Gamow-Teller β^+ decay of deformed nuclei near the proton drip line

F. Frisk,[1] I. Hamamoto,[1] and X. Z. Zhang[1,2]
[1]Department of Mathematical Physics, Lund Institute of Technology, University of Lund, Lund, Sweden
[2]Institute of Atomic Energy, Beijing, The People's Republic of China
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Using a quasiparticle Tamm-Dancoff approximation (TDA) based on deformed Hartree-Fock (HF) calculations with Skyrme interactions, the distribution of the Gamow-Teller (GT) β^+ decay strength is estimated for the HF local minima of even-even deformed nuclei near the proton drip line in the region of $28<Z<66$. The distribution often depends sensitively on the nuclear shape (namely, oblate or prolate). In the region of $Z<50$ the possibility of observing β-delayed proton emission depends sensitively on the excess of Z over $Z=N$. In the region of $Z>50$ almost the entire estimated GT strength is found to lie below the ground states of the even-even mother nuclei, and the observation of the total GT strength by β-delayed charged-particle(s) emission will be of essential importance.

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I. INTRODUCTION

In β-stable nuclei the Gamow-Teller (GT) giant resonance (GR) lies above the ground state, so that it can be populated by charge-exchange reactions such as (p,n) or $(^3\mathrm{He},t)$. In contrast, almost the entire GT strength of medium-heavy nuclei near the proton drip line is expected to lie below the ground states of the mother nuclei and, thus, may be populated in principle by β^+ decay [1]. If the β decay can detect the GT strength up to the giant resonance region, a reduction factor for the GT strength can be experimentally obtained, since the amount of GT strength extracted from charge-exchange reactions has always suffered from the problem of how to subtract the background in the reactions [2]. The knowledge of GT β^+ decays of nuclei with $Z<40$ near proton drip line is also of essential importance for the rapid-proton capture process, the so-called *rp* process, in astrophysics [3]. The deformed proton drip line nuclei, for which the GT strength distribution is estimated in our present work, have a good chance of being studied in the near future by the experimental facilities for radioactive ion beams, which are currently being constructed or planned [4].

In order to obtain the distribution of the total GT strength in proton drip line nuclei, it is essential not only to perform β-γ spectroscopy, but also to measure the processes of β-delayed charged-particle emission [3]. This is because in traditional β-γ spectroscopy the GT β decay to very low-lying states in daughter nuclei, for which the available decay energy is larger, is so much favored in comparison with that to higher-lying states. In Ref. [5] we have studied the distribution of the GT β^+ decay strength of three $N=Z$ deformed nuclei, $^{72}_{36}\mathrm{Kr}_{36}$, $^{76}_{38}\mathrm{Sr}_{38}$, and $^{80}_{40}\mathrm{Zr}_{40}$, having been stimulated by learning [6] of the possibility of measuring the process of the β-delayed proton emission in respective daughter nuclei. Those three $N=Z$ nuclei lie just on the borderline of the nuclear chart in which the major part of GT GR is going to be populated by GT β^+ decay [1]. Namely, the result obtained in Ref. [5] shows that in those nuclei about a half of the total GT strength lies below the ground states of the mother nuclei. In proton drip line nuclei with $Z>50$, it is expected that the peak of the GT GR will lie well below the ground states of the mother nuclei. Thus, in this paper, we study the GT β^+ decay strength distribution in deformed [in our Hartree-Fock (HF) calculation] nuclei in the region of $28<Z<66$ near the proton drip line. We concentrate here on deformed nuclei, since for spherical nuclei a better estimate can be made in spherical shell-model calculations [7]. The deformed shapes of the nuclei presently investigated were predicted more than 10 years ago [8].

When we find a deformed solution in our HF calculations with Skyrme interactions, which has either the lowest energy or the energy very close to that of the lowest minimum with spherical shape, we estimate the distribution of the GT strength based on the HF local minima. We do so partly because which of the energetically close-lying minima becomes lowest depends sometimes on the Skyrme interactions used and partly because all energetically close-lying shapes are interesting since in phenomena such as the *rp* process nuclei have a finite temperature.

In Sec. II our model is described, while in Sec. III the results of numerical calculations are presented and discussed. In Sec. IV a conclusion is given.

II. DESCRIPTION OF OUR MODEL

The model used in the present work is, in essence, the same as the one employed in Ref. [5] and is briefly summarized in the present section. First, we perform deformed HF calculations [9] with Skyrme interactions, using the BCS approximation with a given pairing-gap parameter, which is assumed to be independent of deformation. We have found that the HF local minimum, which in the nuclei studied presently is often obtained for both a prolate and an oblate deformation, appears at nearly the same value of the quadrupole moment even if we vary the value of the constant pairing gap from 1.2 to, say, 0.8 MeV. Since in the ground state of a real nucleus, which is approximated by a HF local minimum, the value of the gap parameter is supposed to be around 1 MeV, the present approximate way of treating the pair correlation may be acceptable. Because we want to avoid using the calculated one-particle levels lying higher up

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in the continuum, we do not solve the BCS equations for a given coupling constant, noting that the proton Fermi levels in the present nuclei are close to the continuum. At the obtained HF minimum we estimate GT excitation modes with the Tamm-Dancoff approximation (TDA), using a schematic separable spin-isospin interaction [10],

$$V_{12}=X_{\sigma\tau}\vec{\sigma}_1\cdot\vec{\sigma}_2\vec{\tau}_1\cdot\vec{\tau}_2. \tag{1}$$

A logically more reasonable model would be to solve the TDA or random phase approximation (RPA) with the effective interaction as the one used in the HF calculation. However, the present Skyrme interaction cannot be used as such a self-consistent effective interaction, since the pair correlation does not come from the Skyrme interaction. In our present work we will be satisfied with using the interaction (1) in the TDA. We have indeed found that the result of Ref. [1], in which the same Skyrme interaction as the one used in the spherical HF calculation is employed in spherical TDA calculations without a pair correlation, can be well reproduced by using the separable interaction (1) with $X_{\sigma\tau}=20/A$ MeV. Some discussion of the strength of the interaction (1) can be found in Ref. [11], in which β-strength functions of many nuclei are evaluated using somewhat different models with different intentions.

The β-decay Q value is a crucial quantity if one is interested in the partial half-life. In many nuclei studied in the present work (especially those in the $50<Z<66$ region), the experimental Q value is not known. We show the calculated Q value of the present β^+ decay, which is defined as

$$Q_{\rm calc}=\lambda_p(Z)-\lambda_n(N+1)-E_p-E_n-0.78 \tag{2}$$

in MeV, where Z (N) denotes the proton (neutron) number of the mother nucleus and E_p (E_n) represents the lowest quasiproton (quasineutron) energy, while λ denotes the Fermi energy and 0.78 MeV comes from $(m_n-m_p-m_e)c^2$.

III. RESULT OF NUMERICAL CALCULATIONS AND DISCUSSIONS

The GT strength shown in all figures (Figs. 1–5) in the present paper is estimated using the bare GT operator. Since the total GT strength observed in charge-exchange reactions populating GT GR in β-stable nuclei is only about half of the sum rule, almost independent of the mass number [2], the GT strength expected to be observed should presumably be obtained by reducing the strength plotted in Figs. 1–5 by a factor of about 2.

In the deformed HF calculations we use the SIII interaction as a standard Skyrme interaction, although in several nuclei we have actually compared the result obtained from the SG2 or the SkM⋆ interaction with that of the SIII interaction. We use $X_{\sigma\tau}=20/A$ MeV for the strength of the interaction (1). Pairing gap parameters $\Delta_p=\Delta_n=1$ MeV are used for all nuclei irrespective of deformation.

We perform TDA calculations using two-quasiparticle (one-proton-quasiparticle and one-neutron-quasiparticle) states, in which all one-proton states with one-particle energies less than +3 MeV and all one-neutron states with negative one-particle energies are included. Since in the present nuclei there is a sufficiently high Coulomb barrier, calculated one-proton states with positive energies but less than +3 MeV may be safely used. By restricting the space of the one-particle levels included in TDA in this way, we miss less than 10% of the total GT strength. A major part of the missing strength is related to the difference between the proton and neutron wave functions with the same quantum numbers and, thus, to the isospin mixture [12]. We have checked that when we solve the TDA equation including all two-quasiparticle states obtained from our deformed HF code, the resulting change of the strength plotted in Figs. 1–5 is not really visible, though some small strength appears in a higher energy region.

A. Deformed nuclei near the proton drip line in the 28<Z<50 region

In Fig. 1 we show the estimated GT strength of $N=Z$ nuclei ${}^{64}_{32}\mathrm{Ge}_{32}$, ${}^{68}_{34}\mathrm{Se}_{34}$, ${}^{72}_{36}\mathrm{Kr}_{36}$, ${}^{76}_{38}\mathrm{Sr}_{38}$, ${}^{80}_{40}\mathrm{Zr}_{40}$, and ${}^{84}_{42}\mathrm{Mo}_{42}$ for the shape of the HF local minima using the SIII interaction. For completeness we have included the nuclei ^{72}Kr, ^{76}Sr, and ^{80}Zr, which are studied in Ref. [5]. Though the nucleus ${}^{60}_{30}\mathrm{Zn}_{30}$ is calculated to be slightly deformed, the result is qualitatively similar to that of ${}^{64}_{32}\mathrm{Ge}_{32}$ and, thus, is not shown in Fig. 1. The lowest minimum has an oblate shape for ^{68}Se, ^{72}Kr, and ^{84}Mo, a spherical shape for ^{80}Zr, and a prolate shape for ^{60}Zn, ^{64}Ge, and ^{76}Sr. However, the difference between the HF total energies of those local HF minima shown in Fig. 1 for a given nucleus is at most 1.5 MeV in the present numerical calculation. The HF total energies for the spherical and oblate minima are nearly the same, especially for ^{80}Zr and ^{84}Mo. In the case that the energy difference between the HF minima is less than 1 MeV, the shape of the lowest HF minimum may sometimes be interchanged when other Skyrme interactions are used. We have checked that even if the interchange happens, the estimated distribution of the GT strength for a given shape in Fig. 1 remains almost unchanged. In the case of ^{80}Zr and ^{84}Mo the observed small excitation energy of the first excited 2^+ state, 290 and 443 keV, respectively [14,15], already indicates that these nuclei are deformed.

Experimental as well as theoretical [see Eq. (2)] Q values of the β^+ decays are indicated in Fig. 1 by arrows. Going from $N=Z=32$ to $N=Z=42$ in Fig. 1, it is seen that the portion of the total GT strength, which lies below the arrows and thus can be energetically populated by β^+ decay, is visibly increasing. Moreover, in heavier $N=Z$ nuclei the possibility for detecting β-delayed proton emission increases appreciably, as is seen from the fact that the dotted line, which indicates the proton separation energy measured (or obtained from systematics of experimental data) for daughter nuclei, lies well below the arrows. From Fig. 1 it is also seen that the shape of the GT strength distribution is noticeably different for the oblate and prolate minima, especially for the nuclei ^{68}Se, ^{72}Kr, ^{76}Sr, ^{80}Zr, and ^{84}Mo.

In Fig. 2 the GT strength estimated for $N=Z+2$ nuclei ${}^{66}_{32}\mathrm{Ge}_{34}$, ${}^{70}_{34}\mathrm{Se}_{36}$, ${}^{74}_{36}\mathrm{Kr}_{38}$, ${}^{78}_{38}\mathrm{Sr}_{40}$, ${}^{82}_{40}\mathrm{Zr}_{42}$, and ${}^{86}_{42}\mathrm{Mo}_{44}$ is shown at the HF local minima. The lowest HF minimum has an oblate shape for ${}^{66}_{32}\mathrm{Ge}_{34}$ and ${}^{70}_{34}\mathrm{Se}_{36}$, a spherical shape for ${}^{82}_{40}\mathrm{Zr}_{42}$ and ${}^{86}_{42}\mathrm{Mo}_{44}$, and a prolate shape for ${}^{74}_{36}\mathrm{Kr}_{38}$ and ${}^{78}_{38}\mathrm{Sr}_{40}$. In ^{82}Zr and ^{86}Mo the difference between the esti-

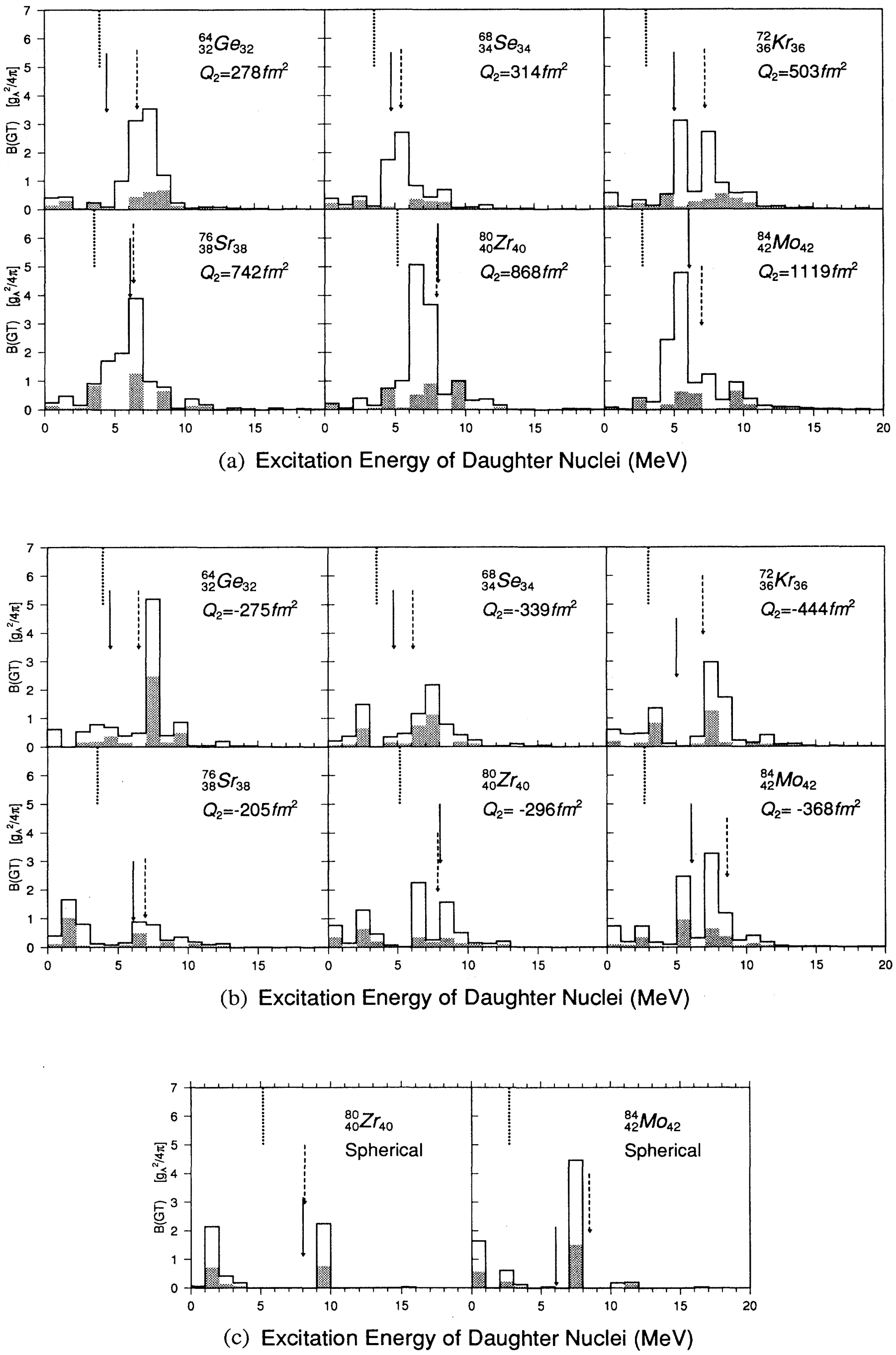

FIG. 1. Distribution of GT strength estimated for β^+ decay of $N=Z$ deformed nuclei in the $28<Z<50$ region, ${}^{64}_{32}\mathrm{Ge}_{32}$, ${}^{68}_{34}\mathrm{Se}_{34}$, ${}^{72}_{36}\mathrm{Kr}_{36}$, ${}^{76}_{38}\mathrm{Sr}_{38}$, ${}^{80}_{40}\mathrm{Zr}_{40}$, and ${}^{84}_{42}\mathrm{Mo}_{42}$, as a function of calculated excitation energy of daughter nuclei. (a) shows the result for prolate shape, (b) for oblate shape, and (c) for spherical shape. The bare GT operator is used in the numerical calculation. The estimated quadrupole moment Q_2 for the respective local HF minima is written. Using the SIII interaction in the HF calculation in which oscillator bases of $N_{\max}=12$ are employed, the lowest HF minimum has an oblate shape for ^{68}Se, ^{72}Kr, and ^{84}Mo, a spherical shape for ^{80}Zr, and a prolate shape for ^{60}Zn, ^{64}Ge, and ^{76}Sr. The summed values per 1 MeV energy bin are plotted as a histogram. The solid line expresses the GT strength populating both $I^\pi=1^+$ states with $K^\pi=1^+$ and those with $K^\pi=0^+$, while the shadowed bins denote the strength populating $I^\pi=1^+$ states with $K^\pi=0^+$. Solid-line arrows indicate the β^+ decay Q values obtained from either experiments or systematics based on measured masses [13], while dashed-line arrows denote the Q value obtained from the present model calculation. Proton separation energies in daughter nuclei from measurements (or from systematics based on experimental data) are indicated by dotted lines.

mated HF total energies for the spherical and oblate shapes is 0.6 MeV.

In going from the $N=Z$ to the $N=Z+2$ nuclei in the neighborhood of the proton drip line, it is seen that a considerable part of the GT strength disappears from the β^+ decay window and, moreover, the observation of β-delayed proton emission becomes impossible or nearly impossible.

In Fig. 3 the GT strength estimated for $N=Z-2$ nuclei ${}^{62}_{32}\mathrm{Ge}_{30}$, ${}^{66}_{34}\mathrm{Se}_{32}$, ${}^{70}_{36}\mathrm{Kr}_{34}$, ${}^{74}_{38}\mathrm{Zr}_{36}$, ${}^{78}_{40}\mathrm{Zr}_{38}$, and ${}^{82}_{42}\mathrm{Mo}_{40}$ is shown at the HF local minima. The lowest HF minimum has an oblate shape for ${}^{66}_{34}\mathrm{Se}_{32}$ and ${}^{70}_{36}\mathrm{Kr}_{34}$, a spherical shape for ${}^{82}_{42}\mathrm{Mo}_{40}$, and a prolate shape for ${}^{62}_{32}\mathrm{Ge}_{30}$, ${}^{74}_{38}\mathrm{Sr}_{36}$, and ${}^{78}_{40}\mathrm{Zr}_{38}$. The difference between the estimated total HF energies of the spherical and the oblate shape in ^{82}Mo is 0.4 MeV. In all $N=Z-2$ nuclei examined here, not only the β-delayed proton emission can occur, but also the β-delayed two-proton emission is possible in higher-lying states with an appreciable amount of the GT strength.

For the $N=Z-2$ nuclei, the final states in the daughter nuclei which can be populated by the GT β^+ decay have either $T=0$ or 1 or 2. The population ratio coming from the isospin Clebsch-Gordan coefficients is 1/3, 1/2, and 1/6, respectively. However, it is difficult to guess the energy difference between the lowest-lying $T=0$, 1, and 2 states in those

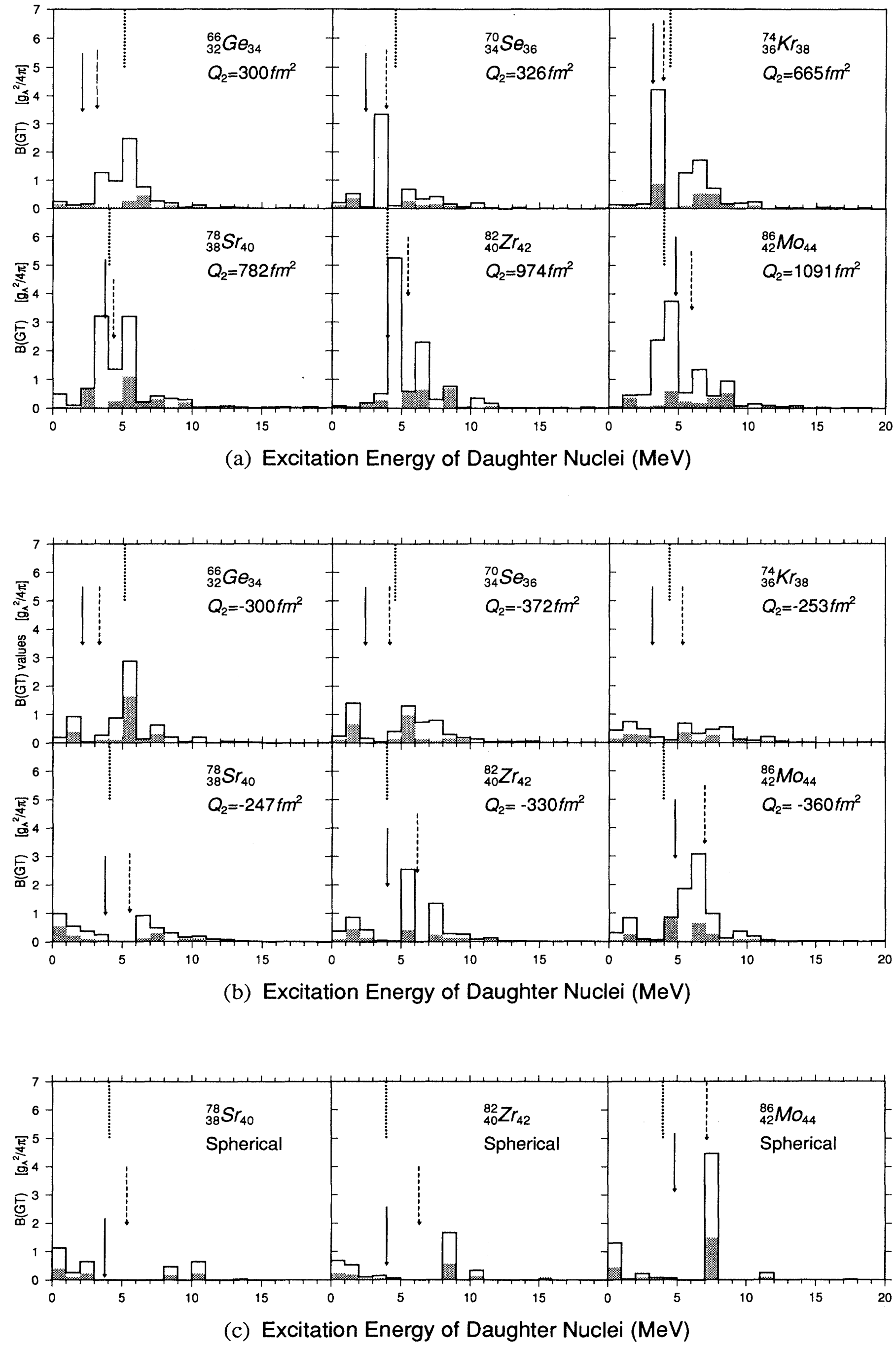

FIG. 2. Distribution of GT strength estimated for β^+ decay of $N=Z+2$ deformed nuclei in the $28<Z<50$ region, $^{66}_{32}Ge_{34}$, $^{70}_{34}Se_{36}$, $^{74}_{36}Kr_{38}$, $^{78}_{38}Sr_{40}$, $^{82}_{40}Zr_{42}$, and $^{86}_{42}Mo_{44}$, as a function of calculated excitation energy of daughter nuclei. (a) shows the result for prolate shape, (b) for oblate shape, and (c) for spherical shape. Using the SIII interaction in the HF calculation in which oscillator bases of $N_{max}=12$ are employed, the lowest HF minimum has an oblate shape for ^{66}Ge and ^{70}Se, a spherical shape for ^{82}Zr and ^{86}Mo, and a prolate shape for ^{74}Kr and ^{78}Sr. The nuclei ^{82}Zr and ^{86}Mo are included here, since HF calculations with Skyrme interactions other than the SIII interaction may produce the lowest HF minimum at a deformed shape. See caption to Fig. 1.

$N=Z$ odd-odd proton drip line nuclei. If we examine the odd-odd nuclei near the β-stability line, for example, it is known that the lowest-lying $T=1$ state of $^{14}_{7}N_7$ is found at an excitation energy of 2.3 MeV, while the ground states of all $N=Z$ odd-odd nuclei in the $f_{7/2}$ shell have $J=0$, which means $T=1$. Therefore, in the present work we have not tried to decompose the GT strength estimated for the β^+ decay of those $N=Z-2$ nuclei into the isospin components of the daughter nuclei.

Furthermore, for the $N=Z-2$ nuclei Fermi β^+ decay is possible to the $T=1$ state (namely, the isobaric analog state) of the daughter nuclei. To what extent this Fermi decay dominates over the GT decay calculated above depends sensitively again on the excitation energy of the isobaric analog state in the daughter nuclei.

B. Deformed nuclei near the proton drip line in the 50<Z<66 region

Restricting ourselves to the nuclei in which a local minimum with a reasonably low energy is obtained for a deformed shape in our HF calculation, in Figs. 4 and 5 (for the $N=Z+4$ and the $N=Z+6$ nuclei, respectively) we present the calculated distribution of the GT strength for the nuclei near the proton drip line with $56\leq Z\leq 64$. We have chosen

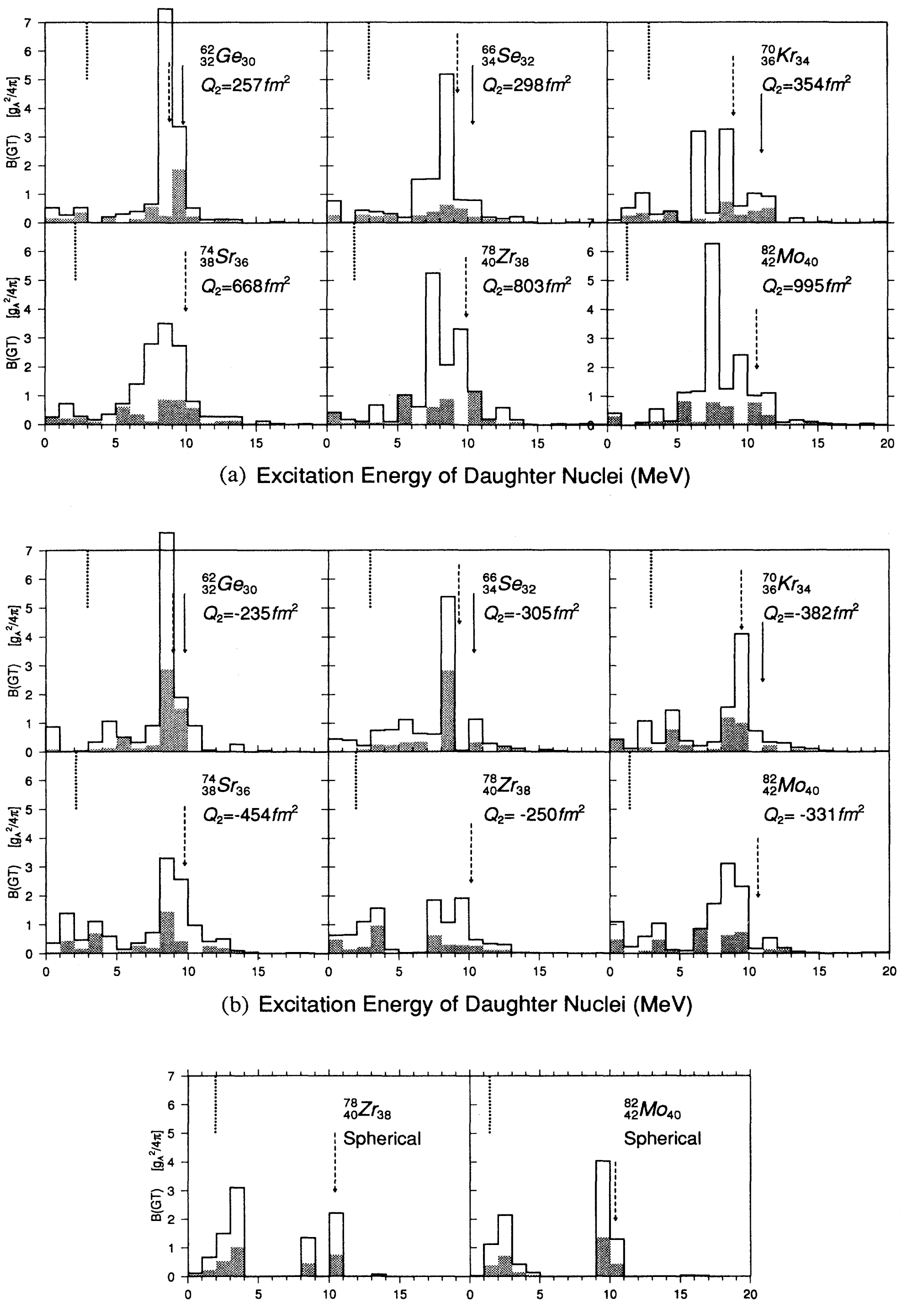

FIG. 3. Distribution of GT strength estimated for β^+ decay of $N=Z-2$ deformed nuclei in the $28<Z<50$ region, $^{62}_{32}Ge_{30}$, $^{66}_{34}Se_{32}$, $^{70}_{36}Kr_{34}$, $^{74}_{38}Sr_{36}$, $^{78}_{40}Zr_{38}$, and $^{82}_{42}Mo_{40}$, as a function of calculated excitation energy of daughter nuclei. (a) shows the result for prolate shape, (b) for oblate shape, and (c) for spherical shape. Using the SIII interaction in the HF calculation in which oscillator bases of $N_{max}=12$ are employed, the lowest HF minimum has an oblate shape for ^{66}Se and ^{70}Kr, a spherical shape for ^{82}Mo, and a prolate shape for ^{62}Ge, ^{74}Sr, and ^{78}Zr. The nucleus ^{82}Mo is included here, since HF calculations with Skyrme interactions other than the SIII interaction may produce the lowest HF minimum at a deformed shape. See caption to Fig. 1.

nuclei in this region of the nuclear chart, since there is a possibility of making those compound nuclei in radioactive ion beam facilities planned or under construction (see, for example, Ref. [4]). In those nuclei not only the β-delayed proton or two-proton emission, but also the β-delayed α emission will be energetically possible. However, the probability of α emission depends sensitively on the formation probability of α particles inside the daughter nuclei, namely, on the nuclear shell structure. Thus the question of whether or not α-particle emission will strongly compete with proton or two-proton emission is not trivial.

In Fig. 4 the GT strength of the $N=Z+4$ nuclei, $^{116}_{56}Ba_{60}$, $^{120}_{58}Ce_{62}$, $^{124}_{60}Nd_{64}$, and $^{128}_{62}Sm_{66}$, estimated for the lowest HF minimum, which has a prolate shape, is shown. Using the SIII interaction, the nucleus ^{128}Sm already lies slightly outside of the proton drip line. Neither Q values of β^+ decay nor Q values of charged particle(s) emission are experimentally known for those nuclei. It is seen that almost the entire strength of GT GR lies inside the β^+ decay window. In these nuclei an oblate HF local minimum exists above the lowest prolate minimum. The difference between the calculated HF total energy of the oblate and the prolate minimum is 1.6, 3.0, 3.7, and 3.7 MeV for ^{116}Ba, ^{120}Ce, ^{124}Nd, and ^{128}Sm, respectively. The distribution of the GT strength for the oblate shape typically shows the presence of

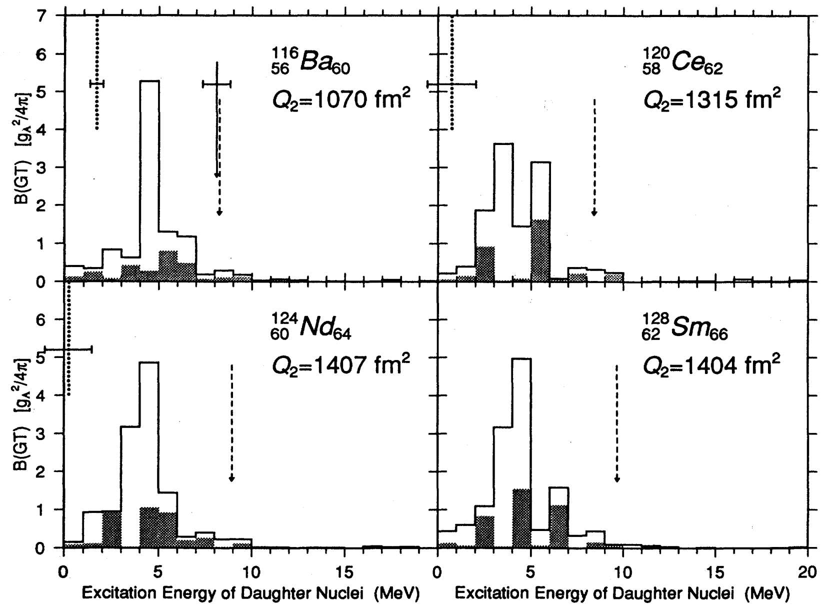

FIG. 4. Distribution of GT strength estimated for β^+ decay of $N=Z+4$ deformed nuclei in the $50<Z<66$ region, as a function of calculated excitation energy of daughter nuclei. Using the SIII interaction in the HF calculation in which oscillator bases of $N_{\max}=12$ are employed, the lowest minimum in these nuclei has prolate shape. The nucleus $^{128}_{62}Sm_{66}$ (and $^{132}_{64}Gd_{68}$) lies slightly outside of the proton drip line. The dashed-line arrows denote the Q value obtained from our model calculation. The Q value of the β^+ decay and the proton separation energy, which are obtained from the systematics based on experimental data, are shown by solid-line arrows and dotted lines, respectively, in the case that the values are given in Ref. [13]. Since the ambiguity of those values is not negligible in these nuclei, it is indicated by the length of the line parallel to the x axis. See also caption to Fig. 1.

two gross peaks and is qualitatively similar to that of ^{80}Zr in Fig. 1.

In the HF calculation we have tried Skyrme interactions other than the SIII interaction. For example, for both prolate and oblate HF minima in the nucleus ^{120}Ce the distribution of the GT strength calculated with the SG2 interaction is very similar to that with the SIII interaction, while the HF solution with the SkM$\star$ interaction lies outside of the proton drip line. The energy difference between the prolate and oblate HF local minima is in most nuclei slightly smaller if we use the SG2 interaction.

In Fig. 5 the calculated result for the $N=Z+6$ nuclei $^{122}_{58}Ce_{64}$, $^{126}_{60}Nd_{66}$, $^{130}_{62}Sm_{68}$, and $^{134}_{64}Gd_{70}$, estimated for the prolate HF minimum, is shown. As seen from the comparison between Figs. 4 and 5, going from $N=Z+4$ to $N=Z+6$ for a given isotope, the calculated Q value of β^+ decay decreases by more than 1 MeV. However, we observe that almost the entire strength of GT GR lies below the Q value and the shape of the distribution of the GT strength remains relatively unchanged. Neither Q values of β^+ decay nor Q values of charged particle(s) emission are experimentally known for these nuclei. An oblate HF local minimum is also

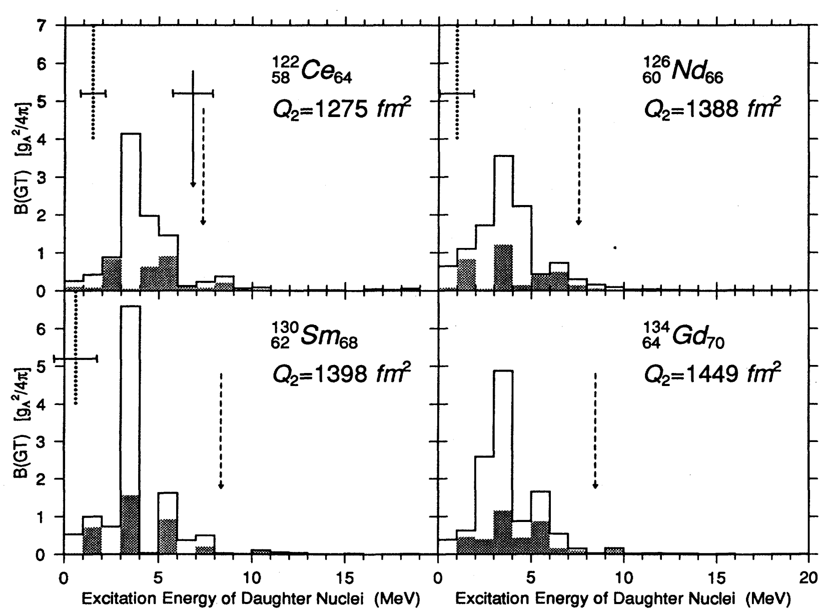

FIG. 5. Distribution of GT strength estimated for β^+ decay of $N=Z+6$ deformed nuclei in the $50<Z<66$ region, as a function of calculated excitation energy of daughter nuclei. Using the SIII interaction in the HF calculation in which oscillator bases of $N_{\max}=12$ are employed, the lowest minimum in these nuclei has prolate shape. All nuclei plotted lie inside of the proton drip line. See also captions to Figs. 1 and 4.

obtained in these nuclei and lies above the lowest prolate HF minimum by 3.0, 3.5, 3.0, and 2.4 MeV for ^{122}Ce, ^{126}Nd, ^{130}Sm, and ^{134}Gd, respectively.

IV. CONCLUSION AND DISCUSSION

We have studied the distribution of the Gamow-Teller β^+ decay strength of even-even deformed nuclei near the proton drip line in the region of $28<Z<66$. In the deformed drip line nuclei with $28<Z<50$ we often obtain the HF local minimum both at a prolate and an oblate shape, for which the estimated HF total energies are very close to each other. Which of the two deformed shapes is lower depends sensitively on the proton or the neutron number and sometimes on the Skyrme interactions. However, the GT strength distribution estimated for a given shape is nearly independent of Skyrme interactions employed and, moreoever, it often depends sensitively on the nuclear shape (oblate or prolate). Changing the neutron number by -2 $(+2)$ from $N=Z$, we have obtained the result that the major part of the GT GR strength appears in (disappears from) the β^+ decay window. Correspondingly, the observation of β-delayed proton emission becomes very easy (nearly impossible).

In the deformed drip line nuclei with $50<Z<66$ we have again found the HF local minimum both at a prolate and an oblate shape. However, the estimated total energy of the HF prolate shape is always lower than that of the HF oblate shape. For nuclei with $N\leqslant Z+6$ almost the entire strength of GT giant resonance is energetically reachable by β^+ decay, and the β-delayed charged-particle emission (proton or two protons or α particle) would be very important for detecting the β^+ decay.

In the presentation of the estimated GT strength we have used the bare GT operator. Therefore, the GT strength expected to be observed should presumably be obtained by reducing the presented values by about a factor of 2. This reduction factor has been observed in charge exchange reactions, but a quantitative value could not really have been pinned down because of the background subtraction problem in the reaction cross sections. If we can observe the β^+ decays to the GT giant resonance in proton drip line nuclei which are investigated in the present work, we may have a good chance to fix the reduction factor of the GT strength in the giant resonance region.

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