An Explanation for Heavy Quark Energy Loss Puzzle by Flow Effects

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Based on our new model potential in the presence of collective flow describing the interaction of the hard jet with scattering centers, an explanation for heavy quark energy loss puzzle is given by collective flow effects. It is shown that the collective flow changes the pole of propagator which lead to reduce significantly the dead cone and change the LPM destructive interference comparing to that in the static medium. Consider the collective flow with velocity $v_s$ along jet direction, the heavy quark energy loss is nearly the same as light quark in the region of $0.065 < v_s < 0.13$. It turns out that the average $v_s$ of rescattering centers is around 0.08, the differences of the effective average energy loss among charm, bottom and light quarks are very little from a full 3D ideal hydrodynamic simulation for 0-10\% central events of Au-Au collision at RHIC energy by including collective effects. The flow dependence of the quark energy loss implies that the light and heavy quark have almost the same suppression of high $p_T$ hadron spectrum in high-energy heavy-ion collisions.

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Introduction — The formation and observation of quark-gluon plasma (QGP) are the most important goals in high energy heavy ion physics. Jet quenching \cite{1} or suppression of large transverse momentum $p_T$ hadrons caused by the energy loss of a propagating parton in a dense medium, has become a powerful tool for the study of properties of QGP. Light quark and gluon jet quenching observed via $\pi$, $\eta$ suppression in Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 62 - 200 GeV$ at the relativistic heavy ion collider (RHIC) has been remarkably consisted thus far with predictions \cite{2,3,4,5} from jet quenching theory. It is believed that a good test of QGP formation is the suppression of light hadrons, than predicted was observed in the $p_T = 4 - 8 \text{ GeV}$ region. Later the collisional energy loss is included to explain the non-photonic single electron data \cite{6,7,8,9,10,11} that shows a much larger suppression of electrons, which is similar to the suppression of light hadrons, than predicted was observed in the $p_T = 4 - 8 \text{ GeV}$ region. The present heavy quark energy loss becomes a puzzle to challenge the scenario of jet quenching.

The currently available studies suffer from one crucial drawback, the medium induced radiative energy loss should be computed in a expanding QCD medium with collective flow instead of a static medium. The medium produced in nucleus-nucleus collisions at RHIC equilibrates efficiently and builds up a flow field. This flow changes the color-electric field and produces a color-magnetic field \cite{15}, and will surely change the parton energy loss. In this letter, based on our previous new model potential \cite{16} with collective flow, we will report a first study of the heavy quark energy loss in the presence of collective flow in perturbative Quantum Chromodynamics (pQCD) and give an explanation for heavy quark energy loss puzzle in the framework of jet quenching theory. Based on our new potential model with collective flow, we find that the flow effects reduces significantly the dead cone of heavy quark jets. We are led to the conclusion that the decrease of the dead cone increases the heavy quark energy loss. Using the full 3D ideal hydrodynamic simulations \cite{17}, we obtained the average flow velocity of rescattering centers and effective average energy loss of heavy quark jets. It turns out that the effective average energy loss of heavy quark jets is nearly the same as the light quark jets, this agrees with the experimental data that the suppression of electrons for heavy quarks is similar to light hadrons.

Flow Effect on Gluon Radiation for Heavy Quark Jet — In our previous work \cite{16} we model the jet interactions in the QGP in the presence of collective flow as random color screened potentials $A^\nu_i(q_i) = (V^\nu_i(q_i), A^\nu_i(q_i))$.

\begin{align}
V^\nu_i(q_i) &= 2\pi\delta(q_i^0 - \mathbf{v} \cdot \mathbf{q}) e^{-i\mathbf{q} \cdot \mathbf{x}} \tilde{v}(\mathbf{q}) T_N(j)/T_N(i) \, , \\
A^\nu_i(q_i) &= 2\pi\delta(q_i^0 - \mathbf{v} \cdot \mathbf{q}) \nu e^{-i\mathbf{q} \cdot \mathbf{x}} \tilde{v}(\mathbf{q}) T_N(j)/T_N(i) \, ,
\end{align}

where $\tilde{v}(\mathbf{q}) = 4\pi\alpha_s/(q^2 - (\mathbf{v} \cdot \mathbf{q})^2 + \mu^2)$, $q_i = (q_i^0, \mathbf{q})$ is the momentum transfer, $\mu$ the Debye screening mass, $\mathbf{v}$ the flow velocity, $T_N(j)$ and $T_N(i)$ the color matrices for the jet and target parton at position $\mathbf{x}$, respectively. The collective flow changes the color-electric field, produces a color-magnetic field and leads to non-zero energy transfer $q_i^0 = \mathbf{v} \cdot \mathbf{q}$ from the target parton to the jet which differs with Gyulassy-Wang’s static potential model \cite{10}.

Here we investigate the rescattering-induced gluon radiation of heavy quark jet by considering the flow effect resulting from the moving parton target. We will work in the framework of opacity expansion developed by Gyulassy, Lévai and Vitev (GLV) \cite{18} and Wiedemann \cite{19}. The opacity is defined as the mean number of collisions in the medium. In the framework of the opacity expan-
sion, the first order opacity contribution is dominant because the higher order corrections contribute little to the radiative energy loss as shown by GLV [13].

In order to compute the medium-induced radiative energy loss to the first order in the opacity expansion, we need to obtain the amplitudes for self-quenching in the vacuum, and for single rescattering and double Born scattering with the same target in the QCD medium in the presence of collective flow. Consider a hard heavy quark jet with mass $M$ and initial energy $E$ produced at $x_0 = (z_0, x_{0\perp})$. It interacts with the target parton at $x_1 = (z_1, x_{1\perp})$ with flow velocity $\mathbf{v}$ by exchanging gluon with four-momentum $q$, radiates a gluon with four-momentum $k$ and polarization $\epsilon(k)$, and emerges with final four-momentum $p$. In Ref. [3], it is shown that gluons in the medium can be be approximated as massive transverse plasmons with mass $m_g \approx \mu/\sqrt{2}$. Then $p$, $k$ and polarization $\epsilon(k)$ can be written in the light-cone components,

\[ k = [2\omega, \frac{k^2 + m_g^2}{2\omega}, k_{\perp}], \quad \epsilon(k) = [0, 2 \epsilon_\perp \frac{\epsilon_{k_{\perp}}}{x E}, \epsilon_\perp], \]

\[ p = [(1-x)E^+ + 2\mathbf{v} \cdot \mathbf{q}, -\frac{\mathbf{p}_{\perp} + M^2}{1-x} E^+ + 2\mathbf{v} \cdot \mathbf{p}_{\perp}], \]

where $\omega = x E$, $E^+ = 2E \gg \mu$.

At zeroth order in opacity, the jet has no interaction with the target parton, we obtain the same radiation amplitude as that in the static medium in Ref. [3],

\[ R^{(0)} = 2ig T_a \frac{k_{\perp} \cdot \epsilon_{\perp}}{k^2 + m_g^2 + x^2 M^2}, \]

which indicates the depletion of radiation in the ”dead cone” [3] at angles

\[ \theta < \theta_{c1} = \sqrt{m_g^2 + x^2 M^2/(x E)}. \]

Based on our new potential with the collective flow of the quark-gluon medium in Eqs. (1) and (2), assuming the flow velocity $|\mathbf{v}| \ll 1$, the radiation amplitudes associated with a single scattering and the double Born rescattering with two scattering centers in the impact limit can be expressed as

\[ R^{(S)} = 2ig \left( C_2 (e^{i \frac{\mathbf{q} \cdot \mathbf{v}_z}{1-x} z_{10} - i \frac{\mathbf{q} \cdot \mathbf{v}_z + m_g}{1-x} z_{10}) [T_{c\perp}, T_0] + H_1 e^{i \frac{\mathbf{q} \cdot \mathbf{v}_z + m_g}{1-x} z_{10}} T_c T_0 + H_1 (1-v_z) e^{i \frac{\mathbf{q} \cdot \mathbf{v}_z}{1-x} z_{10}} T_c T_0 \right) \cdot \epsilon_{\perp} (1-v_z), \]

\[ R^{(D)} = 2ig T_c \left( \frac{C_A}{2} (1+v_z) H_2 e^{i \frac{\mathbf{q} \cdot \mathbf{v}_z + m_g}{1-x} z_{10} - 1) + \frac{C_R}{2} (1-v_z)^2 H_1 e^{i \frac{\mathbf{q} \cdot \mathbf{v}_z + m_g}{1-x} z_{10} - i \frac{m_g}{1-x} z_{10} - 1 - \frac{C_A}{2} C_1 (e^{i \frac{\mathbf{q} \cdot \mathbf{v}_z + m_g}{1-x} z_{10} - e^{i \frac{\mathbf{q} \cdot \mathbf{v}_z + m_g}{1-x} z_{10}})} \frac{C_R}{2} H_1 e^{i \frac{\mathbf{q} \cdot \mathbf{v}_z + m_g}{1-x} z_{10}} \cdot \epsilon_{\perp} (1-v_z)^2, \right) \]

where $z_{10} = z_1 - z_0$, $C_R$ and $C_A$ are the Casimirs of jet in fundamental representation in $d_R$ dimension and the target parton in adjoint representation in $d_A$ dimension, respectively.

\[ \omega_0 = \frac{k_\perp^2}{2\omega}, \quad \omega_1 = \frac{(k_\perp - q_\perp)^2}{2\omega}, \]

\[ \omega_m = \frac{m_g^2 + x^2 M^2}{2\omega}, \quad \omega_M = \frac{v_z x M^2}{(1-v_z)\omega}, \]

\[ H_1 = \frac{k_\perp}{k^2 + m_g^2 + x^2 M^2}, \]

\[ H_2 = \frac{k_\perp}{k^2 + m_g^2 + x^2 M^2}, \]

\[ C_1 = \frac{k_\perp - q_\perp}{(k_\perp - q_\perp)^2 + m_g^2 + x^2 M^2}, \]

\[ C_2 = \frac{k_\perp - q_\perp}{(k_\perp - q_\perp)^2 + m_g^2 + x^2 M^2 - \frac{2v_z}{1-v_z} x M^2}. \]

Different from the static medium case, the single and double Born scattering amplitudes depends on the collective flow of the medium. Our results agree with the GLV results [3] in static medium at zero flow velocity.

In calculating radiation amplitude in Eqs. (8) and (9), compared to the static medium case we can see that the collective flow changes the poles of the propagator as follows: the poles of the quark propagators are shifted by a flow velocity-dependent term $\omega_M$ and then times a flow factor $1/(1-v_z)$. The pole shift leads to that the mass-dependent energy difference $\omega_m$ in Ref. [3] shifts to $\omega_m - \omega_M$ as shown in Eqs. (8) and (9). For the processes that heavy quark jet interacts directly with the target partons, the contribution of shifted pole of both quark propagators cancels each other, the net contribution keeps the same radiation amplitude as that in the static medium except the phase factor, as shown by $H_1$ and $C_1$ terms in Eqs. (8) and (9). From $H_1$ and $C_1$ in Eqs. (10) and (11) we can see easily that these processes have the dead cone $\theta_{c2}$ in Eq. (7) which is same as that in the static medium. For the processes that heavy quark jet interacts with target partons via triple-gluon vertex, the contribution of shifted pole of the quark propagator can’t cancel the contribution coming from the pole of gluon propagator, the flow effects changes the radiation amplitude as shown by $H_2$ and $C_2$ terms in Eqs. (12) and (13). From $H_2$ and $C_2$ in Eqs. (14) and (15) we can see clearly that in these processes the collective flow decreases dead cone $\theta_{c2}$ as

\[ \theta_{c2} = \frac{m_g^2 + x^2 M^2 - (2v_z x M^2)/(1-v_z) }{(x E)}. \]

Compared to the dead cone term $M^2/E^2$ coming from the mass effects, the dead cone change $2v_z x M^2/(1-v_z) x E^2$ coming from the flow effects is proportional to $1/x = E/\omega$, this term deduces significantly the mass-effect dead cone for high energy heavy quark jet. The real dead cone with collective flow effects should be

\[ \theta_c = \min[\theta_{c1}, \theta_{c2}] = \theta_{c2} \geq 0. \]
where $\omega/E$ is the ratio between the dead cone in the medium with flow and that in the static medium as function of flow velocity $v_z$ as $\omega/E = 0.2$. It shows that the dead cone decrease to zero rapidly with increasing $v_z$. The dead cone of bottom quark reduces more strongly than that of charm quark because of the heavier quark mass.

From the radiation amplitude in Eqs. (3) and (9), the medium induced radiation probability to the first order in opacity can be expressed as

$$\frac{dP^{(1)}}{d\omega} = \frac{C_2}{8\pi d_A d_R} \frac{N}{A_\perp} \int \frac{dx}{x} \int \frac{d^2k_\perp}{(2\pi)^2} \int \frac{d^2q_\perp}{(2\pi)^2} P(\omega) \left[ (1-\nu_z)^2 v^2(q_\perp) \left\langle Tr \left[ R(S)^2 + 2Re \left( R_0(1) R(D) \right) \right] \right\rangle \right. $$

$$ \approx \frac{\alpha_s \alpha_C R}{2\pi} \int \frac{dx}{x} \int d^2k_\perp P(x) \nu(q_\perp)^2 (1-\nu_z)^2$$

$$ \left\langle 2C_2 \cdot H_1 \cdot C_1 - H_1 \cdot H_2 \right\rangle \left\langle Re(1-e^{-\frac{2\sqrt{x^2+y^2}}{\omega_m}}) \right\rangle $$

$$+ \left\langle H_2^2 \cdot C_1 \right\rangle \left\langle Re \left( 1-e^{-\frac{2\sqrt{x^2+y^2}}{\omega_m} \cdot \varphi} \right) \right\rangle $$

$$2v_z H_1 C_2 \left\langle Re \left( e^{-\frac{2\sqrt{x^2+y^2}}{\omega_m}} \cdot \varphi \right) \right\rangle $$

$$+ 2v_z \left( H_1 \cdot C_2 - H_2 \right) \left\langle Re \left( 1-e^{-\frac{2\sqrt{x^2+y^2}}{\omega_m} \cdot \varphi} \right) \right\rangle $$

$$-2v_z H_2^2 \left\langle Re \left( 1-e^{-\frac{2\sqrt{x^2+y^2}}{\omega_m} \cdot \varphi} \right) \right\rangle $$

(18)

where $C_2$, $N$, $L$ and $A_\perp$ are, respectively, the Casimir in fundamental representation, the number, the thickness, and the transverse area of the targets, $l_y$ is the mean-free path of the gluon, $\alpha_s = g^2/4\pi$ the strong coupling constant, $P_{gg}(x) \equiv P(x)/x = (1+(A-1)x^2)/x$ the splitting function for $q \rightarrow qg$. $\nu(q_\perp)^2$ is defined as the normalized distribution of momentum transfer from the scattering centers as shown in Ref. [16]. The opacity factor $L/l_y$ reflecting the mean number of rescattering in the medium arises from the sum over the $N$ distinct targets.

The gluon formation factor inside $Re(\cdots)$ in Eq. (18) reflects the destructive interference of the non-Abelian LPM effect [20]. Comparing to the radiated gluon formation time $\tau^\text{static}_{\omega} = 1/(\omega_1 + \omega_m)$ for heavy quark jet goes through the static medium in Ref. [6], from the gluon formation factor in Eq. (18) we see that the radiated gluon formation time in the medium with collective flow contracts by a factor $1-\nu_z$ because of the moving of the target parton. The pole shift of the quark propagator in the presence of collective flow leads to that the radiated gluon formation time in some interference processes changes by replacing $\omega_m$ with $\omega_m - \omega_M$ as shown in the first term in Eq. (18), so that the flow effects result in different gluon formation time for different interference processes. From Eq. (18) we see clearly three different formation time, $\tau_{f1} = (1-\nu_z)/(\omega_1 + \omega_m)$, $\tau_{f2} = (1-\nu_z)/(\omega_1 + \omega_m - \omega_M)$, $\tau_{f3} = (1-\nu_z)/(\omega_M)$. The gluon formation factor should be averaged over the longitudinal target profile which is defined as $\langle \cdots \rangle = \int dz \rho(z) \cdots$.

We take the target distribution as an exponential Gaussian form $\rho(z) = \exp(-z/L_c)/L_c$ with $L_c = L/2$.

As shown in Ref. [6], the scale of the hard scattering can be taken as $Q^2 = 4E^2$, the kinematic limits of the gluon’s transverse momentum are $\mu_1^2 \leq k_t^2 \leq 4\omega E$. From Eq. (18) we get the induced energy loss to the first order of the opacity as $\Delta E = \int d\omega \omega dP^{(1)}/d\omega$. Its numerical results are shown in Fig. 2 for charm, bottom and light quarks as $E/\mu = 20$, $L/l_y = 5$. At zero flow velocity, the light quark energy loss is larger than charm and bottom quark energy loss because of the dead cone from the mass effects of heavy quark jets as shown in Ref. [6] in the static medium. However, the heavy quark energy loss increases with increasing the flow velocity because of the decrease of the dead cone by the flow effects in the medium with collective flow. The heavier the quark mass is, the more rapidly the heavy quark energy loss increases. The light quark energy loss decreases with increasing the flow velocity as shown in our previous work [16]. In the region of $0.065 < v_z < 0.13$, the energy loss of light quark is a bit less than that of bottom quark but a bit larger than that of charm quark. In this region the average heavy and light quark energy loss is possible to be nearly the same.

For A-A collisions at impact parameter $b$, with respect to collision number the average $\nu_z$ of rescattering centers in the QGP medium before freezeout can be expressed as

$$\langle \nu_z \rangle = \frac{\int d^2r \int d\omega \omega_2 \omega_3 \langle v_z \cos \varphi + v_y \sin \varphi \rangle \rho r A_T B}{\int d^2r \int d\omega \omega r A_T B},$$

(19)

where $\varphi$ is the angle between jet and $x$ axis, $v_z = v_{z_j}(r+\mathbf{n}r - \mathbf{b}/2)$, $v_y = v_{y_j}(r+\mathbf{n}r - \mathbf{b}/2)$ are the flow velocity of the expanding elliptic medium along the minor and major semi-axes, $\mathbf{n}$ is the unit vector along jet direction. Parton density $\rho = \rho(\tau, b, r, \mathbf{n} \mathbf{r})$, nuclear thickness

![FIG. 1: The ratio of dead cone in the medium with and without flow as a function of flow velocity in the jet direction when $\omega/E = 0.2$.](image1)

![FIG. 2: The energy loss of charm, bottom and light quarks as function of flow velocity in the jet direction when $E/\mu = 20$, $L/l_y = 5$.](image2)
functions $t_A = t_A(|r|)$, $t_B = t_B(|r - b|)$. Cross section
$\sigma = C_a 2 \pi a_0^2 / \mu^2$ ($C_a = 1$ for $gg$ and $9/4$ for $gg$ scattering) obtained in pQCD\cite{20, 21}, $\mu = g, T(\tau)$ at temperature $T(\tau)$, Using the data from a full 3D ideal hydrodynamic
simulations\cite{17}, we obtain $\langle v_z \rangle$ for 0–10% central
energy. It is shown that the effective average energy loss of
$\mu$ing obtained in pQCD\cite{5, 21}, $\mu = g, T(\tau)$ at temperature $T(\tau)$, Using the data from a full 3D ideal hydrodynamic
simulations\cite{17}, we obtain $\langle v_z \rangle = 0.08$ for 0–10% central
events of Au-Au collisions at RHIC energy, $\langle v_z \rangle$ is inside
the region of $0.065 < v_z < 0.13$ as shown in Fig. 2.

The effective average energy loss of charm, bottom and light quarks as
function of jet energy $E$ in the presence of collective flow for 0–10% central events of Au-Au collisions at RHIC energy.$\langle v_z \rangle$ is inside
The effective average energy loss of parton jet for A-A
collisions can be written as

$$\langle \Delta E \rangle = \frac{\int d^2 r \int \frac{d\omega}{d\tau} \int d\tau \int d\theta \frac{d\theta}{d^2 r} t_{AB}}{\int d^2 r \int d\tau A_{tB}}. \quad (20)$$

The opacity $L/l_g$ in $d\sigma^{(1)} / d\omega$ in Eq. (15) can be expressed as
$L/l_g = \int d\sigma(\tau) \rho(\tau, b, r + nr)$. Fig. 3 is the effective average energy loss of charm, bottom and light quarks as
function of jet energy $E$ in the presence of collective flow for 0–10% central events of Au-Au collisions at RHIC energy. It is shown that the effective average energy loss of
light quark is a bit less than that of bottom quark, but a
bit larger than that of charm quark. The difference of the effective average energy loss among three quarks is very little, which implies that the light and heavy quarks have almost the same suppression of high $p_T$ hadron spectrum for Au-Au collisions at RHIC energy.

Conclusion — In summary, based on new potential in our previous work, we studied the flow effects on energy loss of the heavy quark jets in the quark-gluon medium with collective flow and give an explanation for the heavy quark energy loss puzzle. The collective flow changes the pole of the quark propagators, which lead to reduce significantly the dead cone of radiative gluon and increase obviously the energy loss of heavy quark jets. The collective flow also affect the gluon formation time because of the moving of the target parton and the shifting of the pole of the quark propagators. It has been shown that in the region of $0.065 < v_z < 0.13$, the light and heavy quark energy loss are nearly the same. For 0–10% central events of Au-Au collisions at RHIC energy, by using the data from 3D ideal hydrodynamic simulations we obtain that the average velocity of rescattering centers along the jet direction $\langle v_z \rangle = 0.08$, the difference of the effective average energy loss among the charm, bottom and light quarks is very little. Our results shall have implications for comparisons between theory and experiment in the future.

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[1] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).
[2] P. Jacobs, X. N. Wang, Prog. Part. Nucl. Phys. 54, 443 (2005); X. N. Wang, M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).
[3] M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B 594, 371 (2001); Phys. Lett. B 538, 282 (2002).
[4] I. Vitev, M. Gyulassy, Phys. Rev. Lett. 89, 252301 (2002).
[5] Enke Wang and Xin-Nian Wang, Phys. Rev. Lett. 89, 162301 (2002).
[6] M. Djordjevic and M. Gyulassy, Nucl. Phys. A 733, 265 (2004).
[7] N. Armestro, C. A. Salgado and U. A. Wiedemann, Phys. Rev. D 69, 114003 (2004).
[8] Yu. L. Dokshitzer, D. E. Kharzeev, Phys. Lett. B 519, 199 (2001).
[9] Ben-Wei Zhang, Enke Wang, and Xin-Nian Wang, Phys. Rev. Lett. 93, 072301 (2004).
[10] S. S. Adler, et al., PHENIX Collaboration, Phys. Rev. Lett. 96, 032301 (2006).
[11] B. I. Abelev, STAR Collaboration, Phys. Rev. Lett.98, 192301 (2007).
[12] A. Adare, PHENIX Collaboration, Phys. Rev. Lett.97, 252002 (2006).
[13] J. Bielek, STAR Collaboration, Nucl. Phys. A 774, 697 (2006); X. Dong, Nucl. Phys. A 774, 343 (2006).
[14] A. Adare, PHENIX Collaboration, Phys. Rev. Lett.98, 172301 (2007).
[15] W. A. Horowitz and M. Gyulassy, Phys. Lett. B 666, 320 (2008); J. Noronha, M. Gyulassy and G. Torrieri, arXiv:0906.4099.
[16] Luan Cheng, Enke Wang, arXiv:0902.1896.
[17] T. Hirano, Phys. Rev. C65, 011901(2001); T. Hirano and K. Tsuda, Phys. Rev. C66, 054905 (2002); T. Hirano, U. Heinz, D. Kharzeev, R. Lacey and Y. Nara, Phys. Lett. B636, 299 (2006); Phys. Rev. C77, 044909 (2008).
[18] M. Gyulassy, P. Levai, I. Vitev, Phys. Rev. Lett. 85, 5535 (2000); Nucl. Phys. B 594, 371 (2001).
[19] U. A. Wiedemann, Nucl. Phys. B 588, 303 (2000).
[20] L. D. Landau and I. Pomeranchuk, Dokl. Akad. Nauk Ser. Fiz. 92 (1953) 735; A. B. Migdal, Phys. Rev. 103, 1811 (1956).
[21] Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang and Subrata Pal, Phys. Rev. C 72, 064901 (2005).