + M^{*2}}}
$$

Spin Vector

X-section of Lepton-Baryon Scattering

$$\frac{d^2\sigma}{dk' d\Omega'_k} = \frac{G_F^2}{8\pi^2}\boldsymbol{k}'^2 \sum_{s_i, s_f} \int \frac{d^3p}{(2\pi)^3} \tilde{W}_{BL} (2\pi)\delta(|\boldsymbol{k}| - |\boldsymbol{k}'| + e_i(\boldsymbol{p}) - e_f(\boldsymbol{k} + \boldsymbol{p} - \boldsymbol{k}'))$$
$$\times [1 - f'_l(\boldsymbol{k}')] n_B(e_i)[1 - n_{B'}(e_f)]$$

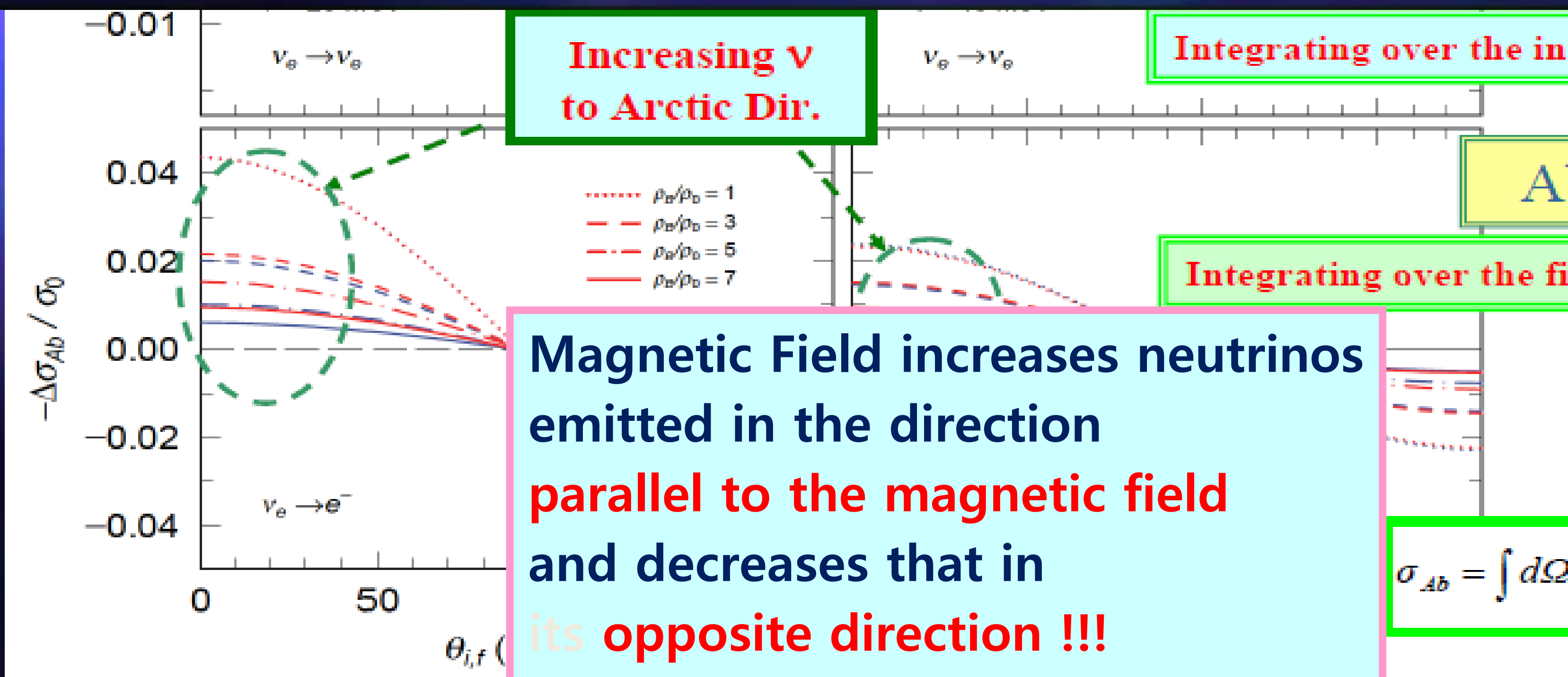
$$\tilde{W}_{BL} = \mathrm{Tr}\left\{ \frac{(\not{k}' + m_f)(1 + \gamma_5 \not{a}_{l'})}{4|\boldsymbol{k}'|} \gamma^\mu (1 - \gamma_5) \frac{\not{k}'}{2|\boldsymbol{k}|} \gamma^\nu (1 - \gamma_5) \right\}$$
$$\times \mathrm{Tr}\left\{ \frac{(\not{p}' + M_f^*)(1 + \gamma_5 \not{a}_f(p'))}{4E_f^*(\boldsymbol{p}')} \gamma_\mu (c_V - c_A \gamma_5) \frac{(\not{p} + M_i^*)(1 + \gamma_5 \not{a}_i(p))}{4E_i^*(\boldsymbol{p})} \gamma_\nu (c_V - c_A \gamma_5) \right\}$$

$$m_f = 0 \quad \text{when } l_f = \nu \qquad m_f = m_e \quad \text{when } l_f = e$$

Results — Scattering and absorption X-sections

Magnetic parts of Cross-Sections

$$\sigma = \sigma_0 + \Delta\sigma \qquad \Delta\sigma \propto B$$



$$\sigma_{Ab} = \int d\Omega_f \frac{d\sigma(\nu_e \to e)}{d\Omega_f}$$

Magnetic Field increases neutrinos emitted in the direction
parallel to the magnetic field
and decreases that in its opposite direction !!!

PRD 86 (2012) 123003 ; PRD83 (2011) 081303(R);
PRC89 (2014) 035801; PRD 90 (2014) 0637302...

Boltzmann Equation

Neutrino Phase Space Distribution Function

$$f(\mathbf{p},\mathbf{r}) \approx f_0(\mathbf{p},\mathbf{r}) + \Delta f(\mathbf{p},\mathbf{r}), \quad f_0(\mathbf{p},\mathbf{r}) = 1/\{1+\exp[(|\mathbf{p}|-\varepsilon_\nu)/T]\}$$

Equib. Part

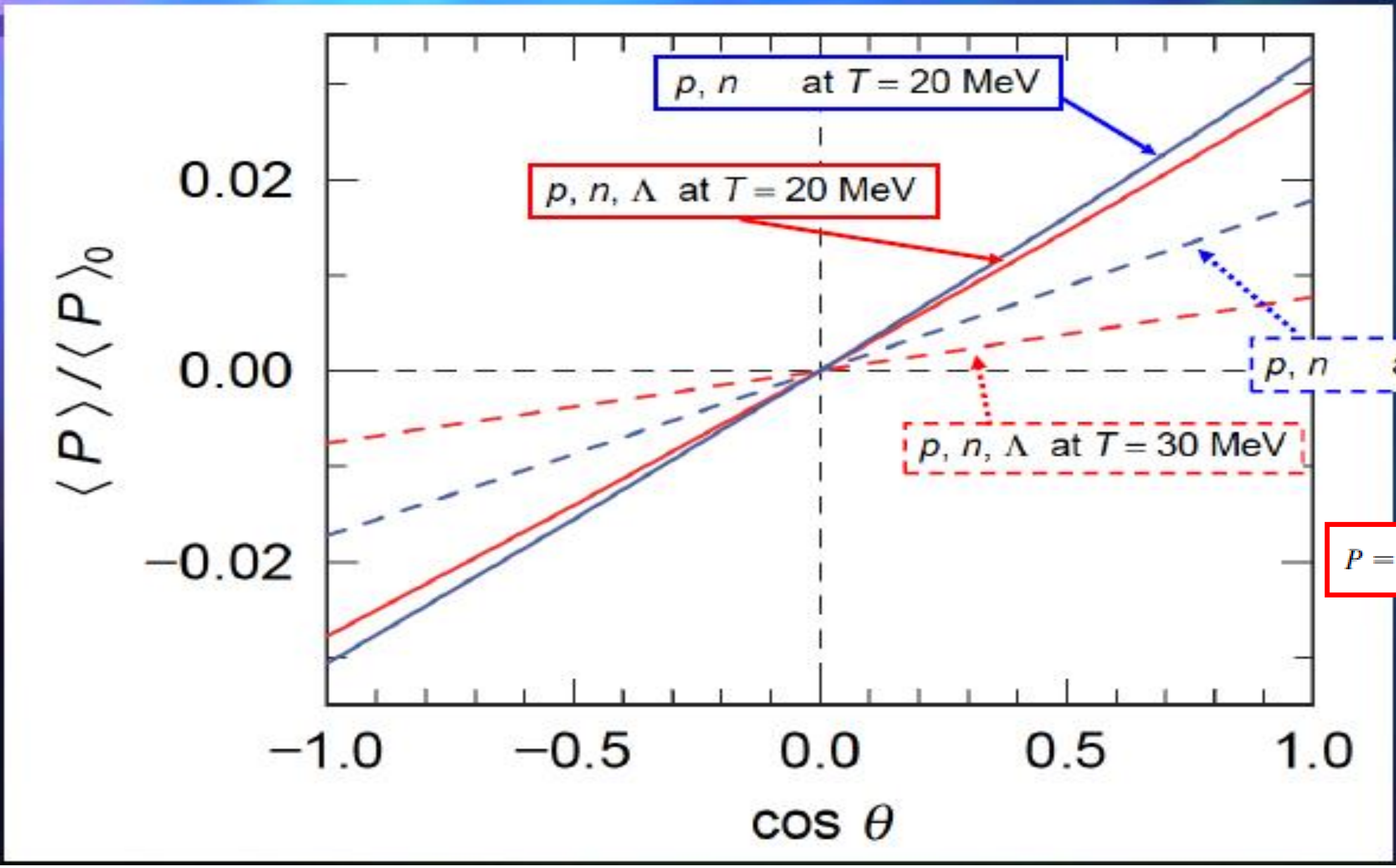
Non-Equib. Part

Angular Dependence of emitted neutrinos

Angular Dependence of Emitted Neutrino

$$< p >= \int drdp(\boldsymbol{p} \cdot \hat{\boldsymbol{u}}) \Delta f(\boldsymbol{p}, \boldsymbol{r})$$

Direction of Emitted Neutrino



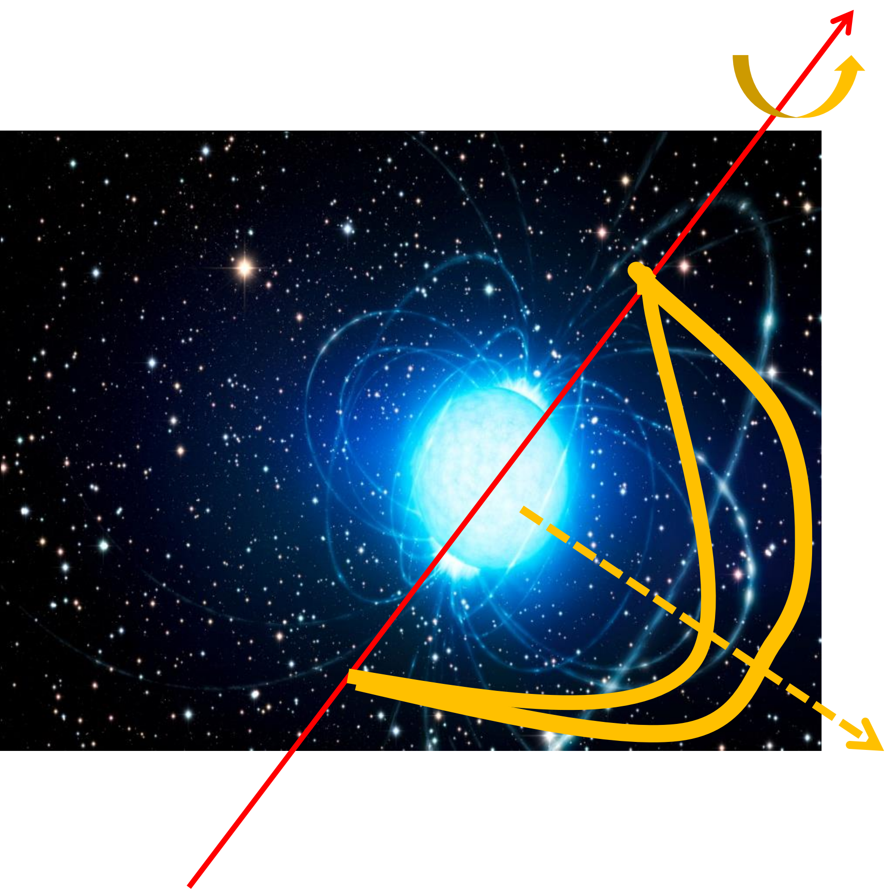
$$P = P_0 + \Delta P \approx P_0 + P_1 \cos\theta$$

Spin Deceleration Toroidal Magnetic Field

PHYSICAL REVIEW C 89, 035801 (2014)

Rapid spin deceleration of magnetized protoneutron star

Tomoyuki Maruyama,[1,2] Jun Hidaka,[2] Toshitaka Kajino,[2,3] Nobutoshi Ya
Myung-Ki Cheoun,[2,5] Chung-Yeol Ryu,[6] and

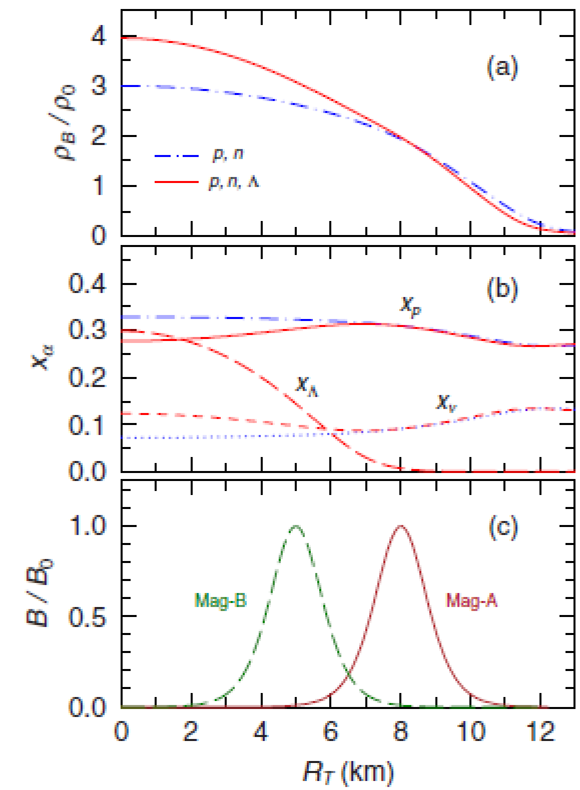


We adopt the following parametrization for the toroidal magnetic field configuration in cylindrical coordinates (r_T, ϕ, z),

$$\vec{B} = B_\phi G_L(z) G_T(r_T) \hat{e}_\phi, \tag{7}$$

where $\hat{e}_\phi = (-\sin\phi, \cos\phi, 0)$ in terms of the azimuthal angle ϕ, and

$$G_L(z) = \frac{4e^{z/a_0}}{[1 + e^{z/a_0}]^2}, \quad G_T(r_T) = \frac{4e^{(r_T - r_0)/a_0}}{[1 + e^{(r_T - r_0)/a_0}]^2}. \tag{8}$$



The ratio of the total rate of angular momentum loss to the total power radiated by neutrinos at a given spherical surface S_N is

$$\left(\frac{c dL_z/dt}{dE_T/dt}\right) = \frac{\int_{S_N} d\Omega_r \int \frac{d^3k}{(2\pi)^3} \Delta f(\boldsymbol{r},\boldsymbol{k})(\boldsymbol{r} \times \boldsymbol{k}) \cdot}{\int_{S_N} d\Omega_r \int \frac{d^3k}{(2\pi)^3} \Delta f(\boldsymbol{r},\boldsymbol{k})\boldsymbol{k} \cdot \boldsymbol{n}}$$

$$\dot{\omega} = -\frac{1}{c I_{NS}} \left(\frac{c dL_z/dt}{dE_T/dt}\right) \mathcal{L}_\nu. \quad (5)$$

For a PNS with spin period P, the angular velocity is $\omega = 2\pi/P$, and the angular acceleration is defined by $\dot{\omega} = -2\pi \dot{P}/P^2$. Thus, we obtain

$$\frac{\dot{P}}{P} = \frac{P}{2\pi c I_{NS}} \left(\frac{c dL_z/dt}{dE_T/dt}\right) \mathcal{L}_\nu. \quad (6)$$

SMaF ⇒ Affect neutrino scattering and absorption in dense matter

TM et al., PRD83, 081303(R) ('11) , PRD86,123003 ('12), PRC89, 035801 '(14)

- **Asymmetry of Neutrino Absorption**

  4.2 % at $\rho_B=\rho_0$, 2.2 % at $\rho_B=3\rho_0$ when T = 20 MeV and B = 10^{17}G

- **Poloidal Magnetic Field Configuration → Kick Velocity**

  $\upsilon_{kick} \approx$ 500 −600 [km/s] when T = 20 MeV and $B = 2\times10^{17}$G

- **Toroidal Magnetic Field Cation → Spin-Down Rate of PNS**

  Spin-Down Ratio P-dot/P ≈ $10^{-6} \sim 10^{-7}$ (1/s) for Asym. ν–Emit

  ≈ 10^{-8} (1/s) for MDR

Perturbation calculation−> Non-perturbation including Landau quantization is in progress

Contents

0. Introduction

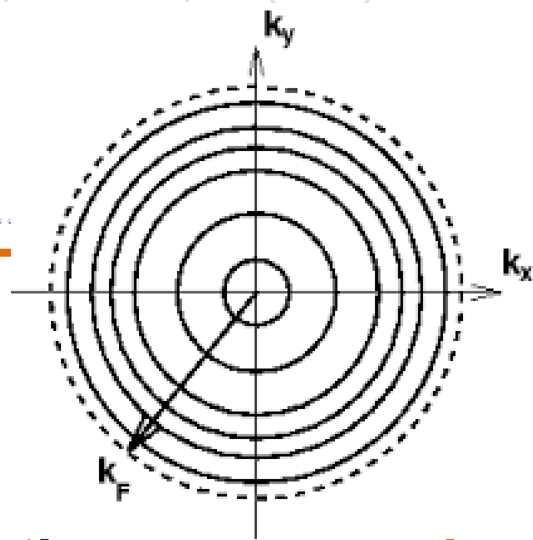
1. **Strong Magnetic Field (SMaF)** in Dense Matter
1-1. Magnetic Field in Neutron Stars

MKC et.al, PRC 82, 025804, (2010); PRC 83, 018802 (2011); JCAP 10, 21 (2013)…

1-2. Pulsar Kick of Neutron Stars
1-3. **Spin Deceleration of** Neutron Stars

PRD 86 (2012) 123003 ; PRD83 (2011) 081303(R);
PRC89 (2014) 035801; PRD 90 (2014) 0637302…

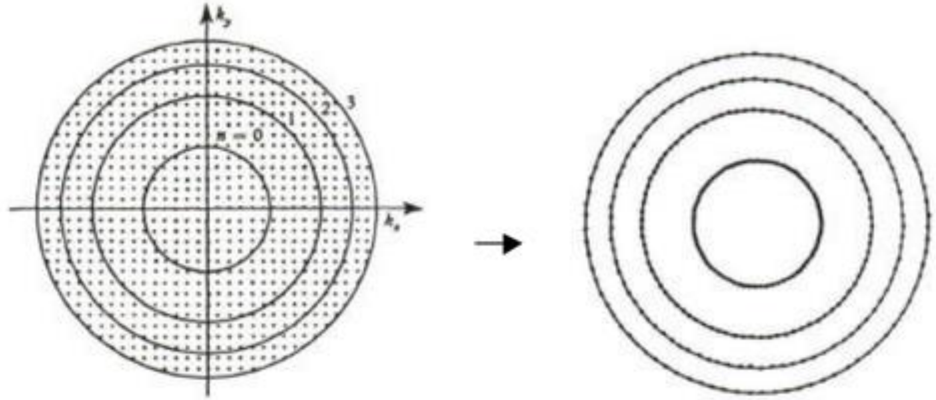
2. **Particle Production by SMaF in Astrophysics**
2-1. Semi Classical Approach
2-2. Quantum Field Approach



3. Meson Production by **SMaF** via **Landau Quantization**

4. Summary and Conclusions

What is
the Landau Quantization ?



Landau quantization in 2D. Without magnetic field, electrons are allowed to occupy any of the quantum states in momentum space indicated by dots on the left figure. In a magnetic field, they can only occupy the circles. Image source: Page on ntnu.edu.tw

As the magnetic field increases, the cylinders expand out (because their energy is proportional to H). **Every time a Landau level crosses the Fermi energy there is an enhanced density of states at the Fermi energy** because the landau levels are highly degenerate. In the image above, the Fermi energy is represented by the sphere drawn by the dashed line. The left-hand image below shows the 2D case.

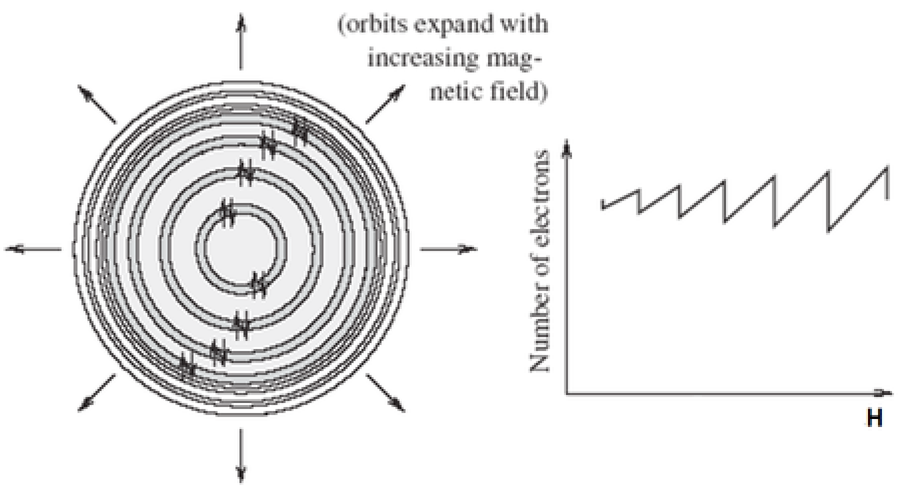
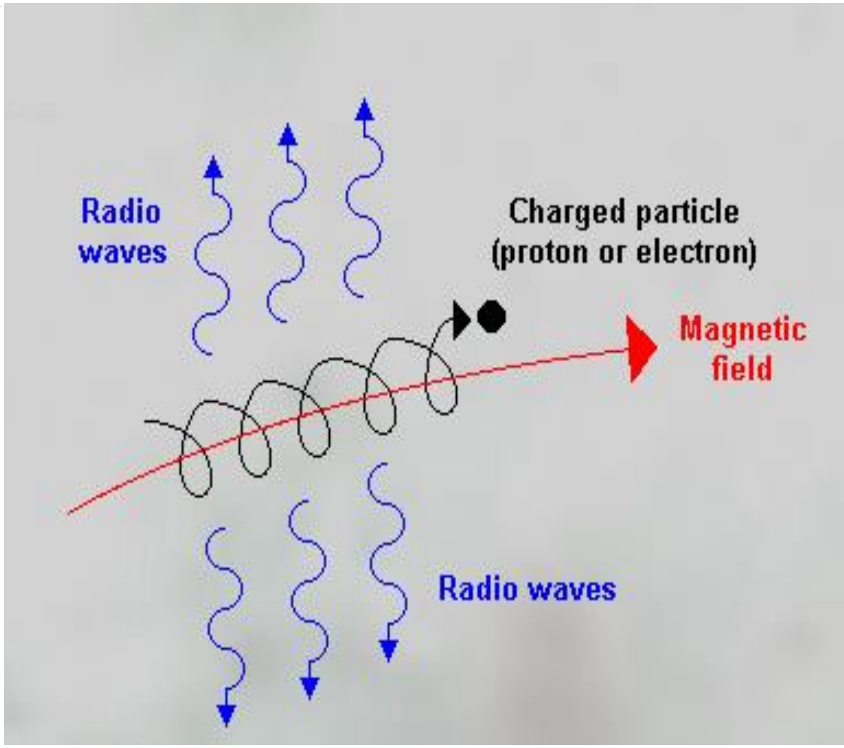
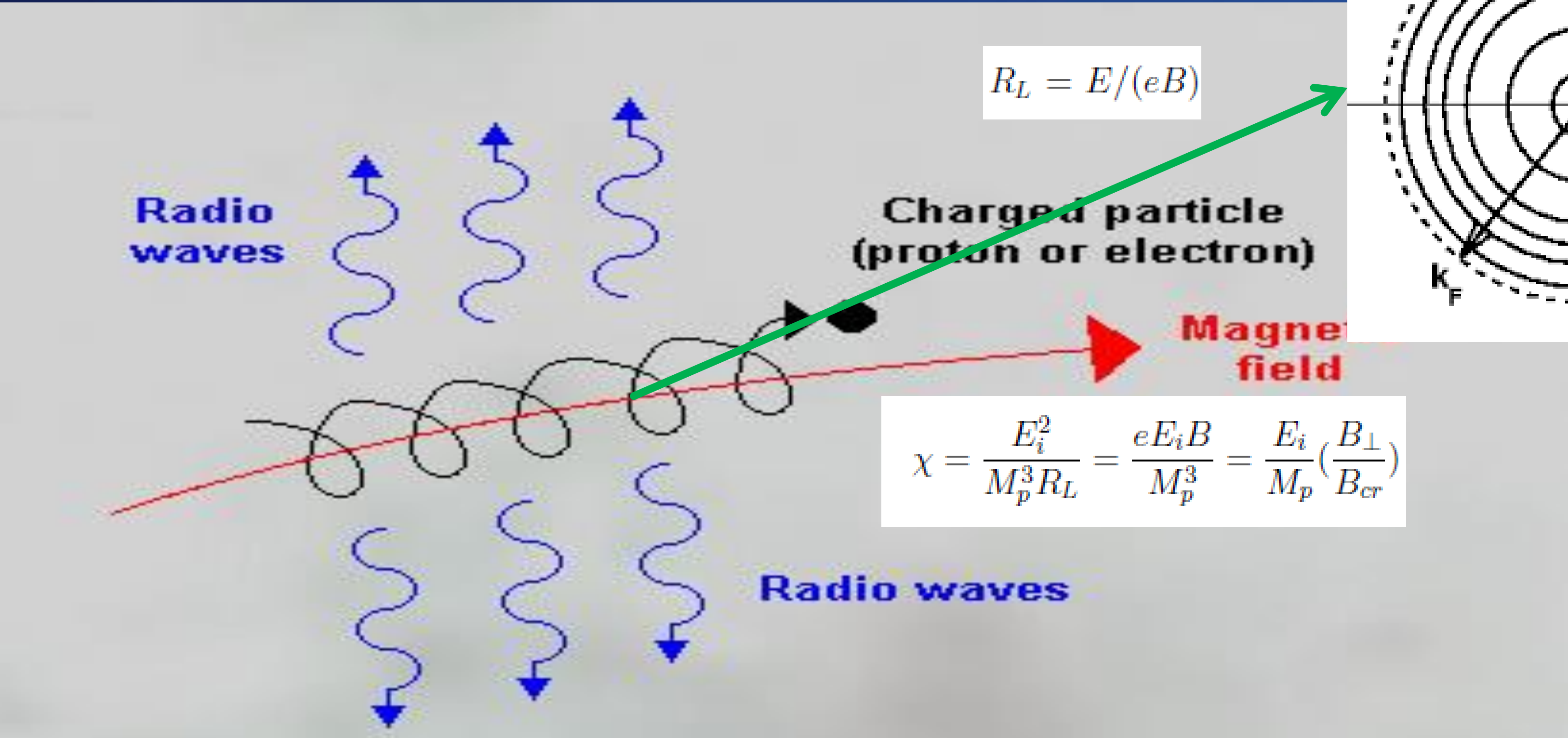


Image source: Lecture notes from Ph5014 (St. Andrews University), Prof. Andrew Mackenzie.

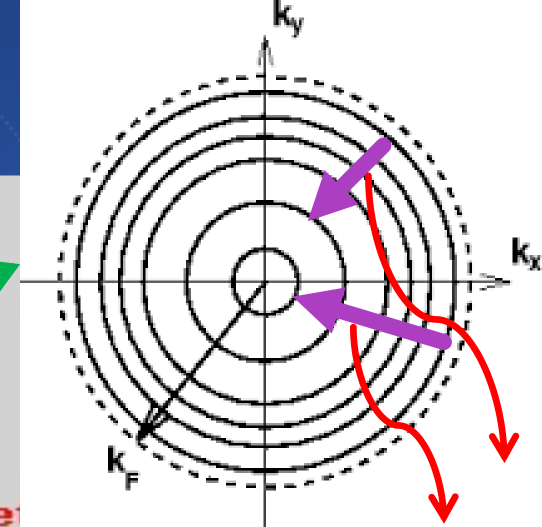


BEYOND SYNCHROTRON RADIATION



$$R_L = E/(eB)$$

$$\chi = \frac{E_i^2}{M_p^3 R_L} = \frac{eE_iB}{M_p^3} = \frac{E_i}{M_p}(\frac{B_\perp}{B_{cr}})$$



§ 2. Formulation

Magnetic Field : $\vec{B} = B\hat{z}.$

Tensor type mean field of ANM

Dirac Eq. $$\left\{\vec{\alpha}(-i\vec{\nabla}_r - e\vec{A}) + \beta m_N + \frac{e\kappa}{2m_N}B\beta\Sigma_z\right\}\tilde{\psi}(\boldsymbol{r}) = \varepsilon\tilde{\psi}(\boldsymbol{r})$$ $\vec{A} = (0, xB, 0)$

Scale Transformation : $M_N = m_N/\sqrt{eB},\ P_i \equiv p/\sqrt{eB},\ X_i = \sqrt{eB}x_i.$

Def: $U_T = \kappa\sqrt{eB}/2m_N = \kappa/2M_N.$

Wave Function

$$\psi \equiv (eB)^{-3/2}\tilde{\psi} = \begin{pmatrix} \lambda_1 f_{n+1}(X-P_y) \\ \lambda_2 f_n\ (X-P_y) \\ \lambda_3 f_{n+1}(X-P_y) \\ \lambda_4 f_n\ (X-P_y) \end{pmatrix} e^{iP_yY+iP_zZ-iEX_0}$$

Dirac Spinor

$$\begin{pmatrix} E-M_N-U_T & 0 & -P_z & -i\sqrt{2(n+1)} \\ 0 & E-M_N+U_T & i\sqrt{2(n+1)} & P_z \\ -P_z & -i\sqrt{2(n+1)} & E+M_N+U_T & 0 \\ i\sqrt{2(n+1)} & P_z & 0 & E+M_N-U_T \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{pmatrix} = 0.$$

Nucleon Green Functional

$$G(X,X',P_yP_z;P_0)=\sum_{n=0}\sum_{s=\pm1}\tilde{F}(X-P_y)\left[\frac{\rho_M^{(+)}(n,s,P_z)}{P_0-E(n,s,P_z)+i\delta}+\frac{\rho_M^{(-)}(n.x.P_z)}{P_0+E(n,s,P_z)+i\delta}\right]\tilde{F}(X'-P_y)$$

$$\rho_M^{(+)}(n,s,P_z) = \frac{[E\gamma_0-\boldsymbol{\gamma P}+M_N+\Sigma_z U_T]}{4E(n,s,P_z)}\left\{1+\frac{sU_T}{\sqrt{2n+1+s+m^2}}+s\gamma_5(a_0\gamma^0-a_z\gamma^3)\right\}$$

$$\rho_M^{(-)}(n,s,P_z) = \frac{[E\gamma_0+\boldsymbol{\gamma P}-M_N-\Sigma_z U_T]}{4E(n,s,P_z)}\left\{1+\frac{sU_T}{\sqrt{2n+1+s+M_N^2}}-s\gamma_5(a_0\gamma^0-a_z\gamma^3)\right\}$$

$$\tilde{F}=\operatorname{diag}\left(f_{n+\frac{s+1}{2}},f_{n+\frac{s-1}{2}},f_{n+\frac{s+1}{2}},f_{n+\frac{s-1}{2}}\right)=f_{n+\frac{s+1}{2}}\frac{1+\Sigma_z}{2}+f_{n+\frac{s-1}{2}}\frac{1-\Sigma_z}{2}.$$

$$a_0=\frac{P_z}{\sqrt{2n+1+s+M_N^2}},\quad a_z=\frac{E}{\sqrt{2n+1+s+M_N^2}}.$$

$$\frac{1}{2}\left(-\nabla_x^2+x^2\right)f_n(x)=\left(n+\frac{1}{2}\right)f_n(x),$$

$$E_T=\sqrt{P_z^2+\left(\sqrt{2n+1+s+M_N^2}+sU_T\right)^2}$$

$$\boldsymbol{P}_T^2=2n+1+s$$

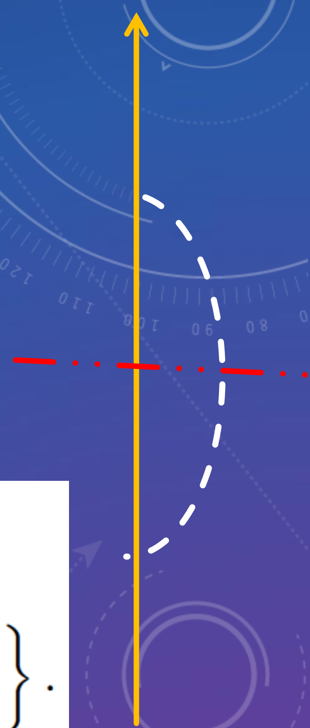
Decay Width of *p* to *p* + π^0 by Proton Green function

πN interaction

$$\mathcal{L} = \frac{i f_\pi}{m_\pi} \psi \gamma_5 \gamma_\mu \tau_a \psi \partial^\mu \phi_a$$

$$\frac{d^3\Gamma_{p\pi}}{dQ^3} = \frac{1}{8\pi^2 E_\pi} \left(\frac{f_\pi}{M_\pi} \right)^2 \sum_{n_f, s_f} \delta(E_f + Q_0 - E_i) W_{if}$$

$$W_{if} = \mathrm{Tr}\left\{ \left[\int dx_1 \tilde{F}^\dagger_{n_i}(x_1) \not{Q} \gamma_5 \tilde{F}_{n_f}(x_1 - Q_y) e^{iQ_x x_1} \right] \rho_M^{(+)}(n_f, s, P_z - Q_z) \right.$$
$$\left. \times \left[\int dx_2 \tilde{F}^\dagger_{n_f}(x_2 - Q_y) \not{Q} \gamma_5 \tilde{F}_{n_i}(x_2) e^{-iQ_x x_2} \right] \rho_M^{(+)}(n_i, s_i, P_z) \right\}.$$



Pion Momentum

$$\boldsymbol{Q} = (0, Q_T, Q_z) = \mathbf{q} / \sqrt{eB}$$

§ 3 Results of π^0 Production

$$E_i = 1\,\text{GeV},\quad B = 5\times 10^{18}\ \text{G}$$

$$\sqrt{eB} = 17.2\ \text{MeV},\quad \frac{e\kappa_p}{2m_N}B = 28.3\ \text{MeV}$$

$$n_{\max} + \frac{s_i+1}{2} = 50\ \text{for}\ s_i = -1$$
$$= 45\ \text{for}\ s_i = +1$$

W/O AMN

$$n_{\max} + \frac{s_i+1}{2} = 47$$

Decay Width

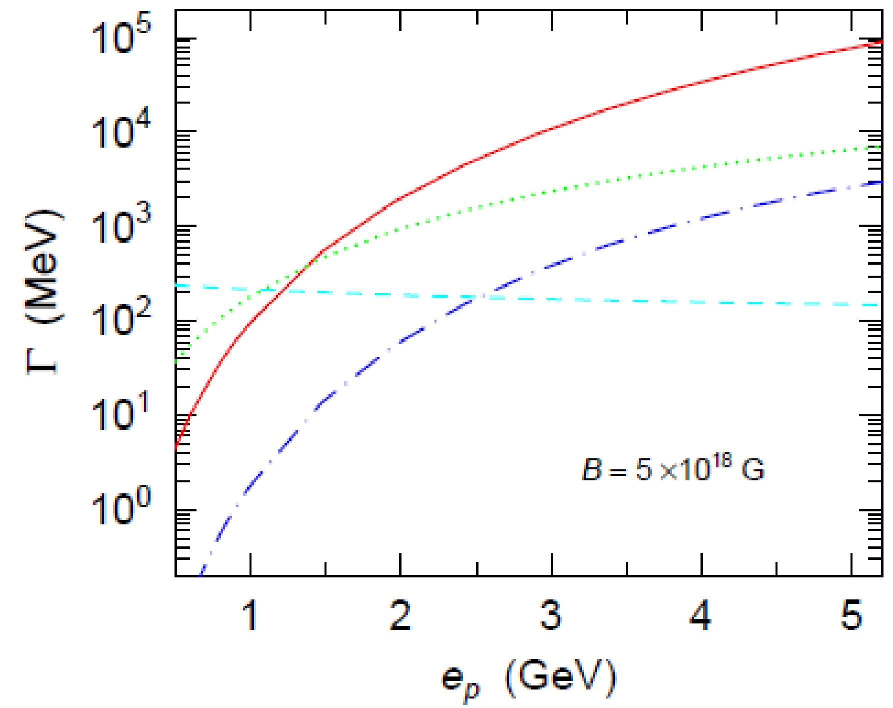


FIG. 2: (Color online) Pionic decay width of proton versus proton incident energy when $B = 5\times10^{18}$G. The decay width is averaged over the proton spin, and the landau number is taken to be maximum. The solid and dot-dashed lines represent the widths of the proton with AMM and without AMM, respectively. The dashed and dotted lines indicate the results in the semi-classical approaches in Refs. [24] and 210 MeV in [25], respectively

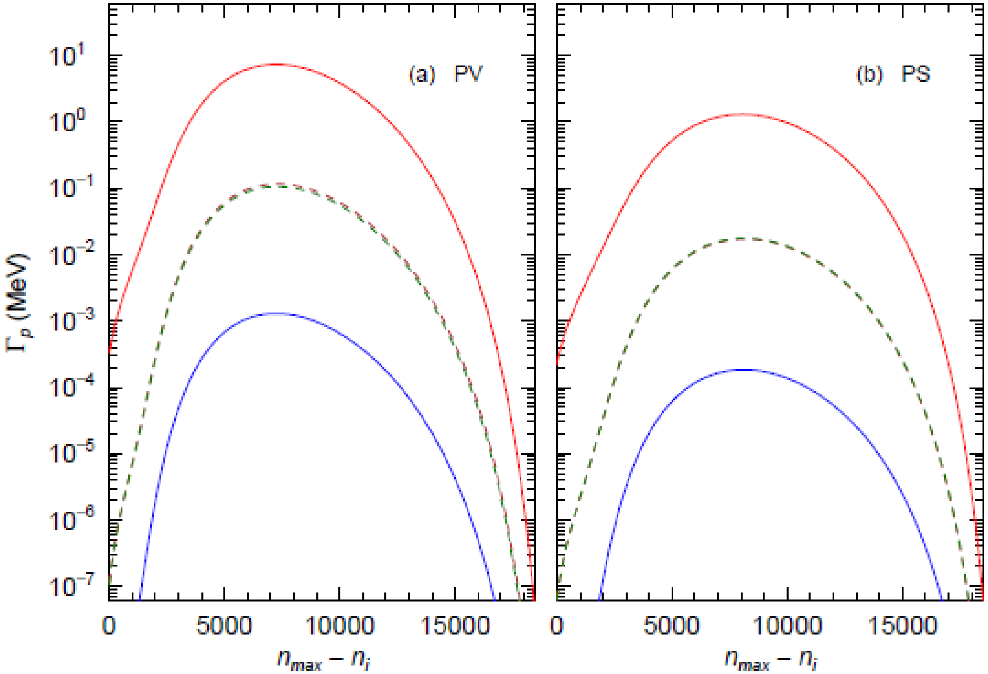
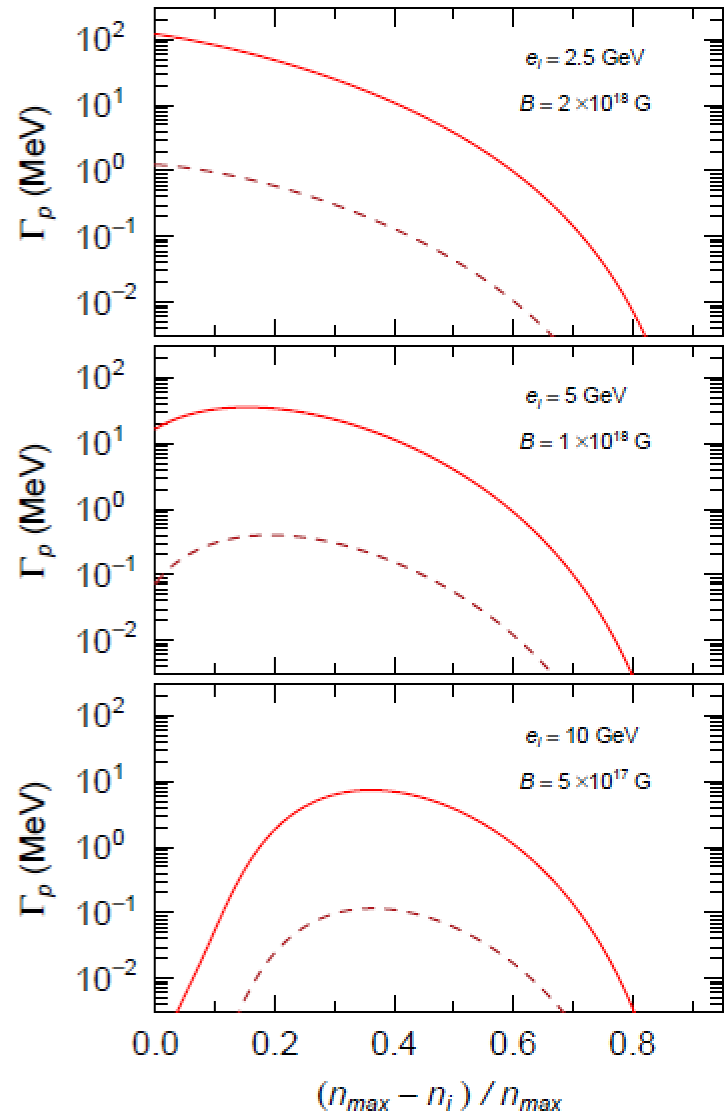


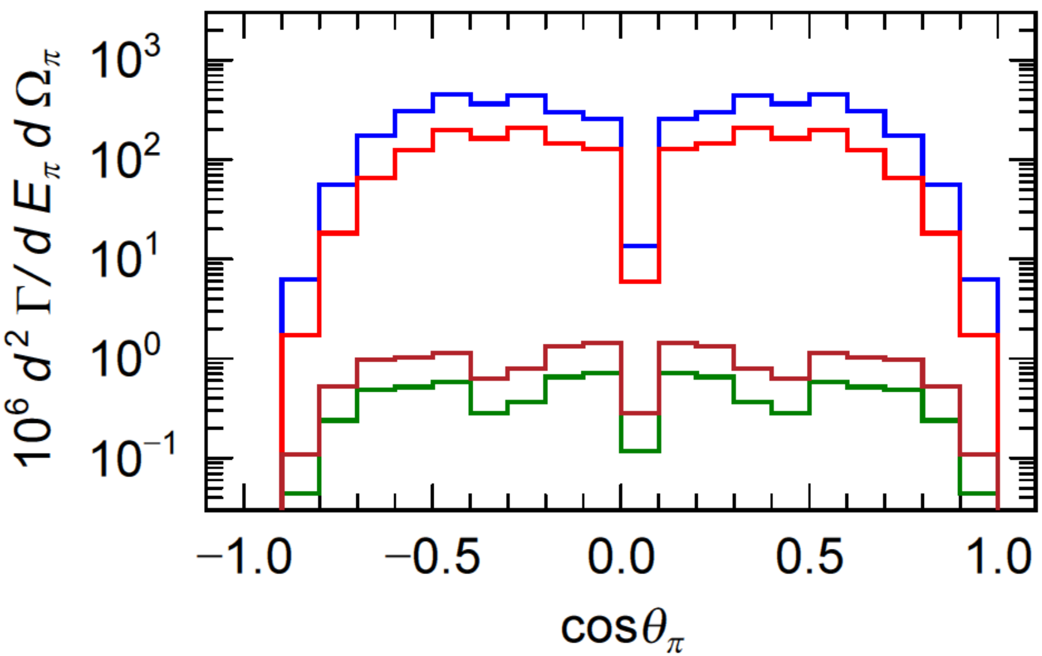
FIG. 1. Decay width of a 10 GeV proton for the synchrotron emission of π's using the vector (a) and pseudo-scalar couplings (b). The solid red and blue lines represent the deca of protons with spin $s_i = -1$ and $s_i = 1$, respectively. The dashed brown and green lines results with $s_i = -1$ and $s_i = 1$, respectively, for case that the anomalous magnetic m omitted.



Competition of Spin flip and AMN interaction

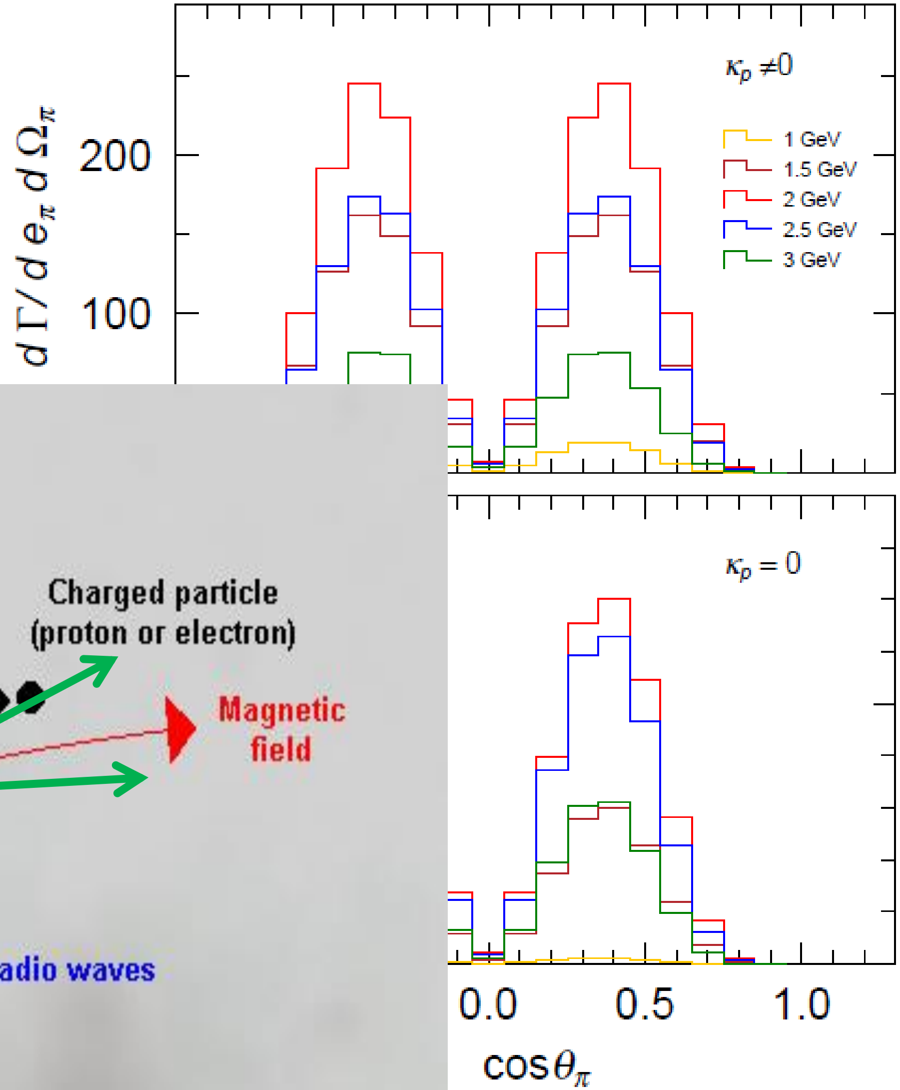
$E_\pi = 300$ MeV

$0 \langle n_{max} - n \langle 9$



Without AMN

spin flip contribution is much larger !!!



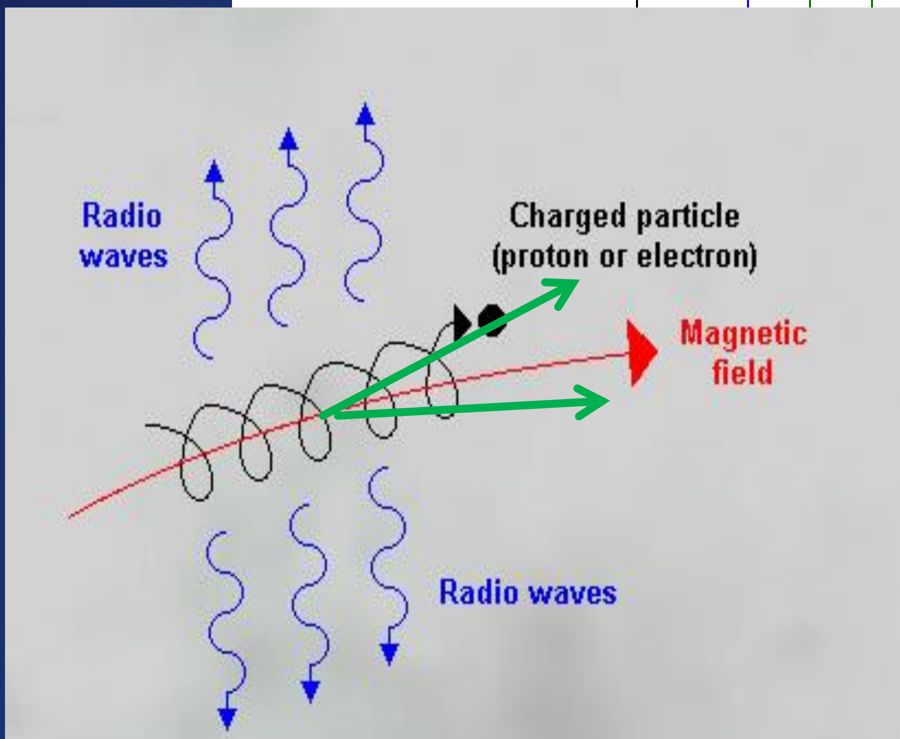


FIG. 4. The differential proton pionic decay width versus the polar angle of pion emission. The widths are averaged over all the initial Landau levels. The AMM is included in the upper panels, and not included in the lower panels. The emitted pion energies are taken to be 1 GeV (orage lines), 1.5 GeV (brown lines), 2 GeV (red lines), 2.5 MeV (blue lines) and 3 GeV (green lines).

$p \rightarrow p + \pi^0$ does not satisfy the energy and momentum conservation in free space, so that it could not happen.

In Q.P, we need larger transition energy and smaller 3 momentum transfer for this event.

SMaF＋ANM　Tensor type Mean field

$s = +1$ (Repulsive), $s = -1$ (Attractive)

$s = -1 \rightarrow s = +1$ **Level difference becomes small**

⇒ **Transition energy becomes large**

⇒ **Similar to free space kinematics**

⇒ **Transition rate increases**

$s = +1 \rightarrow s = -1$ **Level difference becomes large**

⇒ **Transition energy becomes small**

⇒ **Different to free space kinematics**

⇒ **Transition rate decreases**

FUTURE WORKS

- More Physical Quantities

- **Decay of high energy proton in small B field ∼ 10^{15}G** $R_L = E/(eB)$

n : Very large (Classical)

$$M(n_1,n_2) = \int dx f_{n_1}\left(x-\frac{Q_T}{2}\right) f_{n_2}\left(x+\frac{Q_T}{2}\right)$$
$$= (2^{n_1+n_2}\pi n_1! n_2!)^{-1/2} e^{-Q_T^2/4} \int dx e^{-x^2} H_{n_1}\left(x-\frac{Q_T}{2}\right) H_{n_2}\left(x+\frac{Q_T}{2}\right)$$
$$= \sqrt{\frac{n_S!}{n_L!}} f_s \left(\frac{Q_T^2}{\sqrt{2}}\right)^{n_L-n_S} e^{-\frac{Q_T^2}{4}} L_{n_S}^{n_L-n_S}\left(\frac{Q_T^2}{2}\right)$$

Laguerre function → Asymptotic form

- **Vector meson ρ, ω, and neutrino production**

- **Non-perturbative calculation with Landau quantization which include Temperature, density effects …**

Summary and Conclusion for SMaF Physics

1. We calculated neutrino transport inside PNS, which shows an asymmetry with respect to the magnetic field direction in a magnetar, by exploiting RMF, neutrino scattering and Boltzman equation.
2. The asymmetry turns out to be a source of pulsar kicks of neutron stars.
3. For the spin deceleration of neutron star, we also considered toroidal magnetic field, in which we also found the asymmetry leading to the spin deceleration.
4. Additional source of neutrinos, URCA process is also shown to enlarge the asymmetry.
5. In the Universe, we need more deep understanding of strong magnetic field (SMaF) physics, for example, Landau quantization and polarization of particle propagation inside neutron stars. It may lead to new mechanism of cosmic particles (pion, neutrino … emission) .


Thanks for
your attention !!

Back Up Files

Effects of Strong Magnetic Field (SMaF) on the Neutron Stars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8th APCTP-BLTP JINR Joint Workshop

Jeju, June 29 ~ July 04 , 2014

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2. Modified Gravity and Magnetic field in Neutro ... rs
2-1. Modified TOV
2-2. Magnetic field

MKC et.al, PRC 82, 025804, (2010); PRC 83, 018802 (2011); JCAP 10, 21 (2013)...

3. Other properties in Neutron Stars

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Origin of Matter

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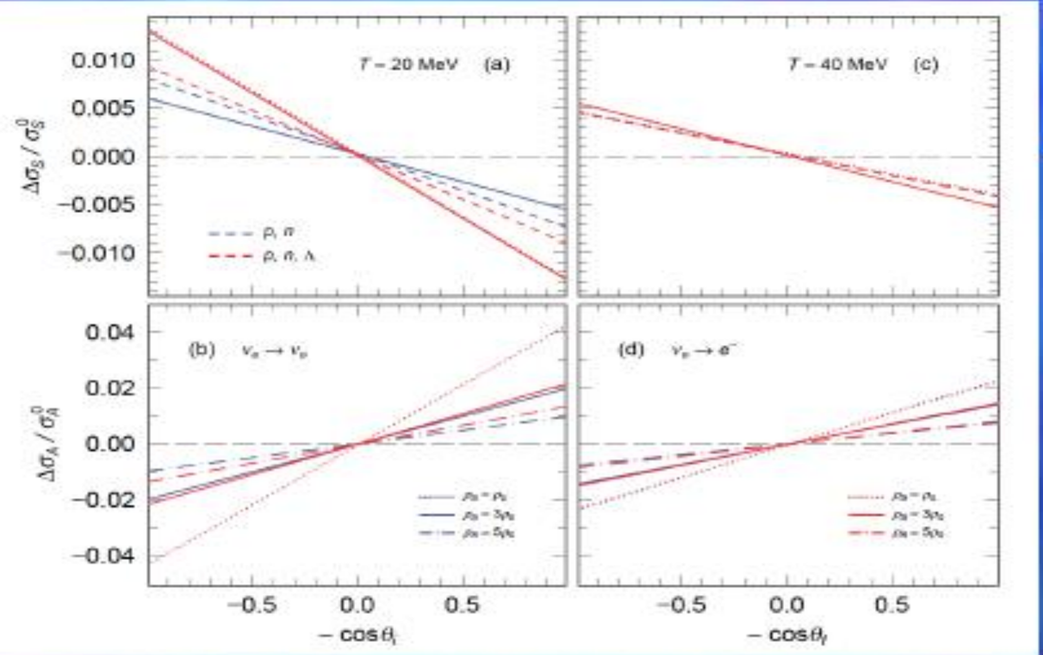
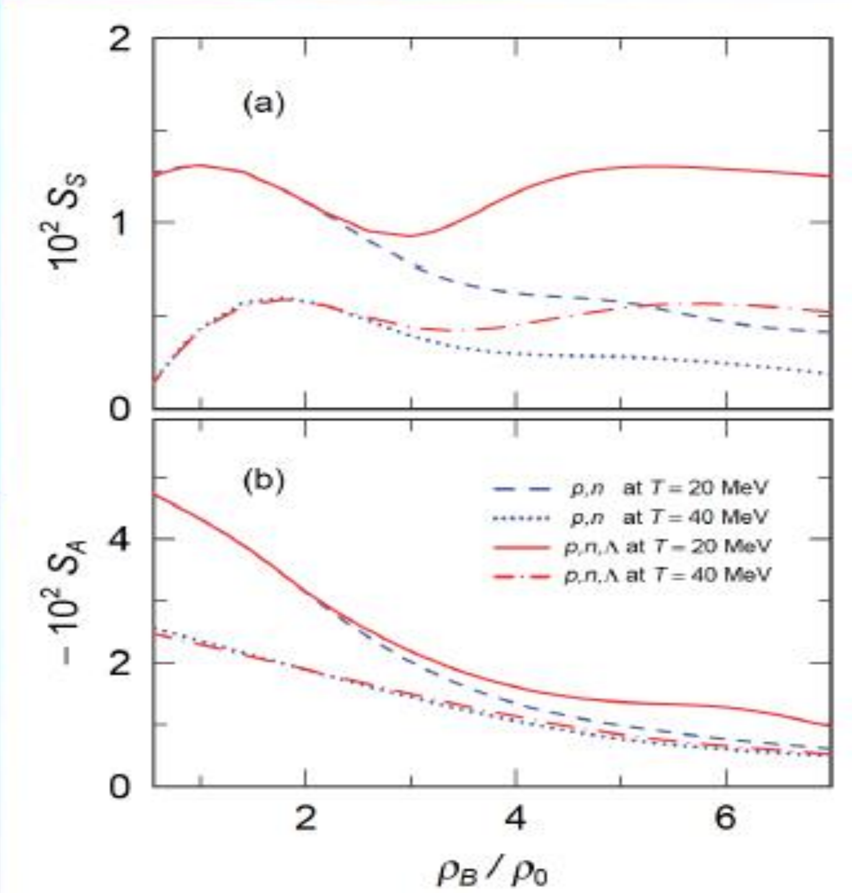
4. Summary and Conclusions

Results — Scattering and absorption X-sections

Magnetic Parts of Cross-Sections





$$\sigma_{S,A} = \sigma_{S,A}^{0}\left(1 + S_{S,A}\cos\theta_{i,f}\right)$$

ted asymmetrically. Along with these assumptions, we ignore the effects of other neutrino processes, such as the direct and moderate URCA processes [35–37], and also the momentum transfer to the medium at each local position.

The time scale for PNS evolution is much larger than that of the emitted neutrino propagating inside the PNS. Therefore, to estimate the neutrino momentum transport, we can conjecture that PNS is static, and that the neutrino transfer makes a continuous current in the equilibrium matter. Furthermore, we simplify the PNS as having a fixed temperature and magnetic field. These simplifying as-

$$f_\nu(\boldsymbol{r}, \boldsymbol{k}) = f_0(\boldsymbol{r}, \boldsymbol{k}) + \Delta f(\boldsymbol{r}, \boldsymbol{k}) = \frac{1}{1 + \exp[(|\boldsymbol{k}| - \varepsilon_\nu(\boldsymbol{r}))/T]} + \Delta f(\boldsymbol{r}, \boldsymbol{k}), \quad (61)$$

where the first and the second terms are the local equilibrium part and the deviation from the equilibrium, respectively, with the neutrino chemical potential $\varepsilon_\nu(\boldsymbol{r})$ at the position $\boldsymbol{r}$. The phase-space distribution functions of other

emission from the f_ν function. This f_ν satisfies the following Boltzmann equation

$$\left(\frac{\partial}{\partial t} + \hat{k} \cdot \frac{\partial}{\partial \boldsymbol{r}}\right) f_\nu(\boldsymbol{r}, \boldsymbol{k}) = I_{\mathrm{coll}} \quad (59)$$

with

$$I_{\mathrm{coll}} = \sum_{i,j} \int \frac{d^3 k_l}{(2\pi)^3} \frac{d^3 p_i}{(2\pi)^3} \frac{d^3 p_j}{(2\pi)^3} W_{if} \{ f_l(\boldsymbol{k}_l) f_j(\boldsymbol{p}_2) \times [1 - f_\nu(\boldsymbol{k})][1 - f_i(\boldsymbol{p}_1)] - f_\nu(\boldsymbol{k}) f_i(\boldsymbol{p}_1) \times [1 - f_l(\boldsymbol{k}_l)][1 - f_j(\boldsymbol{p}_2)]\}, \quad (60)$$