Inverse Isotope Effect on Kondo Temperature in Electron-Rattling System

Takashi Hotta

Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397

(Received June 4, 2009)

In an electron system coupled with anharmonic phonons, i.e., rattling, inverse isotope effect on the Kondo temperature $T_K$ is found to occur by the numerical evaluation of the Sommerfeld constant $\gamma$ of the Anderson-Holstein model. For the anharmonic potential of an oscillator with mass $M$ in which large $\gamma$ has been found to be almost independent of an applied magnetic field, $\gamma$ is significantly suppressed when $M$ is increased, i.e., $T_K$ is enhanced due to the relation of $\gamma \sim T_K^{-1}$ in the Kondo problem, leading to the inverse isotope effect on $T_K$. Since this phenomenon does not occur for harmonic phonons, it can be a key experiment to prove the relevance of rattling to magnetically robust heavy electron state.

KEYWORDS: Rattling, Kondo effect, Isotope effect

In traditional heavy-fermion materials such as CeCu$_2$,\textsuperscript{1} the electronic specific heat coefficient $\gamma$ is significantly suppressed by an applied magnetic field. This can be understood within the standard Kondo effect,\textsuperscript{2} i.e., the singlet formation of local magnetic moment due to the coupling with conduction electrons.\textsuperscript{3} From the viewpoint of the standard Kondo effect originating from spin degree of freedom, it is quite unusual that heavy effective mass is independent of the applied magnetic field. Thus, the magnetically robust heavy-fermion phenomenon observed in SmOs$_2$Sb$_{12}$\textsuperscript{4} has attracted much attention of condensed-matter theorists due to the renewed interest on the realization of non-magnetic Kondo effect.

The theoretical research of the Kondo effect has a history longer than forty years.\textsuperscript{5} It has been widely recognized that the Kondo-like phenomenon generally occurs in a conduction electron system hybridized with a localized entity with internal degrees of freedom. For instance, when electrons are coupled with Einstein phonons, a double-well potential is formed in an adiabatic approximation, leading naturally to a two-level system, in which Kondo has first considered a possibility of non-magnetic Kondo behavior.\textsuperscript{6,7} This two-level Kondo system has been shown to exhibit the same behavior as the magnetic Kondo effect.\textsuperscript{5,9} In the context of heavy-fermion behavior in A15 compounds, Kondo effect with phonon origin has been discussed.\textsuperscript{10,11} Further efforts to include the low-lying levels of local phonon has been done to understand the quasi-Kondo behavior in electron-phonon systems.\textsuperscript{12}

Due to the discovery of the magnetically robust heavy-fermion phenomenon in SmOs$_2$Sb$_{12}$, the research on the Kondo effect with phonon origin seems to revive in recent years. This phenomenon occurs on the filled skutterudite structure, in which rare-earth guest atom is surrounded by the cage composed of twelve pnictogens. Then, the rare-earth ion easily moves around potential minima or wide bottom of the potential inside the pnictogen cage. This anharmonic motion is called rattling, which is believed to have significant effect on electronic properties of filled skutterudites.

As an extension of the two-level Kondo problem, the four- and six-level Kondo systems have been analyzed to clarify the effect of rattling in filled skutterudites.\textsuperscript{13,14} The origin of heavy mass has been discussed on the basis of the Anderson-Holstein model.\textsuperscript{15–19} The present author has discussed the magnetic field dependence of Sommerfeld constant in the Anderson-Holstein model.\textsuperscript{20} Then, it has been shown that large $\gamma$ becomes magnetically robust when the bottom of the potential becomes flat due to the effect of anharmonicity. From these efforts, it has been gradually understood that magnetically robust heavy-fermion phenomenon actually occurs in electron-rattling systems, but we do not have an evidence for the relevance of rattling to this intriguing phenomenon. Thus, it is meaningful to consider an experiment which confirms the contribution of rattling to the Kondo effect.

In this letter, we show that inverse isotope effect occurs in the magnetically robust heavy electron state. For the purpose, we numerically evaluate the Sommerfeld constant $\gamma$ of the Anderson model coupled with local oscillation of guest atom. For the anharmonic potential in which $\gamma$ is almost independent of an applied magnetic field, when we increase the mass of the oscillator $M$, we observe the decrease of $\gamma$, i.e., the increase of the Kondo temperature $T_K$ due to the relation of $\gamma \sim T_K^{-1}$ in the Kondo problem. Namely, in the expression of $T_K \propto M^{-n}$, the exponent $n$ becomes negative. This is the inverse isotope effect on $T_K$, which can be an evidence for the relevance of anharmonic phonons to the Kondo effect, since it does not occur for harmonic phonons.

Let us first discuss how the isotope effect appears in the local electron-rattling state. The local term is expressed as $H_{\text{loc}} = U n_1 n_\downarrow + g n Q + P^2/(2M) + V(Q)$, where $U$ denotes Coulomb interaction, $n_\sigma = d_\sigma^\dagger d_\sigma$, $d_\sigma$ is an annihilation operator of localized electron with spin $\sigma$ at an impurity site, $g$ is the electron-phonon coupling constant, $n = n_\uparrow + n_\downarrow$, $Q$ is normal coordinate of the oscillator, $P$ is the corresponding canonical momentum, $M$ is the mass of the oscillator, and $V(Q)$ is the potential for the oscillator. Here we express $V(Q)$ as $V(Q) = kQ^2/2 + k_4Q^4 + k_6Q^6$, where $k$ is a spring constant and we consider fourth- and sixth-order anharmonicity, $k_4$ and $k_6$, in the potential. Note that we use such units as $\hbar = k_B = 1$ in this paper.

By following the standard procedure of quantization of phonons, we introduce the phonon operator $a$ defined through $Q = (a + a^\dagger)/\sqrt{2\hbar M}$, where $\hbar$ is the phonon energy, given by $\hbar = \sqrt{k/M}$. Then, we obtain

$$H_{\text{loc}} = U n_1 n_\downarrow + \omega \alpha(a + a^\dagger)n + \omega(a^\dagger a + 1/2) + \beta_3 \omega(a + a^\dagger)^4 + \beta_4 \omega(a + a^\dagger)^6,$$

where $\alpha$ indicates the non-dimensional electron-phonon
coupling constant defined by $\alpha=q^2/(2M\omega^3)$ and non-dimensional anharmonicity parameters, $\beta_3$ and $\beta_6$, are given by $\beta_3=(1/3M\omega^2)$ and $\beta_6=(1/8M\omega^2)$, respectively.

Here we explain $M$ dependence of parameters. First we note the relation $\omega \propto M^{-1/2}$, since we usually consider that the spring constant $k$ does not depend on $M$. From the definition, $\alpha$ itself depends on $M$ as $\alpha \propto M^{1/2}$. Then, $\alpha\omega$ does not depend on $M$. Here it is instructive to recall the isotope effect in BCS superconductor. Namely, the $M$ dependence of superconducting transition temperature $T_c$ occurs only through $\omega$, since the effective attraction between electrons mediated by harmonic phonons is given by $\alpha\omega$. Then, we obtain the famous formula $T_c \propto M^{-1/2}$ for the BCS superconductor. Concerning anharmonicity parameters, we also consider that $k_4$ and $k_6$ are independent of $M$. Thus, we obtain that $\beta_4 \propto M^{-1/2}$ and $\beta_6 \propto M^{-1}$.

In this paper, we set $\bar{\omega}=\sqrt{\bar{m}}$, $\bar{\alpha}=\sqrt{\bar{m}}\beta_4=\beta_4/\sqrt{\bar{m}}$, and $\beta_6=\beta_6/\bar{m}$, where $\bar{m}$ denotes the mass ratio of the oscillator when we substitute the oscillator atom with its isotope. The quantities without tilde denote those for $m=1$. For the actual calculations, we define the phonon basis as $|\ell\rangle=(a^{\dagger})^\ell|0\rangle/\sqrt{\beta_4}$, where $\ell$ is the phonon number and $|0\rangle$ is the vacuum state. The phonon basis is truncated at a finite number, which is set as 1000 in this paper.

We briefly explain the change of the potential shape due to $\beta_4$. The potential is rewritten as $V(q)=\alpha\omega(q^2+16\beta_4q^4+64\alpha^2\beta_6q^6)$, where $q$ is the non-dimensional length given by $q=Q\omega^2/\bar{m}$. Note that $V(q)$ is independent of $M$, since $\bar{\alpha}=\alpha\omega$, $\bar{\beta}_4=\alpha\beta_4$, and $\bar{\beta}_6=\alpha^2\beta_6$. In Fig. 1(a), we show $V(q)/\alpha\omega$ for several values of $\beta_4$ for $\beta_6=10^{-5}$ and $\bar{\beta}_6=10^{-5}$. For $\beta_4=0$, $V(q)$ has a single minimum at $q=0$. When we decrease $\beta_4$, shoulder-like structure begins to appear around $q=\pm4$ and the bottom of the potential becomes relatively wide. For $\beta_4<0.00274$, potential minima at $q \neq 0$ appear. When $\beta_4$ is smaller than $-0.003$, a couple of minima at $q \neq 0$ are gradually deep. In the following, the potential in the region of $-0.003<\beta_4<-0.002$ is called the rattling type.

As mentioned above, there occurs attractive interaction $U_{ph}$ between electrons mediated by phonons. The effective interaction $U_{eff}$ is evaluated by $U_{eff}=U-U_{ph}=E_0^0+E_2^0-2E_1^0$, where $E_n^0$ is the ground-state energy of $H_{loc}$ for local electron number $n$. For the case of harmonic potential ($\beta_4=\beta_6=0$), $U_{ph}$ is analytically evaluated as $U_{ph}=2\alpha\omega$. Thus, we obtain $U_{eff}=U-2\alpha\omega$, which does not depend on $M$, when we simply assume that $U$ is not affected by $M$.

On the other hand, for the anharmonic potential, significant $M$ dependence appears in $U_{eff}$, which will be a source of the isotope effect on the Kondo temperature. In order to visualize the $M$ dependence of $U_{eff}$, we consider the variation of $U_{eff}$ due to the increase of $M$, given by $\delta U_{eff}=U_{eff}(m)-U_{eff}(1)$, where $U_{eff}(m)$ is the effective interaction for $m$. Since $U$ is assumed to be unchanged by $M$, the variation occurs only through the change of $U_{ph}$.

In Fig. 1(b), we plot $\delta U_{eff}$ as a function of $\beta_4$ for $m=1.05$, $\beta_6=10^{-5}$, $\alpha=2$, and $U/\omega=10$. For harmonic potential, $\delta U_{eff}$ is zero, as shown by the red line. For anharmonic potential, $U_{eff}$ is decreased, i.e., $U_{ph}$ is increased, due to the increase of $M$ for the potential with single minimum, while $U_{eff}$ is increased with the increase of $M$ for the potential with a couple of deep minima at $q \neq 0$. For the rattling-type potential, the variation of $U_{ph}$ due to the increase of $M$ is relatively large, since the flat potential easily deforms by electron-phonon coupling.

Let us now consider the hybridization between localized and conduction electrons. The Hamiltonian is called the Anderson-Holstein model, given by

$$H = \sum_{k\sigma} \varepsilon_k c_{k\sigma}^\dagger c_{k\sigma} + \sum_{k\sigma} (Vc_{k\sigma}^\dagger d_{\sigma} + h.c.) + \mu n + H_{loc},$$

where $\varepsilon_k$ denotes the dispersion of conduction electron, $c_{k\sigma}$ is an annihilation operator of conduction electron with momentum $k$ and spin $\sigma$, $\mu$ is a chemical potential, and $V$ is the hybridization between conduction and localized electrons. In the following, we set $V/D=0.25$, where $D$ is a half of the conduction bandwidth. Note that we adjust $\mu$ to consider the half-filling case, even though we do not mention explicitly.

For the evaluation of the Sommerfeld constant $\gamma$ of the Anderson-Holstein model, we employ a numerical renormalization group (NRG) method, where we include efficiently the conduction electron states near the Fermi energy by discretizing momentum space logarithmically. In the actual calculation, we introduce a cut-off $\Lambda$ for the logarithmic discretization of the conduction band. Due to the limitation of computer resources, we usually keep only $L$ low-energy states. In this paper, we set $\Lambda=5$ and $L=2000$. By using the NRG method, we calculate the Sommerfeld constant $\gamma$ at a low temperature $T$. Note that $T$ is defined as $T_N=A/((N-1)/2)$.
in the NRG calculation, where $N$ denotes the number of the renormalization step. We actually evaluate $\gamma$ through the relation of $\gamma=C/T$ at a low temperature $T$, where $C$ is the specific heat of localized electron. Namely, it is necessary to obtain $C$ with high accuracy. For the purpose, we evaluate it by the numerical derivative of the entropy $S$ through the relation of $C=\partial S/\partial \log T=(S_{N-1}-S_{N})/\log(A^{1/2})$, where $S_{N}$ is the entropy at the step $N$.

Here we summarize the previous NRG results of $\gamma$ for $m=1$.\textsuperscript{20} We have found that phonon-mediated attraction is largely enhanced for $-0.0027<\beta_{4}<-0.0021$, in which the potential has wide bottom and $\delta U_{\text{eff}}$ is negative with large absolute value. There occurs a strong cancellation between Coulomb repulsion and the phonon-mediated attraction, just when the potential shape is deformed from the rattling type. We have shown that in such a situation, spin and charge fluctuations are comparable to each other, leading to the emergence of electron-rattling complex state with large and magnetically robust $\gamma$. In the present notation, magnetically robust large $\gamma$ has been found around at $\beta_{4} \approx -0.0021$ and $-0.0027$.

Now we consider the isotopic effect on $\gamma$ through the relation of $\gamma(C)/\gamma(1)$ vs. $\beta_{4}$ for $U/D=2$, $\alpha=2$, $\omega/D=0.2$, and $m=1.05$. Numerical results are shown by red circles. Solid curve is obtained from the analytic expression of $T_{K}$ of the effective s-d model except for the region with $U_{\text{eff}}<0$. (b) Exponent $\eta$ in the relation of $T_{K} \propto M^{-\eta}$ vs. $\beta_{4}$ for several values of $U$. Other parameters are $\alpha=2$, $\omega/D=0.2$, and $\beta_{0}=10^{-5}$.

For $\beta_{4}>0.0021$ and $\beta_{4}<0.0027$, we observe $\gamma(m)/\gamma(1)>1$. For $-0.0021>\beta_{4}>-0.0027$ with relatively wide bottom in the potential, when $m$ is increased, $\gamma$ is decreased, i.e., $T_{K}$ is increased due to the relation of $\gamma \sim T_{K}^{-1}$ in the Kondo problem.\textsuperscript{23} This is the inverse isotope effect, since in the standard isotopic effect, the relevant temperature is decreased with the increase of $M$, as observed in the BCS superconductor.

The inverse isotope effect is caused by the further decrease of negative effective interaction $U_{\text{eff}}$ in the region of $-0.0021>\beta_{4}>-0.0027$ due to the increase of $M$, as found in Fig. 1(b). Note that $\beta_{4}=-0.0021$, $\delta U_{\text{eff}}$ is negative, but $U_{\text{eff}}$ is positive with large absolute value. In this case, the change in $T_{K}$ is determined by the exchange interaction, not by $U_{\text{eff}}$. When $U_{\text{eff}}$ is positive and is larger than the width of the virtual bound state, the Anderson-Holstein model is reduced to the isotropic s-d model with the exchange interaction $J$,\textsuperscript{19} expressed as

$$J = V^{2} \sum_{\ell=0}^{\infty} \left[ \frac{|\Phi_{\ell}^{(0)}(1)^{2}|}{E_{\ell}^{(0)}-\mu} + \frac{|\Phi_{\ell}^{(0)}(1)|^{2}}{E_{\ell}^{(0)}+\mu-E_{\ell}^{(0)}} \right], \quad (3)$$

where $|\Phi_{\ell}^{(0)}(1)|$ is the $\ell$-th eigenstate of $H_{\text{loc}}$ for electron number $n$ with the eigenenergy $E_{\ell}^{(0)}$. Then, $T_{K}$ is given by the well-known formula $T_{K} = D e^{-1/(2\rho)}$, where $\rho$ is the density of states at the Fermi energy. The solid curve in Fig. 2(a) indicates $[T_{K}(m)/T_{K}(1)]^{-1}$. Except for the region with negative $U_{\text{eff}}$, the numerical results are reproduced by the rough estimation of $T_{K}$. For $U_{\text{eff}}<0$, analytic expression of $T_{K}$ is not obtained, but we observe the tendency in the solid curve toward the decrease of $[T_{K}(m)/T_{K}(1)]^{-1}$. Thus, it is believed that the inverse isotope effect is the essential feature of the anharmonic potential.

In Fig. 2(b), we show the $\beta_{4}$ dependence of the exponent $\eta$ in the formula of the isotopic effect $T_{K} \propto M^{-\eta}$. For the evaluation of $\eta$, it is convenient to use the relation $\eta=\log[\gamma(m)/\gamma(1)]/\log m$ for $m$ near unity. Here we set $m=1.05$. When $\gamma(m)/\gamma(1)$ is smaller than unity, the exponent becomes negative, directly suggesting the inverse isotope effect. When we increase $U$, the region with negative $\eta$ is not so rapidly suppressed, as found in the results for $U/D=2.2$ and 2.5. In particular, for $U/D=3$, $U_{\text{eff}}$ is found to be always positive in the present parameters, but we still find the negative $\eta$. Thus, the effective attraction is not the only condition for the appearance of the inverse isotope effect. Rather, the key issue is the heavy electron state dressed by rattling phonons, when the potential bottom becomes wide. From the above results, $\eta$ is negative only for the rattling-type potential, including the region with magnetically robust $\gamma$.

In order to confirm that the inverse isotope effect occurs only for anharmonic phonons, we discuss the results for harmonic phonons, i.e., $\beta_{2}=\beta_{3}=0$. Roughly speaking, the electronic state is understood by the comparison of $U$ and $2\omega$. For $U>2\omega$, the local electron state has double degeneracy of spin degree of freedom, even though the Coulomb interaction is weakened by the attraction mediated by phonons. In this region, the model is described by the s-d model with the exchange interaction $J$. On the other hand, for $U<2\omega$, the vacant and double-occupied states are degenerate, leading to the situation of the two-level Kondo system. In such a case, the Anderson-Holstein model is effectively reduced to the anisotropic s-d model, in which the longitudinal exchange
interaction $J_1$ is different from the transverse component $J_2$. Due to the immobility of bi-polaron in comparison with single polaron, $J_2$ is smaller than $J_1$. As for more details, readers can consult with Ref. 19.

In Fig. 3, we depict the $U$ dependence of $\gamma(m)/\gamma(1)$ for $m=1.05$, $\alpha=2$, $\omega/D=0.2$, and $\beta=\beta_0=0$. For comparison, we depict the curve obtained from the analytic forms of $T_K$ of the effective $s$-$d$ model. Since the expressions of $T_K$ are obtained in the strong-coupling limit, the numerical results should not perfectly agree with the analytic ones. Nevertheless, the overall behavior is well reproduced by the solid curve, even though the present situation is not in the strong-coupling limit. It is not surprising that the isotope effect is also found in $T_K$ for harmonic phonons, since the virtual phonon excitations are included in the expressions for $J$, $J_1$, and $J_2$. Here we emphasize that $\gamma(m)/\gamma(1)$ is always increased, namely, $T_K(m)/T_K(1)$ is decreased, when we increase $m$. Thus, the isotope effect on $T_K$ appears for harmonic phonons, but $T_K$ is always decreased with the increase of $m$.

In order to detect the inverse isotope effect, we should estimate experimentally $\gamma$ from the specific heat measurement, e.g., of SmOs$_4$Sb$_{12}$ with isotope of Sm, since we consider the oscillation of guest atom. The idea is simple, but it is challenging to find the direct evidence of the relevance of rattling to the Kondo effect. In the present paper, we have considered the isotope effect on $\gamma$, but we have also checked that the same effect appears in magnetic susceptibility $\chi$, although the results are not shown here. Since the correspondence between $\chi$ and $T_K$ is clear in general, it may be more practical to discuss experimentally the isotope effect on $\chi$. In any case, we believe that the change of $\gamma$ and $\chi$ in the compound including isotope is detectable in experiments.

Three comments are in order. (i) We should pay due attention to the effect of local interaction, when we discuss the actual periodic system from the impurity model. For instance, the magnitude of $\eta$ in the periodic system may not be so large in comparison with the present results. The point is that $\eta$ becomes negative for magnetically robust heavy electron state. (ii) When we substitute Sm with its isotope in SmOs$_4$Sb$_{12}$, $T_K$ may be distributed, which makes it difficult to detect the isotope effect on $\gamma$ and $\chi$. This point seems to be related to the improvement of sample quality due to the increase of filling fraction of rare earth atom in the pnictogen cage of filled skutterudites. (iii) In general, $T_K$ should be distinguished from the so-called coherence temperature concerning the formation of heavy electron state. The relation between $T_K$ and observables is not so clear in actual heavy-electron materials. When rattling is relevant to the heavy electron state, the isotope effect may significantly appear in the coherence temperature. This point may be discussed on the basis of the periodic Anderson-Holstein model, but it is one of future issues.

In summary, the Sommerfeld constant $\gamma$ of the Anderson-Holstein model has been evaluated by the NRG method. For the rattling-type potential of the oscillator, when we increase the mass of the oscillator, we have found the decrease of $\gamma$, i.e., the increase of $T_K$. The same effect also occurs in the magnetic susceptibility $\chi$. Then, we have concluded that the inverse isotope effect on $T_K$ occurs, if the magnetically robust $\gamma$ originates from rattling phonons. We expect that the measurements of $\gamma$ and $\chi$ in SmOs$_4$Sb$_{12}$ including Sm isotope will be performed in future.

The author thanks Y. Aoki for discussions. This work has been supported by a Grant-in-Aid for Scientific Research on Innovative Areas “Heavy Electrons” (No. 20102008) of the Ministry of Education, Culture, Sports, Science, and Technology, Japan. The computation in this work has been done using the facilities of the Supercomputer Center of Institute for Solid State Physics, University of Tokyo.

1) G. R. Stewart, B. Andraka, C. Quitmann, B. Treadway, Y. Shapira, and E. J. McNiff, Jr.: Phys. Rev. B 37 (1988) 3344.
2) J. Kondo: Prog. Theor. Phys. 32 (1964) 37.
3) K. Yosida: Phys. Rev. 147 (1966) 223.
4) S. Sanada, Y. Aoki, H. Aoki, A. Tsuchiya, D. Kikuchi, H. Sugawara, and H. Sato: J. Phys. Soc. Jpn. 74 (2005) 246.
5) The Kondo effect and related phenomena have been reviewed in J. Phys. Soc. Jpn. 74 (2005) 1-238.
6) J. Kondo: Physica B+C 84 (1976) 40.
7) J. Kondo: Physica B 84 (1976) 207.
8) K. Vladar and A. Zawadowski: Phys. Rev. B 28 (1983) 1564.
9) K. Vladar and A. Zawadowski: Phys. Rev. B 28 (1983) 1582.
10) T. Matsuura and K. Miyake: J. Phys. Soc. Jpn. 55 (1986) 29.
11) T. Matsuura and K. Miyake: J. Phys. Soc. Jpn. 55 (1986) 610.
12) S. Yotsuhashi, M. Kojima, H. Kasuno, and K. Miyake, J. Phys. Soc. Jpn. 74, 49 (2005).
13) K. Hattori, Y. Hirayama and K. Miyake: J. Phys. Soc. Jpn. 74 (2005) 3306.
14) K. Hattori, Y. Hirayama and K. Miyake: Proc. 5th Int. Symp. ASR-WYP-2005: Advances in the Physics and Chemistry of Actinide Compounds, J. Phys. Soc. Jpn. 75 (2006) Suppl. p. 238.
15) A. C. Hewson and D. Meyer: J. Phys.: Condens. Matter. 14 (2002) 427.
16) G. S. Jeon, T.-H. Park and H.-Y. Choi: Phys. Rev. B 68 (2003) 045106.
17) H. C. Lee and H.-Y. Choi: Phys. Rev. B 69 (2004) 075109.
18) K. Mitsumoto and Y. Ōno: Physica C 426-431 (2005) 330.
19) T. Hotta: J. Phys. Soc. Jpn. 76 (2007) 084702.
20) T. Hotta: J. Phys. Soc. Jpn. 77 (2008) 103711.
21) H. R. Krishna-murthy, J. W. Wilkins and K. G. Wilson: Phys. Rev. B 21 (1980) 1003.
22) N. Andrei, K. Furuya and J. H. Lowenstein: Rev. Mod. Phys. 55 (1983) 331.
23) K. Tanaka, T. Namiki, A. Imamura, M. Ueda, T. Saito, S. Tatsuoka, R. Miyazaki, K. Kuzuhara, Y. Aoki, and H. Sato: J. Phys. Soc. Jpn. 78 (2009) 063701.