Spin-isospin response in finite nuclei from an extended Skyrme interaction

Peiwei Wen,[1,2] Li-Gang Cao,[1,3,4,5] J. Margueron,[6] and H. Sagawa[7,8]
[1]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
[4]Kavli Institute for Theoretical Physics China, CAS, Beijing 100190, China
[5]Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, China
[6]Université de Lyon, Université Lyon 1 and CNRS/IN2P3, Institut de Physique Nucléaire de Lyon, 4 rue Enrico Fermi, 69622 Villeurbanne, France
[7]Center for Mathematics and Physics, University of Aizu, Aizu-Wakamatsu, Fukushima 965-8580, Japan
[8]RIKEN, Nishina Center, Wako 351-0198, Japan

(Received 5 January 2014; revised manuscript received 19 March 2014; published 9 April 2014)

The magnetic dipole ($M1$) and the Gamow-Teller (GT) excitations of finite nuclei have been studied in a fully self-consistent Hartree-Fock (HF) plus random phase approximation (RPA) approach by using the Skyrme energy density functionals with spin and spin-isospin densities. To this end, we adopt the extended interactions which include spin-density dependent terms and stabilize nuclear matter with respect to spin instabilities. The effect of the spin-density dependent terms is examined in the spin-flip excited state calculations. The numerical results show that those terms give appreciable repulsive contributions to the $M1$ and GT response functions of finite nuclei.

DOI: 10.1103/PhysRevC.89.044311 PACS number(s): 21.60.Jz, 24.30.Cz, 24.30.Gd, 25.40.Kv

I. INTRODUCTION

The properties of spin asymmetric matter are still very difficult to access experimentally since the ground states of nuclei have a weak or an almost zero spin-polarization: even-even spherical nuclei are not spin-polarized, while their closest odd nuclei can be weakly spin-polarized by the last unpaired nucleon, but with a moderate impact on the ground-state energy [1]. In well deformed nuclei, ground-state spin and parity assignments are still difficult to predict globally [2]. It is therefore difficult to probe the nuclear interaction in spin and spin-isospin channels from the ground-state properties of nuclei. However, in the excitation spectra of nuclei, some collective modes can provide a unique opportunity to explore the nuclear interactions in spin and spin-isospin channels [3–5]. The magnetic dipole ($M1$) and Gamow-Teller (GT) excitations are the most common collective modes of spin and spin-isospin types in nuclei. These modes have been extensively studied during the last decade, and much information on spin and spin-isospin excitations is now available [5,6]. They are of interest not only in nuclear physics but also in astrophysics. They play, for instance, an important role in predicting β decay half-lives of neutron-rich nuclei involved in the r process of the nucleosynthesis [7]. In core-collapse supernova, the GT transitions of pf-shell nuclei give an important contribution to the weak interaction decay rates that play an essential role in the core-collapse dynamics of massive stars [8–10]. The neutrino-induced nucleosynthesis may take place via GT processes in a neutron-rich environment [11]. For neutrino physics and double β decay, accurate GT matrix elements are necessary to understand the nature of neutrinos [12].

In the beginning of the 1980s, GT experiments made great progress when the (p,n) facility at the Indiana University Cyclotron Facility became operational. In 1981, the Skyrme SGII interaction was designed to give, for the first time, a detailed description of the GT data [13]. Some other Skyrme interactions, such as SLy230a and SLy230b [14], SLy4 and SLy5 [15], SkO [16], and more recently SAMi [17], have been determined with special attention to the spin and spin-isospin properties of nuclear matter and nuclei. Calculations of GT within the relativistic framework were done more recently [18,19]. The relation between the spin or the spin-isospin excitations and the central part of the nuclear interaction is, however, not a one-to-one relation, and other effects should be considered such as the spin-orbit splitting of the single-particle states and the residual spin-orbit interaction in the random phase approximation (RPA) calculations [20].

Recently an extension of the Skyrme interaction, including spin-density and spin-isospin-density dependent terms, was proposed by some of the present authors [1,21]. At variance with predictions in nuclear matter of *ab initio* methods based on realistic bare interactions [22–25], most of the standard Skyrme interactions predict spin or spin-isospin instabilities beyond the saturation density of nuclear matter [26]. The additional parameters of the extended Skyrme interaction were therefore adjusted to reproduce the results given by microscopic G matrix calculations better. The extension of the Skyrme interaction was designed to keep the simplicity of the standard Skyrme interaction and to remove the ferromagnetic instability or to shift it to larger density. However, as discussed in Ref. [27], for some Skyrme interactions which are fitted to reproduce the equation of state of nuclear matter given by microscopic Bruckner-Hartree-Fock (BHF) calculations up to a larger density region, it is difficult to get convergence when solving the mean field equations for finite nuclei sometimes.

The extended spin-density dependent terms can improve the properties of the Skyrme energy density functional in spin and spin-isospin channels by adding the weak repulsive effect. For example, the dimensionless Landau parameter G_0'

is increased by about 0.3 for four interactions: SLy5 [15], LNS [28], BSk16 [29], BSk17 [30]. In Refs. [1,21], the authors explored the effect of spin-density dependent terms on the response functions and the mean free path of neutrinos in nuclear matter as well as the ground-state properties of finite odd nuclei. The model proposed in Refs. [1,21] was constrained by microscopic G matrix predictions in uniform matter. It will be quite interesting to investigate the effect of the proposed extension of the Skyrme interaction for the spin and spin-isospin excitations of finite nuclei. In the present work, we study the contribution of spin-density dependent terms to the $M1$ and GT excitations in finite nuclei ^{48}Ca, ^{90}Zr, and ^{208}Pb with a fully self-consistent HF plus RPA framework [31]. The BSk16, BSk17, LNS, and SLy5 Skyrme parameter sets are employed in our calculations by adding the spin-density dependent terms. The new parametrizations are called BSk16st, BSk17st, LNSst, and SLy5st, which are the same as those used in Refs. [1,21]. In the present study we switch on and off the spin-density dependent terms in excited states calculations to see how much they affect the spin and spin-isospin response functions in finite nuclei.

This paper is organized as follows. In Sec. II we will briefly report the theoretical framework of the RPA based on the Skyrme interaction and its extension. The results and discussion are presented in Sec. III. Section IV is devoted to the summary anda perspective on future work.

II. FORMULA

We adopt the standard form of Skyrme interaction with the notations of Ref. [15]. The two nucleons are interacting through a zero-range, velocity dependent and density dependent Skyrme interaction with space, spin, and isospin variables $\boldsymbol{r}_i$, $\boldsymbol{\sigma}_i$ and $\boldsymbol{\tau}_i$ which reads [15]:

$$\begin{aligned} V(\boldsymbol{r}_1,\boldsymbol{r}_2) &= t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}) \\ &\quad + \tfrac{1}{2}t_1(1+x_1P_\sigma)[\boldsymbol{P}'^2\delta(\boldsymbol{r})+\delta(\boldsymbol{r})\boldsymbol{P}^2] \\ &\quad + t_2(1+x_2P_\sigma)\boldsymbol{P}'\cdot\delta(\boldsymbol{r})\boldsymbol{P} \\ &\quad + \tfrac{1}{6}t_3(1+x_3P_\sigma)\rho^\alpha(\boldsymbol{R})\delta(\boldsymbol{r}) \\ &\quad + iW_0(\sigma_1+\sigma_2)\cdot[\boldsymbol{P}'\times\delta(\mathbf{r})\boldsymbol{P}], \end{aligned} \tag{1}$$

where $\boldsymbol{r}=\boldsymbol{r}_1-\boldsymbol{r}_2$, $\boldsymbol{R}=\frac{1}{2}(\boldsymbol{r}_1+\boldsymbol{r}_2)$, $\boldsymbol{P}=\frac{1}{2i}(\nabla_1-\nabla_2)$, $\boldsymbol{P}'$ is the Hermitian conjugate of $\boldsymbol{P}$ (acting on the left), $P_\sigma=\frac{1}{2}(1+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)$ is the spin-exchange operator, and $\rho=\rho_n+\rho_p$ is the total nucleon density. Within the standard formalism, the total binding energy of a nucleus can be expressed as the integral of a Skyrme density functional [15], which includes the kinetic-energy term $\mathcal{K}$, a zero-range term $\mathcal{H}_0$, the density dependent term $\mathcal{H}_3$, an effective-mass term $\mathcal{H}_{\rm eff}$, a finite-range momentum dependent term $\mathcal{H}_{\rm fin}$, a spin-orbit term $\mathcal{H}_{\rm so}$, a spin-gradient term $\mathcal{H}_{\rm sg}$, and a Coulomb term $\mathcal{H}_{\rm Coul}$.

It was mentioned in Refs. [1,21] that the spin-density dependent terms may lead very important effects on the spin and the spin-isospin properties of finite nuclei and nuclear matter. That is, the dimensionless Landau parameter G_0' is increased by about 0.3 for four interactions: SLy5, LNS, BSk16, and BSk17. The related formulas and discussions of the properties of Landau parameters are presented in the Appendix. The improved Skyrme energy density functional in spin and spin-isospin channels will give also substantial contributions to the spin and spin-isospin excitations in finite nuclei, such as $M1$ and GT excitations. In present work, we will study the effect of spin-density dependent terms on the spin dependent $M1$ and GT excitations in finite nuclei ^{48}Ca, ^{90}Zr, and ^{208}Pb.

Here, we will summarize briefly the formulas for RPA calculations. The calculations are done within the Skyrme HF plus RPA. The well known RPA method [32,33] in matrix form is given by

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix}\begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} = E_\nu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix}, \tag{2}$$

where E_ν is the energy of the νth RPA state and X^ν, Y^ν are the corresponding forward and backward amplitudes, respectively. The matrix elements A and B are expressed as

$$A_{mi,nj} = (\epsilon_m-\epsilon_n)\delta_{mn}\delta_{ij} + \langle mj|V_{\rm res}|in\rangle, \tag{3}$$

$$B_{mi,nj} = \langle mn|V_{\rm res}|ij\rangle. \tag{4}$$

The particle-hole (p-h) matrix elements are obtained from the Skyrme energy density functional including all the terms in Eqs. (3)–(5). The explicit forms of the matrices A and B are given in Ref. [31] in the case of Skyrme force. In general, the expression of the residual interaction is derived from the second derivative of the energy density with respect to the density $\rho_{\rm st}$ with the spin and isospin indices,

$$V_{\rm res} = \sum_{{\rm st}s't'} \frac{\delta^2 H}{\delta\rho_{\rm st}\delta\rho_{s't'}}, \tag{5}$$

where H is the HF energy density functional. According to Eq. (5), the antisymmetrized particle-hole interaction induced by the spin-density dependent terms (A1) are expressed as

$$\begin{aligned} V_{\rm res}^{\rm qq} &= v_0^{\rm qq}\delta(\vec{r}_1-\vec{r}_2) + v_\sigma^{\rm qq}\delta(\vec{r}_1-\vec{r}_2)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2, \\ V_{\rm res}^{\rm qq'} &= v_0^{\rm qq'}\delta(\vec{r}_1-\vec{r}_2) + v_\sigma^{\rm qq'}\delta(\vec{r}_1-\vec{r}_2)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2, \end{aligned} \tag{6}$$

where the functions v_0 and v_σ depend only on the radial coordinate r and their detailed expressions are given by

$$\begin{aligned} v_0^{\rm qq}(r) &= -\frac{t_3^s}{12}\big(x_3^s-1\big)\rho_s^{\gamma_s} - \frac{t_3^{\rm st}}{12}\big(x_3^{\rm st}-1\big)\rho_{\rm st}^{\gamma_{\rm st}}, \\ v_0^{\rm qq'}(r) &= \frac{t_3^s}{12}\big(x_3^s+2\big)\rho_s^{\gamma_s} + \frac{t_3^{\rm st}}{12}\big(x_3^{\rm st}+2\big)\rho_{\rm st}^{\gamma_{\rm st}}, \\ v_\sigma^{\rm qq}(r) &= \frac{t_3^s}{48}\big[\gamma_s(\gamma_s-1)\rho_s^{\gamma_s-2}\big(3\rho^2-\big(2x_3^s+1\big)\rho_t^2-\rho_{\rm st}^2\big) \\ &\quad + \rho_s^{\gamma_s}\big((\gamma_s+1)(\gamma_s+2)\big(2x_3^s-1\big)-2\big)\big] \\ &\quad + \frac{t_3^{\rm st}}{48}\big[\gamma_{\rm st}(\gamma_{\rm st}-1)\rho_{\rm st}^{\gamma_{\rm st}-2}\big(3\rho^2+\big(2x_3^{\rm st}-1\big)\rho_s^2 \\ &\quad - \big(2x_3^{\rm st}+1\big)\rho_t^2\big) \\ &\quad + \rho_{\rm st}^{\gamma_{\rm st}}\big(-(\gamma_{\rm st}+1)(\gamma_{\rm st}+2)+2(2x_3^{\rm st}-1)\big)\big], \end{aligned}$$

TABLE I. The centroid energies of low energy (high energy) peaks of GT response functions in ^{208}Pb with the parameters of spin-density dependent terms listed in Table III. The units are in MeV.

	SLy5	SLy5st1	SLy5st2	SLy5st3	SLy5st
^{208}Pb	9.87(18.13)	10.17(18.39)	10.45(18.63)	10.69(18.87)	10.92(19.07)

$$v_\sigma^{qq'}(r) = \frac{t_3^s}{48}\big[\gamma_s(\gamma_s-1)\rho_s^{\gamma_s-2}\big(3\rho^2-\big(2x_3^s+1\big)\rho_t^2-\rho_{st}^2\big) + \rho_s^{\gamma_s}\big((\gamma_s+1)(\gamma_s+2)\big(2x_3^s-1\big)+2\big)\big] + \frac{t_3^{st}}{48}\big[-\gamma_{st}(\gamma_{st}-1)\rho_{st}^{\gamma_{st}-2}\big(3\rho^2+\big(2x_3^{st}-1\big)\rho_s^2 - \big(2x_3^{st}+1\big)\rho_t^2\big) + \rho_{st}^{\gamma_{st}}\big((\gamma_{st}+1)(\gamma_{st}+2)+2\big(x_3^{st}-1\big)\big)\big]. \quad (7)$$

We will use the following operator for $M1$ excitation:

$$\hat{F}_{M1} = \sum_{i=1}^{A}\{g_i^s\overrightarrow{s_i}+g_i^l\overrightarrow{l}\}, \quad (8)$$

where the spin g factors are $g^s = 5.586$ for protons and $g^s = -3.826$ for neutrons, respectively, and the orbital g factors are $g^l = 1.0$ for protons and g^l=0.0 for neutrons, respectively, in units of the nuclear magneton $\mu_N = e\hbar/2mc$. We will also study the charge-exchange GT excitations. The GT external operator reads

$$\hat{F}_{GT\pm} = \sum_{i=1}^{A}\overrightarrow{\sigma}(i)t_\pm(i). \quad (9)$$

III. RESULTS AND DISCUSSIONS

The ground-state properties of nuclei ^{48}Ca, ^{90}Zr, and ^{208}Pb are calculated in the coordinate space with a box approximation. The radius of the box is taken to be 20 fm in which the continuum is discretized in the large box. The 70 MeV energy cutoff in the single-particle energy is adopted in the calculations. With this energy cutoff, we have checked that the Gamw-Teller Ikeda sum rules are satisfied by 99.97% with and without the spin-density dependent terms. Main calculations are performed including or excluding the spin-density dependent terms on top of the SLy5 parameter set. For comparisons, we study also the results of other parameter sets, BSk16, BSk17, and LNS.

In Refs. [1,21], the parameters of spin-density dependent terms are introduced to reproduce the BHF results better. We investigate firstly the effect of spin-density dependent terms on the GT excitation in ^{208}Pb. For even-even nucleus ^{208}Pb, the spin-density and spin-isospin density have no contribution to the ground state properties. Only the residual interactions related to t_3^s and t_3^{st} in RPA contribute to the excitation energies of GT states. We introduce various values of t_3^s and t_3^{st} in the calculations changing simultaneously by a step of 1500 MeV fm$^{3\gamma_s-2}$ for t_3^s and 5000 MeV fm$^{3\gamma_{st}-2}$ for t_3^{st}. The values of parameters are listed in Table III in the Appendix. The results are shown in Table I and Fig. 1. With larger t_3^s and t_3^{st} values, the peaks of GT response function are pushed upwards gradually. The energy shift is about 0.25 MeV for both the low-lying and high-lying response functions between the neighboring two sets of parameters in Table I. The energy weighted sum rule values are also increased by 16% in ^{208}Pb by the spin-density dependent terms in SLy5st interaction.

In Fig. 2, we display the response functions for GT excitation in ^{48}Ca, ^{90}Zr, and ^{208}Pb calculated by the Skyrme interactions with and without the contribution of the spin-density dependent terms denoted by SLy5st and SLy5, respectively. The solid (dotted) line represents the results including (excluding) the spin-density dependent terms in the RPA calculations. The dots show the corresponding experimental GT response. For ^{48}Ca, the inclusion of spin-density dependent terms slightly pushes the GT response function upwards. The centroid energies are 10.36 and 10.75 MeV when one excludes and includes those terms. The theoretical results given by SLy5 and SLy5st are both close to the experimental value 10.5 MeV [34]. Unfortunately, calculations with SLy5 and SLy5st parameter sets cannot reproduce the low-lying state which is found around 3.0 MeV experimentally. For ^{90}Zr and ^{208}Pb, as one can see from Fig. 2, the inclusion of the spin-density dependent terms tends to slightly increase the high-lying strength on the one hand and to decrease the low-lying strength on the other hand. The excitation energies are shifted up in energy for both the low-lying and high-lying strengths by the spin-dependent terms. Without the spin-density dependent terms, the centroid energies of the low-lying and high-lying strengths are 5.23 MeV (9.87 MeV) and 16.26 MeV (18.13 MeV) for ^{90}Zr (^{208}Pb). Including the spin-density dependent terms, the centroid energies of the low-lying and high-lying strengths become 5.53 MeV (10.92 MeV) and 16.68 MeV (19.07 MeV) for ^{90}Zr (^{208}Pb).

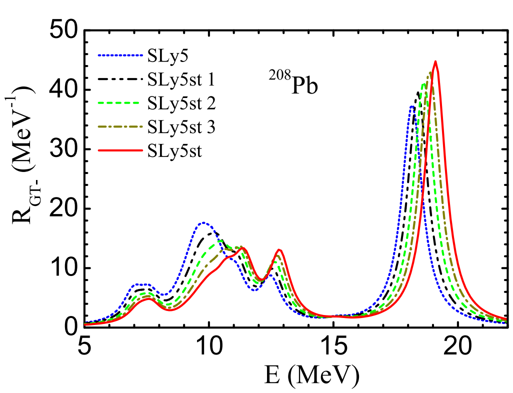

FIG. 1. (Color online) RPA response functions of ^{208}Pb for GT excitation calculated by the Skyrme HF plus RPA approach based on the SLy5 interaction by increasing the parameters t_3^s and t_3^{st} gradually from SLy5 to SLy5st with the given steps. The parameters are listed in Table III. See the text for details.

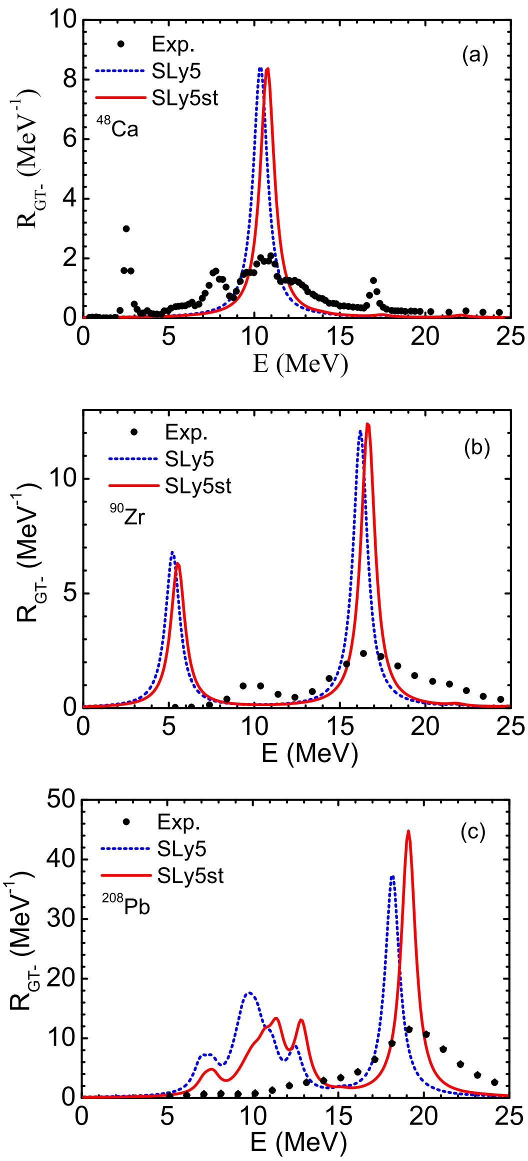

FIG. 2. (Color online) RPA response functions of ^{48}Ca (a), ^{90}Zr (b), and ^{208}Pb (c) for GT excitations calculated by the Skyrme HF plus RPA approach based on the SLy5 interaction. The solid (dotted) line is the result given by including (excluding) the spin-density dependent terms. A Lorentzian smearing parameter equals 1 MeV. The experimental responses from Refs. [34,36,37] are shown by the dots.

The energy shift is 0.3 MeV (1.05 MeV) for the low-lying and 0.42 MeV (0.94 MeV) for the high-lying states in ^{90}Zr (^{208}Pb). The energy shift given by the Skyrme HF plus RPA calculations is qualitatively the same as those estimated by the semiclassical Steinwedel-Jensen model for ^{208}Pb in Ref. [21]. The upward shift of the centroid energies can be understood as follows: the spin-density dependent terms give a strong repulsive contribution to the matrix elements of RPA for the GT calculations because the residual interactions or the Landau parameter G_0' changes to be more positive from -0.14 to 0.15 when the spin-density dependent terms are included. It also can be seen that the RPA collective state located at 19.07 MeV with the spin-density dependent terms in ^{208}Pb is very close to the experimental GT excitation energy of 19.2 ± 0.2 MeV [35,36]. For ^{90}Zr, the calculated values with or without the contribution of the spin-density dependent terms are larger than the experimental value of 15.60 MeV [37]. There also exist theoretical GT results[17,38] given by Skyrme interactions SGII, SAMi and SKO′ for ^{208}Pb. Compared to the experimental data of 19.2 ± 0.2 MeV in ^{208}Pb, the results given by SGII and SKO′ Skyrme interactions overestimate and underestimate by about 1.8 MeV. For a more recent parameter set of the SAMi interaction, the peak energy is 19.3 MeV, which reproduces the experimental data very well.

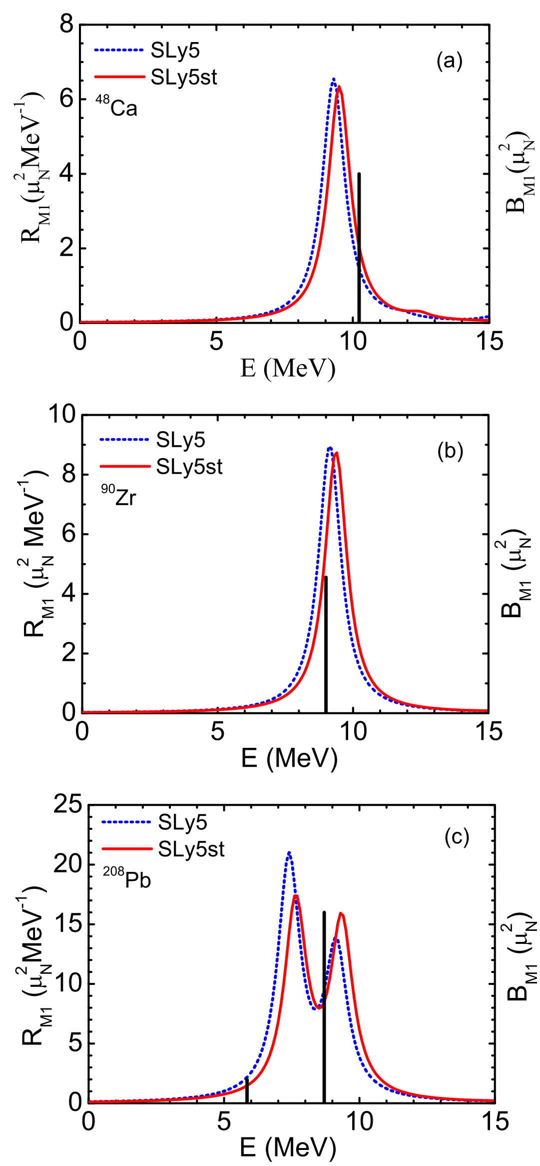

FIG. 3. (Color online) RPA response functions of ^{48}Ca (a), ^{90}Zr (b), and ^{208}Pb (c) for $M1$ excitations calculated by the Skyrme HF plus RPA approach based on the SLy5 interaction. The solid (dotted) line is the result given by including (excluding) the spin-density dependent terms. A Lorentzian smearing parameter equals 1 MeV. The experimental $B(M1)$ values from Refs. [39–45] are shown by the bars.

TABLE II. The energies of GT and $M1$ excitations for ^{48}Ca, ^{90}Zr, and ^{208}Pb calculated within BSk16, BSk17, and LNS interactions with and without the contribution from spin-density dependent terms (SDDT). For GT peaks in ^{90}Zr and ^{208}Pb, two values correspond to the low energy and high energy peaks, respectively. The values in fifth and eighth columns are the energy shift due to the spin-density dependent terms. The units are MeV.

		GT			$M1$		
		No SDDT	with SDDT	Energy shift	No SDDT	with SDDT	Energy shift
^{48}Ca	BSk16	10.69	11.00	0.31	9.3	9.8	0.5
	BSk17	10.66	11.28	0.62	9.6	10.4	0.8
	LNS	12.04	12.48	0.44	10.1	10.3	0.2
	SLy5	10.36	10.75	0.39	9.3	9.5	0.2
^{90}Zr	BSk16	7.25(16.72)	7.44(17.06)	0.19(0.34)	8.9	9.5	0.6
	BSk17	6.85(16.61)	7.16(17.31)	0.31(0.70)	9.1	10.2	1.1
	LNS	7.43(17.32)	7.74(17.81)	0.31(0.49)	9.5	9.7	0.2
	SLy5	5.23(16.26)	5.53(16.68)	0.30(0.42)	9.1	9.4	0.3
^{208}Pb	BSk16	11.61(18.55)	11.92(19.34)	0.31(0.79)	4.7(7.6)	5.6(8.0)	0.9(0.4)
	BSk17	11.28(18.38)	11.89(20.02)	0.61(1.64)	4.8(7.9)	6.3(8.6)	1.5(0.7)
	LNS	11.45(19.60)	12.22(20.56)	0.77(0.96)	7.4(9.5)	7.6(9.8)	0.2(0.3)
	SLy5	9.87(18.13)	10.92(19.07)	1.05(0.94)	7.4(9.1)	7.6(9.3)	0.2(0.2)

We also investigate the effect of the extended Skyrme interaction on the $M1$ excitation by the RPA calculations for ^{48}Ca, ^{90}Zr, and ^{208}Pb. The results are shown in Fig. 3. The spin-density dependent terms are included or excluded in the calculations to clarify their influence. For the RPA results of ^{208}Pb, the proton $1h_{11/2} \rightarrow 1h_{9/2}$ configuration contributes mainly to the lower energy peak of the response function, and the neutron $1i_{13/2} \rightarrow 1i_{11/2}$ configuration plays the main role in the higher energy peak. For ^{90}Zr (^{48}Ca), the $M1$ response function mainly comes from the neutron configuration of $1g_{9/2} \rightarrow 1g_{7/2}$ ($1f_{7/2} \rightarrow 1f_{5/2}$). The results show that the inclusion of the spin-density dependent terms increases the energies of $M1$ states in ^{48}Ca, ^{90}Zr, and ^{208}Pb. The peak energies of $M1$ excitation in ^{208}Pb are 7.6 MeV (7.4 MeV) for the lower one and 9.3 MeV (9.1 MeV) for the higher one, including (excluding) the spin-density dependent terms. The peak energy of the $M1$ excitation in ^{90}Zr is 9.4 MeV (9.1 MeV) by including (excluding) the spin-density dependent terms. The energy shift is less than 0.3 MeV for both ^{90}Zr and ^{208}Pb. For ^{48}Ca, the peak energy of the $M1$ excitation is 9.5 MeV (9.3 MeV) by including (excluding) the spin-density dependent terms. The energy shift is about 0.2 MeV, which is almost the same as those of ^{90}Zr and ^{208}Pb. The effect of the spin-dependent terms is predicted to be smaller on the distribution of the $M1$ response function compared with that on the GT excitation. This can be understood by the change of the Landau parameters when the spin-density dependent terms are included. The difference of G_0 which contributes to the $M1$ excitation is about 0.07 (from 1.12 to 1.19), while the change of G_0' which plays the dominant role in GT excitation is about 0.3 (from -0.14 to 0.15). In Fig. 3 we show also the experimental data of the $M1$ excitations for For ^{48}Ca, ^{90}Zr, and ^{208}Pb. The experimental data for the $M1$ excitations in ^{208}Pb are found at $E_x = 5.85$ MeV for the low-lying component and between $E_x = 7.1$ and 8.7 MeV for the high-lying component [39–41], while in ^{90}Zr the $M1$ strengths exist between $E_x = 9.0$ and 9.53 MeV [42–44]; for ^{48}Ca, the experimental excited energy is 10.23 MeV [45]. We can see that the present theoretical results, taking or not taking into account the contribution of the spin-density dependent terms, slightly overestimate the experimental data in energy for ^{90}Zr and ^{208}Pb, but underestimate the experimental data for ^{48}Ca.

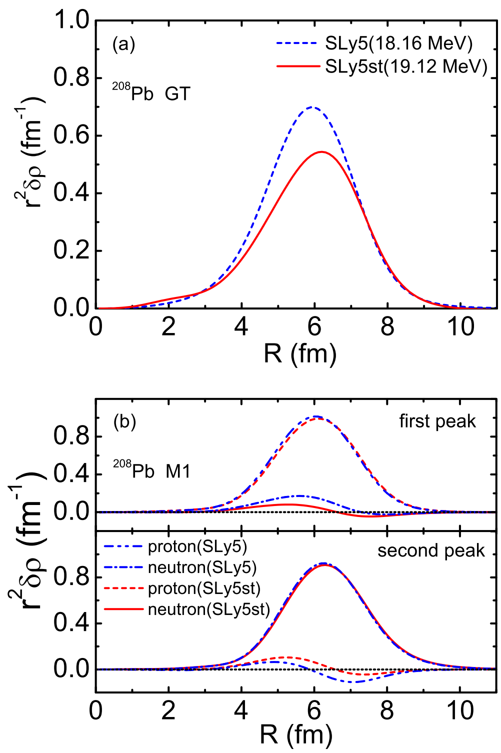

FIG. 4. (Color online) Calculated transition densities of GT (a) and $M1$ (b) excitations in ^{208}Pb given by SLy5 and SLy5st.

To make our conclusion more general, we have also calculated the GT and $M1$ response functions for ^{48}Ca, ^{90}Zr, and ^{208}Pb by using other parameter sets LNSst, BSk16st, and BSk17st taken from Refs. [1,21]. For BSk17st, all the Skyrme parameters are refitted to obtain reasonable ground-state properties with the spin-density dependent terms. The calculated peak energies are shown in Table II with and without the contributions of spin-density dependent terms. We find that the peak energies of GT and $M1$ response functions for all the parameter sets are shifted upward by including the spin-density dependent terms. The energy shift is between 0.2 and 1.6 MeV depending on the parameter sets used; i.e., repulsive effects are found always for the parameter sets LNSst, BSk16st, and BSk17st in this study, but with some quantitative variations.

The calculated transition densities of GT and $M1$ states in ^{208}Pb are shown in Fig. 4. Due to the contribution of the spin-density dependent terms, the transition densities of GT states are changed slightly. The changes in the transition densities of $M1$ excitations are appreciable just around the nuclear surface.

IV. SUMMARY AND PERSPECTIVE

In summary, we have studied the effect of the spin-density dependent terms of the Skyrme energy density functional on the $M1$ and GT giant excitations in ^{48}Ca, ^{90}Zr, and ^{208}Pb using Skyrme HF plus RPA calculations. The calculations are carried out with the SLy5, BSk16, BSk17, and LNS Skyrme interactions and their extended Skyrme interactions, in which the spin-density dependent terms are added to the parameter set to mimic the BHF results in spin and spin-isospin channels. The inclusion of spin-density dependent terms is known to give no contribution to the ground state of even-even nuclei, while the residual interactions from the spin-density dependent terms give substantial repulsive effect and shift the $M1$ and GT response functions of finite nuclei to higher energy.

The main conclusion we can draw from the present study is that the spin and spin-isospin response functions can be changed without altering the ground-state properties. Since the parameters related to the spin-density dependent terms are introduced to the existing Skyrme interaction, it is unclear whether the new interaction improves the agreement with the experimental data of spin dependent excitations or not. A better strategy could be to perform a global fitting of the parameters of the spin independent and spin dependent density terms on the same footing. Recently, the effect of tensor force on the various response of nuclear systems was studied extensively [46–48] and the important contributions to the spin and spin-isospin response in nuclear matter and finite nuclei were pointed out. It is a future challenge to include both the spin dependent terms and the tensor force in the parameter fit procedure. This study will be discussed in a forthcoming paper.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China under Grants No. 10875150 and No. 11175216, and is supported in part by the Project of Knowledge Innovation Program (PKIP) of Chinese Academy of Sciences, Grant No. KJCX2-EW-N01. This work is partially supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology by a Grant-in-Aid for Scientific Research under Program No. (C(2))20540277.

APPENDIX: LANDAU PARAMETERS

The Skyrme interaction has been extended to include spin-density dependent terms which can improve the properties of the energy density functional in the spin and spin-isospin channels [21]. That is,

$$V^{\text{add.}}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \tfrac{1}{6}t_3^s\big(1 + x_3^s P_\sigma\big)[\rho_s(\boldsymbol{R})]^{\gamma_s}\delta(\boldsymbol{r}) + \tfrac{1}{6}t_3^{\text{st}}\big(1 + x_3^{\text{st}} P_\sigma\big)[\rho_{\text{st}}(\boldsymbol{R})]^{\gamma_{\text{st}}}\delta(\boldsymbol{r}), \quad \text{(A1)}$$

where $\rho_s = \rho_\uparrow - \rho_\downarrow$ is the spin density and $\rho_{\text{st}} = \rho_{n\uparrow} - \rho_{n\downarrow} - \rho_{p\uparrow} + \rho_{p\downarrow}$ is the spin-isospin density. The spin symmetry is satisfied if the power of the density dependent terms γ_s and γ_{st} are both even integers.

In the following study, the spin-density dependent terms (A1) are added to the original Hamiltonian. Then the density dependent part of the Skyrme energy density functional,

$$\mathcal{H}_3 = \frac{t_3}{48}\rho^\alpha\big[3\rho^2 + (2x_3 - 1)\rho_s^2 - (2x_3 + 1)\rho_t^2 - \rho_{\text{st}}^2\big], \quad \text{(A2)}$$

has the extra density dependent terms $\mathcal{H}_3^s$ and $\mathcal{H}_3^{\text{st}}$, which read

$$\mathcal{H}_3^s = \frac{t_3^s}{48}\rho_s^{\gamma_s}\big[3\rho^2 + \big(2x_3^s - 1\big)\rho_s^2 - \big(2x_3^s + 1\big)\rho_t^2 - \rho_{\text{st}}^2\big], \quad \text{(A3)}$$

$$\mathcal{H}_3^{\text{st}} = \frac{t_3^{\text{st}}}{48}\rho_{\text{st}}^{\gamma_{\text{st}}}\big[3\rho^2 + \big(2x_3^{\text{st}} - 1\big)\rho_s^2 - \big(2x_3^{\text{st}} + 1\big)\rho_t^2 - \rho_{\text{st}}^2\big], \quad \text{(A4)}$$

TABLE III. Parameters of the spin-density dependent terms t_3^s (in MeV fm$^{3\gamma_s - 2}$), t_3^{st} (in MeV fm$^{3\gamma_{\text{st}} - 2}$), x_3^s, and x_3^{st} for the interactions used in the text. We also show the dimensionless Landau parameters G_0 and G_0' obtained from various Skyrme parameter sets with and without the spin-density dependent terms.

	t_3^s	t_3^{st}	x_3^s	x_3^{st}	γ_s	γ_{st}	G_0	G_0'
SGII							0.02	0.51
SAMi							0.15	0.35
SLy5							1.12	−0.14
SLy5st1	0.15×10^4	0.5×10^4	−3	0	2	2	1.14	−0.07
SLy5st2	0.30×10^4	1.0×10^4	−3	0	2	2	1.16	0.04
SLy5st3	0.45×10^4	1.5×10^4	−3	0	2	2	1.18	0.08
SLy5st	0.60×10^4	2.0×10^4	−3	0	2	2	1.19	0.15
BSk16st	2.00×10^4	1.5×10^4	−2	0	2	2	−0.32	0.75
BSk17st	4.00×10^4	3.0×10^4	−0.5	−3	2	2	−0.03	0.99
LNSst	0.60×10^4	1.5×10^4	−1	0	2	2	0.95	0.45

where $\rho_t = \rho_n - \rho_p$. The mean field potential U_q, where $q = n, p$, gets additional terms

$$U_q^{\text{add.}} = \frac{t_3^s}{12}\rho_s^{\gamma_s}\left[\left(2 + x_3^s\right)\rho - \left(1 + 2x_3^s\right)\rho_q\right] + \frac{t_3^{\text{st}}}{12}\rho_{\text{st}}^{\gamma_{\text{st}}}\left[\left(2 + x_3^{\text{st}}\right)\rho - \left(1 + 2x_3^{\text{st}}\right)\rho_q\right]. \quad \text{(A5)}$$

In symmetric nuclear matter the Landau parameters G_0 and G_0' [49] are also modified by the additional terms

$$\frac{G_0^{\text{add.}}}{N_0} = \frac{t_3^s}{48}\gamma_s(\gamma_s - 1)\left[3\rho^2 - \left(2x_3^s + 1\right)\rho_t^2 - \rho_{\text{st}}^2\right]\rho_s^{\gamma_s - 2} + \frac{t_3^{\text{st}}}{12}\left(x_3^{\text{st}} - \frac{1}{2}\right)\rho_{\text{st}}^{\gamma_{\text{st}}} + \frac{t_3^s}{24}\left(x_3^s - \frac{1}{2}\right)(\gamma_s + 1)(\gamma_s + 2)\rho_s^{\gamma_s}, \quad \text{(A6)}$$

$$\frac{G_0'^{\text{add.}}}{N_0} = \frac{t_3^{\text{st}}}{48}\gamma_{\text{st}}(\gamma_{\text{st}} - 1)\left[3\rho^2 + \left(2x_3^{\text{st}} - 1\right)\rho_s^2 - \left(2x_3^{\text{st}} + 1\right)\rho_t^2\right]\rho_{\text{st}}^{\gamma_{\text{st}} - 2} - \frac{t_3^s}{24}\rho_s^{\gamma_s} - \frac{t_3^{\text{st}}}{48}(\gamma_{\text{st}} + 2)(\gamma_{\text{st}} + 1)\rho_{\text{st}}^{\gamma_{\text{st}}}. \quad \text{(A7)}$$

In Table III we show the parameters used in this study and the Landau parameters G_0 and G_0' at saturation density calculated with the corresponding Skyrme interactions. To keep the spin symmetry, we set γ_s and γ_{st} equal to 2. The values for the other parameters t_3^s, t_3^{st}, x_3^s, and x_3^{st} are fixed by an optimal fit of the BHF results in spin and spin-isospin channels in a higher density region than the normal density. The density dependence of the Landau paramaeters is also shown in Fig. 5. The spin instabilities have been discussed in Ref. [21]; as shown in Fig. 5, the contributions of the spin-density dependent terms are repulsive enough to remove the spin instabilities for BSk16st, BSk17st, LNSst, and SLy5st parameter sets. For the parameter sets SGII and SAMi, the spin instabilities appear at densities 0.441 fm^{-3} (0.803 fm^{-3}) and 0.641 fm^{-3} (0.838 fm^{-3}) in the spin (spin-isospin) channel.

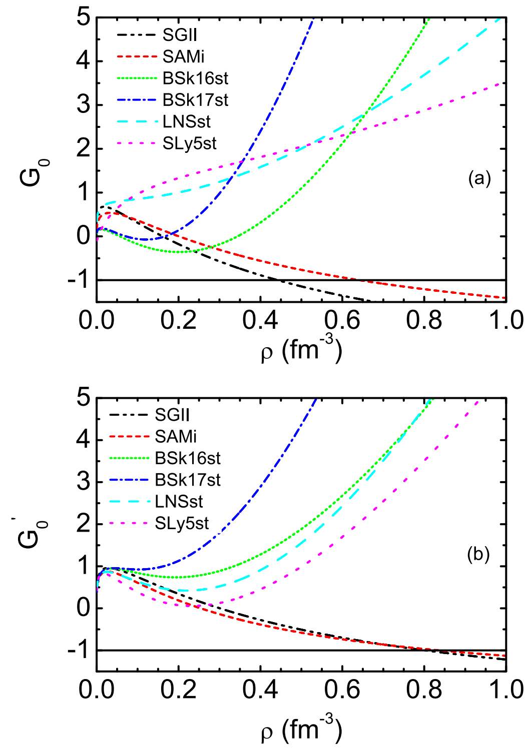

FIG. 5. (Color online) The Landau parameters G_0 (a) and G_0' (b) as a function of densiy ρ in symmetric nuclear matter. The results are calculated by using SGII, SAMi, BSk16st, BSk17st, LNSst, and SLy5st parameter sets.

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