Direct-decay properties of charge-exchange spin giant resonances

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An extended continuum-RPA approach is applied to describe direct-decay properties of spin giant resonances in $^{208}$Bi and $^{90}$Nb. Partial branching ratios for direct proton decay from these resonances are evaluated. The branching ratio for $\gamma$-decay from the spin-dipole resonance to the Gamow-Teller resonance (main peak) is estimated. The saturation-like behaviour of the mean doorway-state spreading width in $^{208}$Pb is discussed in connection with the branching ratio for direct proton decay from the spin-monopole resonance and the Gamow-Teller strength distribution.

For the last few years, considerable efforts have been undertaken at RCNP (Osaka) and at KVI (Groningen) to investigate direct-decay properties of charge-exchange spin giant resonances. In particular, (i) the partial branching ratios for proton decay from the Gamow-Teller (GT) and spin-dipole (SD) giant resonances in $^{208}$Bi \cite{1,2} and $^{90}$Nb \cite{3} to neutron-hole states in, respectively, $^{207}$Pb and $^{89}$Zr have been deduced from ($^3$He,tp) coincidence experiments; (ii) the same type of experiment has been performed to search for the isovector spin-monopole (IVSM) and isovector monopole (IVM) giant resonances in $^{208}$Bi \cite{4}; (iii) the branching ratio for $\gamma$-decay from the SDR to the GTR in the mentioned nuclei is expected to be deduced from the ($^3$He,t$\gamma$) coincidence experiments \cite{5}.

These experimental studies stimulate us to develop a rather simple and transparent approach to describe the branching ratios for direct proton decay and $\gamma$-emission and, as a result, to understand better the particle-hole (p-h) structure of the mentioned spin giant resonances. The approach originally proposed in Refs. \cite{6,7} and extended in Refs. \cite{8,9} is based on: (i) the continuum-RPA (CRPA) with the use of a phenomenological mean field and the Landau-Migdal p-h interaction, as input quantities; (ii) a phenomenological description for the coupling of (p-h)-type doorway states to many-quasiparticle configurations. The isoscalar part of the nuclear mean field and the Landau-Migdal parameters are ingredients of the approach. The isovector part of the nuclear mean field and the mean Coulomb field are calculated in a self-consistent way. Some parameters of the model used in calculations of properties of spin GRs in $^{208}$Bi and $^{90}$Nb (the isoscalar mean field depth $U_0$, and the Landau-Migdal parameters $f'$ and $g'$) are listed in Table 1. Other parameters of the isoscalar field are taken from Ref. \cite{6}. Another ingredient of the approach is the
smearing parameter, or the mean doorway-state spreading width, \( I \). The \( I \) value is found for each considered GR to reproduce the experimental total width of the resonance in calculations of the energy-averaged strength function. In Table 2 the calculated partial branching ratios for direct proton decay from the GTR and SDR in \(^{208}\text{Bi} \) are given and show a rather good agreement with the experimental data [1,2]. Regarding its physical meaning the smearing parameter is close to the imaginary part of the optical potential. For this reason, we propose to use a saturation-like parametrization for \( I(\omega) \) (\( \omega \) is the excitation energy measured from the parent-nucleus ground-state). Such a parametrization, originally used in applying to the familiar dipole GR [3], allows us to roughly reproduce the \( I \) values from Table 2 as well (Figure 1).

Table 1
The isoscalar mean field depth \( U_0 \), and the Landau-Migdal parameters \( f' \) and \( g' \). The calculated relative strength \( y \) of the GT main peak and the calculated branching ratio for \( \gamma \)-decay from the SDR\(^{-}\) to the GTR (main peak) in \(^{90}\text{Nb} \) and \(^{208}\text{Bi} \) are also given.

| Nucleus | \( U_0 \), MeV | \( f' \)  | \( g' \)  | \( y \)  | \( b_\gamma \) \( \times 10^{-4} \) |
|---------|---------------|---------|---------|---------|-----------------|
| \(^{90}\text{Nb} \) | 53.3 | 0.96 | 0.70 | 0.79 | 4.7 |
| \(^{208}\text{Bi} \) | 54.1 | 1.0 | 0.78 | 0.69 | 2.4 |

The reason why the IVSM/IVM giant resonances are observed in the proton decay channel [1] can be understood by comparing the total width of these resonances in the CRPA monopole strength functions (about 11 - 12 MeV [10,11]) with the appropriate value \( I = 4.2 \) MeV (Figure 1). As follows from this comparison, the proton direct-decay channel is expected to be the main decay channel for these resonances. To estimate the partial and total proton direct-decay branching ratios for the IVSMR in \(^{208}\text{Bi} \), we solve the respective CRPA equations with substitution of \( \omega \) by \( \omega + \frac{i}{2} I \). In calculations with the corrected spin-monopole one-body operator (see below) the above-mentioned model parameters were also used. The results in Table 2 show that the proton direct-decay channel is the main decay channel for the IVSMR. A similar result is also obtained for the IVMR [12]. The calculated total width of these monopole resonances (about 14 MeV) is not in disagreement with the experimental data [14]. However, as follows from recent data on searching for the IVSMR in \(^{nat}\text{Pb} \) and \(^{90}\text{Zr} \) target nuclei via the \((p,n)\)-reaction at 795 MeV incident energy [14], the IVSMR total width may be larger. In this case, the larger \( I \) value results in decreasing the calculated value of \( b^{tot} \) without a marked change of the relative partial branching ratios.

We also calculated the CRPA spin-monopole strength functions using the corrected one-body operators \( \left( \frac{r^2}{R^2} - a^2 \right) \sigma \tau^{(-,+)} \) (\( R \) is the nuclear radius). The parameter \( a^2 = 0.78 \) is found from the condition that the GTR (main peak) has zero corrected spin-monopole strength. Such a choice of the spin-monopole operator ensures exhausting the main part of the corrected NEWSR (equals to 6.3) by the IVSMR, which is actually the overtone of the GTR. The calculated strength functions exhibit resonance-like behaviour. Some
Table 2
Calculated and experimental branching ratios for direct proton decay from isovector spin giant resonances in $^{208}$Bi to neutron-hole states in $^{207}$Pb. All ratios are given in %. Contributions from decay to deep-hole states are taken with the spectroscopic factor $S_{\nu} = 1$. The mean doorway-state spreading widths and experimental total widths are also shown.

| $\nu$   | $S_{\nu}$ | GTR     | SDR$^{(-)}$ | IVSMR$^{(-)}$ |
|---------|-----------|---------|-------------|---------------|
|         |           | $b_{\nu}$ [8] | $b_{\nu}^{exp}$ [1] | $b_{\nu}$ [8] | $b_{\nu}^{exp}$ [2] | $b_{\nu}$ |
| 3p$_{\frac{1}{2}}$ | 1.0       | 1.53    | 1.8±0.5     | 0.95          | 0.95 ± 0.28 | 1.9 |
| 2f$_{\frac{5}{2}}$ | 0.98      | 1.46    | inc. in p$_{\frac{3}{2}}$ | 1.94          | 2.10 ± 0.61 | 5.4 |
| 3p$_{\frac{3}{2}}$ | 1.0       | 1.37    | 2.7±0.6     | 2.18          | 2.79 ± 0.81 | 4.0 |
| 1i$_{\frac{13}{2}}$ | 0.91      | 0.03    | 0.2±0.2     | 3.80          | 3.41 ± 0.98 | 21.4 |
| 2f$_{\frac{7}{2}}$ | 0.7       | 0.09    | 0.4±0.2     | 4.02          | 3.14 ± 0.91 | 5.7 |
| 1h$_{\frac{9}{2}}$ | 0.61      | 0.002   |             | 1.17          | 0.97 ± 0.27 | 3.8 |
| $\sum b_{\nu}$ | 4.5       | 4.9±1.3 | 14.1        | 13.4 ± 3.9   | 43.2 |
| $b^{tot}$     | 4.5       |         |             | 17.3         | 66 |
| $I$ ($\Gamma^{exp}$) | 3.55   | (3.72)  | 4.7         | (8.4)        | 4.0 |

Table 3
Parameters of the IVSMR$^{(-,+)}$ in the $^{208}$Pb parent nucleus, calculated in the CRPA.

|                           | IVSMR$^{(-)}$ | IVSMR$^{(+)}$ |
|---------------------------|---------------|---------------|
|                           | $\bar{\omega}$, MeV | $\omega_{peak}$, MeV | FWHM, MeV | $x$ | $\bar{\omega}$, MeV | $\omega_{peak}$, MeV | FWHM, MeV | $x$ |
| This work                 | 35.6          | 36.9          | 10.0      | 0.8 | 15.1          | 16.2          | 2.0      | 0.2 |
| Ref. [10]                 | 44.5          | 42.5          | 12.5      | -   | 17.7          | 17.8          | 1.0      | -   |
Another interesting observation in our CRPA calculations is that the pygmy-IVSMR forms the high-energy “tail” of the GT-strength distribution in $^{208}$Bi and exhausts about 17% of the Ikeda sum rule (ISR) within the excitation energy interval $E_x = 19 - 30$ MeV, while the low-energy part of the GT-strength distribution exhausts about 12%. The calculated relative strength $y$ of the GT main peak of 69% (Table 1) is not in disagreement with the experimental value $y^{\text{exp}} = (60 \pm 15)\%$ [1]. The smeared distribution can be evaluated with the use of $I(\omega)$ shown in Figure 1. The comparison of the calculated GT strength distribution (Figure 2) with that deduced from the (pn) data [15] allows one to verify the p-h structure of the GT-strength distribution in $^{208}$Bi.

The isospin splitting of spin GRs in nuclei having not-too-large neutron excess is an additional element of the description. We calculate the CRPA strength function for the GTR $T_\succ$-component in $^{90}$Nb by the equation:

$$S_\succ(\omega) = \frac{1}{2T} S_{M1}(\omega - \Delta).$$

(1)

Here $T = 5$ is the isospin of the parent-nucleus ground state, $S_{M1}$ is the CRPA strength function corresponding to the M1 one-body operator $\sigma_\tau^{(3)}$, and $\Delta$ is the Coulomb displacement energy. In calculations of $S_{M1}$ we put the Landau-Migdal parameter $g = 0$, because the results only slightly depend on this parameter. The calculated mean excitation energy of the $T_\succ$ GTR exceeds the energy of the main GTR peak by 4.9 MeV. This value agrees with the experimental GTR isospin-splitting energy 4.7 MeV [16] and 4.4 MeV [3].

Figure 1. The energy dependence of the smearing parameter for $^{208}$Pb [9]. The values of doorway spreading widths (asterisks) for spin GRs are also shown together with the respective total widths (in parenthesis).
We evaluate the partial branching ratios for direct proton decay from the GTR (main peak) and SDR in $^{90}$Nb in the same way as it was done for the spin GRs in $^{208}$Bi [8]. The results are listed in Table 4. The total branching ratio for direct proton decay from the GTR in $^{90}$Nb is found to be much smaller than that for the GTR in $^{208}$Bi (Table 2). The difference is due to the relatively low GTR excitation energy in $^{90}$Nb as compared with the escape-proton threshold.

Another possibility to check the p-h structure of spin GRs is to study $\gamma$-transitions between the resonances. In connection with the expected experimental data [5] we evaluate the branching ratios $b_\gamma$ for E1-transitions from the SDR to the GTR (main peak) in $^{208}$Bi and $^{90}$Nb. To simplify the consideration, we assume that the main GT state has a wave function close to that of the “ideal” GT state:

$$|G_i\rangle = (N - Z)^{-1/2} \sum_a \sigma_a^{(i)} \tau_a^{(-)} |0\rangle. \quad (2)$$

Such an assumption allows us to express the decay probability for each SD doorway state via its SD strength and, therefore, to reduce the problem to the calculation of the SD energy-averaged strength function. The evaluated branching ratio is multiplied by the factor $y$, which is the calculated relative (to the ISR) strength of the main GT state. In such a way we take into account the difference of the real main GT state from the “ideal” one. The calculated values of $b_\gamma$ are given in Table 1 [17].

In conclusion, we apply an extended continuum-RPA approach to evaluate: (i) the partial branching ratios for direct proton decay from the GTR and SDR in $^{90}$Nb, and from the IVSMR in $^{208}$Bi; (ii) the branching ratio for $\gamma$-decay from the SDR to the GTR
Table 4
The calculated branching ratios for direct proton decay from the GTR and SDR\(^{(-)}\) in \(^{90}\)Nb to neutron-hole states in \(^{89}\)Zr (assuming \(S_\nu = 1\)). All ratios are given in \%. The experimental total widths of the resonances is taken from Ref. [15].

| \(\nu\)   | GTR  | SDR\(^{(-)}\) |
|----------|------|---------------|
| 1g\(^+_2\)| 0.05 | 10.0          |
| 2p\(^+_2\)| 0.06 | 1.6           |
| 2p\(^+_3\)| 0.06 | 3.6           |
| 1f\(^+_5\)| 0.003| 1.7           |
| \(\sum \nu b_\nu\) | 0.17 | 16.9          |
| \(b_\nu^{\text{tot}}\) | 0.17 | 17.1          |
| \(I (\Gamma^{\text{exp}})\) | 4.4 (4.4) | 5.0 (7.9) |

(main peak) in \(^{90}\)Nb and \(^{208}\)Bi; (iii) the GT strength distribution in \(^{208}\)Bi for a wide excitation energy interval. The calculation results are expected to be compared with the coming experimental data.

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REFERENCES
1. H. Akimune et al., Phys. Rev. C 52 (1995) 604.
2. H. Akimune et al., Phys. Rev. C 61 (2000) 011304-1.
3. J. Jänecke et al., Contribution to this Conf.
4. R.G.T. Zegers et al., Phys. Rev. Lett. 84 (2000) 3779.
5. M. Fujiwara, M.N. Harakeh, and A. Krasznahorkay, private communication.
6. S.E. Muraviev, and M.H. Urin, Nucl. Phys. A 572 (1994) 267.
7. G.A. Chekomazov, and M.H. Urin, Phys. Lett. B 354 (1995) 7.
8. E.A. Moukhai, V.A. Rodin, and M.H. Urin, Phys. Lett. B 447 (1999) 8.
9. V.A. Rodin, and M.H. Urin, Phys. Lett. B 480 (2000) 45.
10. N. Auerbach, and A. Klein, Phys. Rev. C 30 (1984) 1032.
11. N. Auerbach, and A. Klein, Nucl. Phys. A 395 (1983) 77.
12. M.L. Gorelik, and M.H. Urin, to be published.
13. A. Errel et al., Phys. Rev. C 34 (1986) 1822.
14. D. Prout et al., Submitted to Phys. Rev. C.
15. T. Wakasa, private communication.
16. D.E. Bainum et al., Phys. Rev. Lett. 44 (1980) 1751.
17. V.A. Rodin, and M.H. Urin, to be published.