On direct proton decay of the Gamow-Teller giant resonance

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Abstract. The semi-microscopic approach to the description of giant resonances in medium-heavy mass closed-shell nuclei is implemented to treat partial probabilities of direct-proton decay of the Gamow-Teller giant resonance (GTGR) in $^{208}$Bi. The corresponding experimental data are reasonably explained.

1 Introduction

Partial probabilities of direct nucleon decay of giant resonances (GRs) carry information about the particle-hole (p-h) structure and damping mechanisms of GRs. Therefore, these probabilities should be related to the main properties of GRs and included in their full description. As applied to medium-heavy mass closed-shell nuclei, this aim can be achieved within the semi-microscopic approach to the description of giant resonances (SMAGR). The present formulation of this approach has been initially given in [1] and then extended to a number of implementations (see the reviews [2, 3]). The SMAGR is a generalization of the standard and non-standard versions of the continuum- Random-Phase-Approximation (cRPA) developed to take into account a spreading effect. The latter is described phenomenologically in terms of the energy-dependent imaginary part of an effective optical-model potential directly used in cRPA equations [2, 3].

Being the spin-flip partner of the isobaric analog resonance (IAR), the GTGR corresponds to the $1^+$ collective proton-(neutron-hole)-type nuclear excitations. In spite of a lot of experimental studies of the GTGR (predominantly via the direct (p,n)- and (3He,te)-reactions), the proton decay of the GTGR in $^{208}$Bi has only been studied by the coincident $^{208}$Pb(3He,tp) experiments [4]. The same method has later been used for studying proton decay of the GTGR overtones, isovector giant spin-monopole resonance (IVGSMR$^{(1)}$) in $^{208}$Bi [5]. The unique experiment on excitation of the GTGR in $^{116}$Sb with the resonance $^{117}$Sn(p,n$_{tot}$)-reaction [6] should be also mentioned. Along with the anomalously small total width ($\approx 1$ MeV), the partial (elastic) proton width of the mentioned GTGR has been measured as well.

Using the modern version of the SMAGR [1–3], in the present work we revise the previous calculations of the partial direct-proton-decay probabilities performed in [7] for the GTGR in $^{208}$Bi. The new elements of our analysis are: (i) taking the spreading effect on the escaped-proton wave function into account; (ii) the use of the energy-averaged decay-channel strength function (instead of the Breit-Wigner parametrization of the proper cRPA strength function); (iii) the use of the proton optical-model penetrability (instead of the penetrability calculated for a schematic single-particle potential). The method and results briefly described in Sect. 2 will be published soon together with the study of the GT strength distribution in a wide excitation energy interval [8].

2 Direct-proton-decay probabilities for the GTGR in $^{208}$Bi

As applied to description of charge-exchange excitations, the cRPA radial equations for the basic quantities are given in [7]. Extension of these equations on taking the spreading effect into account is described in [2, 3] in a rather schematic form. As applied to the semi-microscopic description of $0^+$ charge-exchange excitations (including IAR), the radial equations for the energy-averaged basic quantities are explicitly given in [9]. These quantities are: the effective field $V_{1}^{\pm}(x, \omega)$ and strength function $S_{1}^{\pm}(\omega)$, corresponding to an external single-particle field $V_{\nu}^{\pm} = V(\nu)\tau_{\nu}^{\pm}$ ($\omega$ is the excitation energy counted off the ground-state energy of the parent (even-even) nucleus); the proton-escape amplitude $M_{\nu}^{\pm}(\omega)$ and partial proton-decay-channel strength function $S_{\nu}^{\pm}(\omega) = |M_{\nu}^{\pm}(\omega)|^2$ ($\nu = n, (\nu)$ is the full set of the quantum numbers of a neutron-hole state, populated after direct proton decay, $\nu = j, l, \sum$). In the semi-microscopic description of the $1^+$ charge-exchange excitations we suggest to use, for short, the equations of Ref. [9] after the following substitutions:

$$\sigma_{MT}^{\pm}(\omega) \rightarrow \sigma_{MT}^{\pm}(\omega), \quad V(\nu) \rightarrow 1, \quad F' \rightarrow G'. \quad (1)$$

$$\sum_{\nu} n_{\nu}(2j_{\nu} + 1)\delta_{\nu(\nu)} \rightarrow \frac{1}{3} \sum_{\nu} n_{\nu}(\pi)\pi(\nu)^{2}. \quad (2)$$

In Eq. (1) $\sigma_{MT}$ are the spherical Pauli matrices; $F' = CF$, $G' = CG' (C = 300$ MeV fm$^3$) are the intensities of the isovector part of the Ladau–Migdal particle-hole interaction: $F_{(x, y)}(x, y) \rightarrow (F' + G'\sigma_{MT})_{(x, y)}$. In Eq. (2) $\pi = j, I_{\nu}$ are the single-proton quantum numbers linked to $\nu$ via the corresponding selection rules; $n_{\nu}$ are the neutron occupation numbers. The partial proton-decay-channel strength functions for the GTGR are properly

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modified: \( S^{-1}(\omega) = \sum_{\sigma} S^{-1}_{\gamma(\sigma)}(\omega) \). These strength functions determine the corresponding partial direct-proton-decay branching ratios as follows:

\[
b^{-1}_{\gamma}(\delta) = \frac{\int S^{-1}_{\gamma}(\omega)d\omega}{\int S^{-1}(\omega)d\omega},
\]

where integration is performed over the resonance. It is noteworthy that almost the same equations determine within SMAGR the partial branching ratios for direct proton decay of the IVGSMR. The difference is in the choice of the radial dependence of the external field \( V(r) \rightarrow R^2 - \hbar \), where the scaling parameter \( \hbar \) is chosen from the condition of “non-exciting” the GTGR [3, 10].

A mean field and particle-hole interaction together with the imaginary part \( W(r, \omega) \) of the effective optical-model potential are the input quantities for calculations within the SMAGR the giant-resonance strength function. The partial direct-nucleon-decay branching ratios are then calculated without the use of additional model parameters. In our calculations a phenomenological mean field and Landau–Migdal interaction are used. The mean-field parameters (together with the parameter \( f' \)) are found, as described in [11] but with the use of another mean-field geometrical parameter \( r_0 = 1.21 \text{ fm} \). In calculations of the strength function of the GTGR in \(^{208}\text{Pb} \) we used two adjustable parameters: the intensity \( g' \) of the Landau–Migdal interaction to reproduce in calculations the observed GTGR energy; the intensity of \( W(r, \omega) \) to reproduce in calculations the total width of the considered GTGR. The calculated strength function \( S^{-1}(\omega) \) is shown in figure 1.

Before comparing the calculated partial direct-proton-decay branching ratios \( b^{-1}_{\gamma} \) of Eq. (3) with the corresponding experimental values, we recalculate the partial proton-decay-channel strength functions \( S^{-1}_{\gamma(\sigma)} \) to take into account two points: (i) the difference of the experimental neutron-hole state excitation energies \( E^{\exp}_{\gamma} \) of the product nucleus \(^{207}\text{Pb} \) from the calculated energies \( E_{\gamma} = E^{\text{calc}}_{\gamma} - E^{\text{calc}}_{\text{PN}} \) (\( E^{\text{calc}}_{\gamma} \) are determined by the mean field); (ii) the difference of the experimental spectroscopic factors \( S_{\gamma} \) for the mentioned one-hole states from unity. (Both of these differences are shown in Table 1). In view of the discussed points we recalculate the partial proton-decay-channel strength functions to the following effective values:

\[
S_{\gamma(\sigma)}(\omega) = S_{\gamma}S_{\gamma(\sigma)}(\omega)T_{\gamma}(E^{\exp})/T_{\gamma}(E^{\text{calc}}).
\]

Here, \( \epsilon = \epsilon_{\gamma} + \omega \) is the escaped-proton energy; \( T_{\gamma}(\epsilon) \) is the optical-model penetrability (the seizure coefficient) for the partial proton wave. Because of changing over the GTGR the potential-barrier penetrability for escaped protons, the energy dependence of the calculated decay-channel strength functions \( S_{\gamma}(\omega) \) is noticeably different from that of the giant-resonance strength function \( S^{-1}(\omega) \) (figure 1). The proton branching ratios \( b_{\gamma} \) calculated for the GTGR in \(^{208}\text{Bi} \) in accordance with Eqs. (3), (4) for the energy interval \( \omega = 12–26 \text{ MeV} \) are found in a reasonable agreement with the corresponding experimental data (Table 1).

In conclusion of this Section we note, that the similar description of the partial (and total) direct-proton-decay branching ratios for the IVGSMR in \(^{208}\text{Bi} \) leads to different results [3, 10]. The total branching ratios (about 50%) is in reasonable agreement with the experimental data of [5], while the calculated and experimental distributions of the partial branching ratios over decay channels are noticeably different: population of deep neutron-hole states in \(^{207}\text{Pb} \) has been unexpectedly observed in [5]. Up to now there is no explanation of this observation.

### Table 1. The calculated partial direct-proton-decay branching ratios for the GTGR in \(^{208}\text{Bi} \) in a comparison with the experimental data.

| \( \gamma^{-1} \) | \( S_{\gamma} \) | \( E_{\gamma}^{\text{calc}} \) | \( E_{\gamma}^{\exp} \) | \( b_{\gamma}(\delta) \), % | \( b_{\gamma}^{\exp}, \% \) |
|----------------|----------------|----------------|----------------|----------------|----------------|
| \( 3p_{1/2} \) | 1.0            | 0              | 0              | 1.0            | 1.8 (5)        |
| \( 2f_{5/2} \) | 0.98           | 895            | 570            | 1.3            | 2.6 (7)        |
| \( 3p_{3/2} \) | 1.0            | 1078           | 898            | 1.4            | 0.2 (2)        |
| \( 1i_{3/2} \) | 0.91           | 2011           | 1633           | 0.05           | 0.4 (2)        |
| \( 2f_{7/2} \) | 0.5            | 3614           | 2340           | 0.7            | 0.4 (2)        |
| \( 1h_{9/2} \) | 0.61           | 4373           | 3413           | 0.1            | 4.55 (1.3)     |

\( E^{\text{calc}} = E^{\text{PN}} - E^{\text{PN}} \) (\( E^{\text{PN}} \) are determined by the mean field); (ii) the difference of the experimental spectroscopic factors \( S_{\gamma} \) for the mentioned one-hole states from unity. (Both of these differences are shown in Table 1). In view of the discussed points we recalculate the partial proton-decay-channel strength functions to the following effective values:

Within the semi-microscopic approach to description of giant resonances in closed-shell nuclei the reasonable description of the experimental data on direct proton decay of the Gamow-Teller giant resonance in \(^{208}\text{Bi} \) is obtained. Extension of experimental studies of direct proton decay of the GTGR and its overtone for other nuclei seems to be necessary together with generalization of the semi-microscopic approach on description of giant-resonance damping for open-shell nuclei.

3 Conclusive remarks
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