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Direct proton decay and microscopic structure of the spin-dipole resonance in ^{208}Bi

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The microscopic structure of the spin-dipole resonance (SDR) at $E_x = 21.1$ MeV in ^{208}Bi has been investigated in the ^{208}Pb(^{3}He,t)^{208}Bi reaction at $E(^3\mathrm{He}) = 450$ MeV and very forward scattering angles. Protons emitted due to the decay of the SDR were measured in solid-state detectors in coincidence with tritons detected with the high resolution magnetic spectrometer Grand Raiden. The total and partial branching ratios for proton decay from the SDR to the residual neutron-hole states in ^{207}Pb have been measured. The deduced escape widths are found to be in good agreement with recent theoretical estimates.

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Recently, the microscopic structure of the Gamow-Teller resonance (GTR) in ^{208}Bi has been reliably investigated through the analyses of the proton decay data from the ^{208}Pb(^{3}He,tp)^{207}Pb reaction at $E(^3\mathrm{He}) = 450$ MeV [1,2]. These experimental results have been used as a standard for the theoretical treatment of GTR, and indeed helped to solve a long-standing problem concerning a discrepancy between the experimental total width and branching ratios for proton decay from the GTR in ^{208}Bi measured earlier [3] and those calculated in different theoretical approaches [4–6].

The isovector spin-flip dipole resonance (SDR), characterized by $\Delta T = 1$, $\Delta S = 1$, and $\Delta L = 1$ transfer, is located at an excitation energy in ^{208}Bi of $E_x = 21.1 \pm 0.8$ MeV above the GTR at $E_x = 15.6 \pm 0.2$ MeV [2]. Whereas the GTR has $0\hbar\omega$ proton-particle and neutron-hole ($1p-1h$) configurations, coupled with other complex many-particle–many-hole ($np-nh$) configurations with the same $J^\pi = 1^+$, the SDR has $1\hbar\omega$ proton-particle and neutron-hole ($1p-1h$) configurations with $J^\pi = 0^-$, 1^-, and 2^-. This resonance also decays to the low-lying neutron-hole states in ^{207}Pb by direct proton emission, the study of which therefore furnishes information on its microscopic structure.

Theoretical predictions for proton decay from the giant resonances depend on the microscopic model and the choice of the residual nucleon-nucleon (NN) interaction used in the nuclear-structure calculations. Therefore, the validity of the theoretical treatments in calculating the microscopic structures of the SDR and GTR can be tested by comparing with reliable experimental decay widths.

In our earlier work [2], we reported on the total and partial proton-decay branching ratios of the isobaric analog state (IAS) and the GTR, and a preliminary result for the total proton branching ratio for the SDR in ^{208}Bi. In this Rapid Communication, we present for the first time the experimental results for the total and partial branching ratios of proton decay from the SDR in ^{208}Bi and compare these to recent calculations [7].

The ^{208}Pb(^{3}He,tp)^{207}Pb experiment was carried out at the Research Center for Nuclear Physics (RCNP), Osaka University, using the spectrometer Grand Raiden [8]. The experimental technique is described in Ref. [2]. The detection system of Grand Raiden allowed the reconstruction of the scattering angle at the target via ray-tracing techniques. The singles ^{208}Pb(^{3}He,t)^{208}Bi spectrum obtained at 1° is shown in Fig. 1. In this spectrum, various charge-exchange giant resonances in ^{208}Bi can be observed and in particular the SDR which peaks at 1°. The singles spectrum of Fig. 1 was decomposed by a least-squares fitting procedure into its various components, the low-lying discrete levels, the IAS, GTR, SDR, and the nonresonant background. The various parameters of the resonances, i.e., excitation energy, width, and cross section, were determined. These were published earlier in Ref. [2].

In this fitting, weak contributions from the giant dipole resonance GDR ($\Delta S = 0, \Delta L = 1$) expected at essentially the same excitation energy have been neglected. At the present high bombarding energies, the central spin-isospin term,

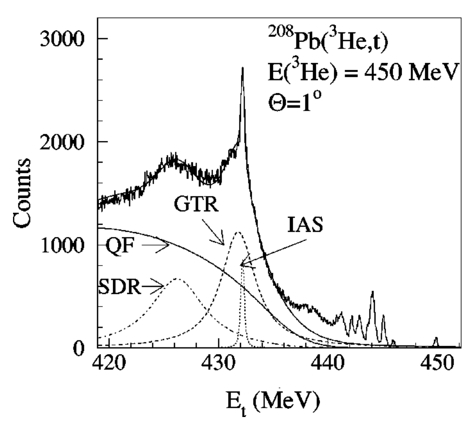

FIG. 1. A singles triton energy spectrum from the ^{208}Pb(^{3}He,t) reaction taken at 1° and at $E(^3\mathrm{He}) = 450$ MeV. The dashed, dotted, dot-dashed, and solid lines represent the results of χ^2 fits obtained for the Gamow-Teller resonance, the isobaric analog resonance, the spin-flip dipole resonance, and the nonresonant background, respectively.

$V_{\sigma\tau}$, of the *NN* interaction strongly dominates over the central isospin term, V_τ. Therefore, contributions from the GDR to the excitation cross section should be small compared to those of the SDR as discussed in Ref. [9]. It should be noted, however, that the GDR will have a similar angular distribution ($\Delta L=1$ transfer) and a similar structure to the SDR. Experimentally, the yield ratio for the SDR and GDR can be estimated using the IAS cross section relative to the GTR cross section. We observe a yield ratio $R(\mathrm{GTR/IAS})=(163\pm33\ \mathrm{mb/sr})/(9.2\pm2\ \mathrm{mb/sr})\approx17.7$ at $\theta=0°$. In spite of its relatively small cross section, the IAS can be observed in the spectra, even at $\theta=1°$, only because of its narrow width. Since the terms V_τ and $V_{\sigma\tau}$ are responsible for exciting the IAS and GDR and the GTR and SDR, respectively, the same value can be expected for the ratio $R(\mathrm{SDR/GDR})$. This ratio is increased even more when quenching of the GTR is taken into account. Assuming no quenching for the SDR and a quenching factor of ~0.6 for the GTR, the ratio can be estimated as $R(\mathrm{SDR/GDR})\approx30$. The above ratio was confirmed by independent calculations using the distorted-wave Born approximation (DWBA) with microscopic wave functions. The calculated ratio $R(\mathrm{SDR/GDR})$ at 1° was ~35.

The SDR consists of three components, 0^-, 1^-, and 2^- which are not resolved in energy. These components are expected to overlap because of their large widths, which are larger than the differences in their excitation energies. Proton decay from the SDR was studied by measuring protons emitted at backward angles in coincidence with tritons detected in Grand Raiden. Eight solid-state detectors (SSD) were arranged in two rings at 132° and 157° in the laboratory system in an axially symmetric configuration around the beam axis. Each ring contained four silicon SSDs of 5 mm thickness each set at azimuthal angles 45°, 135°, 225°, and 315°.

Two-dimensional scatter plots of triton energy versus proton-decay energy (not shown here), gated on events with scattering angles centered at $\theta\approx0°$ and 1°, were generated for the prompt peak in the timing spectrum. Both solid angles were taken equal, and had a horizontal opening angle, $\Delta\theta_h=0.90°$, and a vertical opening angle, $\Delta\theta_v=2.28°$. The loci for decay of the IAS, GTR, and SDR to the ground state and low-lying neutron-hole states in ^{207}Pb (i.e., $3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, $1i_{13/2}$, $2f_{7/2}$) can be observed along lines corresponding to $E_t+E_p=$const. It should be noted that in the present analyses of the proton decay from the SDR, the gains of the SSDs were finely adjusted in the final off-line analysis to allow adding the accumulated data with improved statistics but no loss in energy resolution. The total energy resolution obtained for E_t+E_p of 580 keV was not sufficient to completely resolve the decays to the first and second excited states of ^{207}Pb at $E_x=570$ keV and 898 keV, respectively. The final neutron-hole-state spectra in ^{207}Pb obtained by projecting the coincidence events onto the axis of excitation energy for ^{207}Pb and by applying gates on the excitation energy regions of the GTR+IAS and SDR in ^{208}Bi and on the angles $\theta\approx0°$ and 1° for the GTR+IAS and SDR, respectively, are shown in Figs. 2(a) and 2(b). For more details on the experimental setup and data reduction, see Ref. [2].

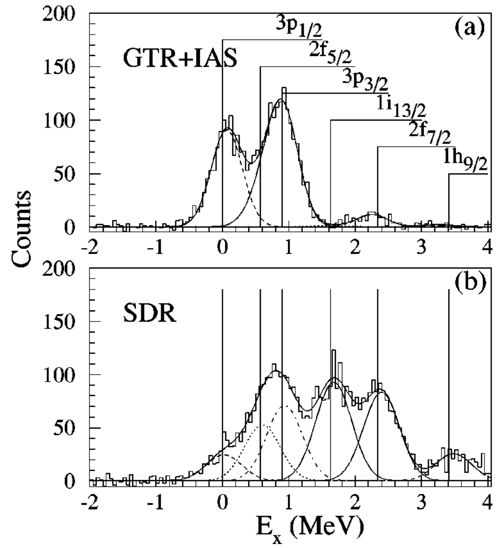

FIG. 2. The final-state spectrum of neutron-hole states in ^{207}Pb obtained by gating proton decay from (a) the Gamow-Teller resonance and the isobaric analog resonance with the gate on the scattering angles centered at 0°, and (b) the spin-flip dipole resonance with the gate on scattering angles centered at 1°. The centroid positions of the various neutron-hole states in ^{207}Pb are indicated. The results of χ^2 fits for peaks corresponding to these neutron-hole states are also shown.

It is clear from the comparison between the two final-state spectra that the population pattern of the various neutron-hole states for the SDR is quite different from that for the GTR+IAS. The $1i_{13/2}$ and $2f_{7/2}$ are more strongly and the $3p_{1/2}$ more weakly populated in the case of proton decay from the SDR. This can be understood qualitatively by considering the increase of the proton energy available above the Coulomb barrier and also the average decrease of the centrifugal barrier for the decay protons as compared to the GTR+IAS. There is also a clear indication for proton decay from the SDR to the broad $1h_{9/2}$ deep-neutron-hole state in ^{207}Pb. These qualitative arguments are confirmed by the detailed analysis of the data.

In Fig. 3 the relative branching ratios for proton decay from the IAS, GTR, and SDR regions to the various neutron-hole states in ^{207}Pb are shown as a function of excitation energy. These were obtained by generating the final-state spectra for 1 MeV excitation-energy bins. These final-state spectra were then fitted to obtain the contributions to decay to the neutron-hole states in ^{207}Pb. From this detailed comparison of relative branching ratios to neutron-hole states, it can easily be seen that decay to the high-spin neutron-hole states $1i_{13/2}$ and $1h_{9/2}$ from the ‘‘low-spin’’ SDR gain in importance for higher excitation energies because of the increase in proton decay energy.

The total width of a giant resonance, such as the IAS, GTR, and SDR, can be written as the sum of the spreading width, $\Gamma^\downarrow$, and the escape width, $\Gamma^\uparrow$. At relatively low excitation energies in heavy nuclei, as is the case for the GTR and SDR in ^{208}Bi, the spreading width results predominantly in statistical neutron decay because statistical proton decay is strongly suppressed by the Coulomb barrier. The escape

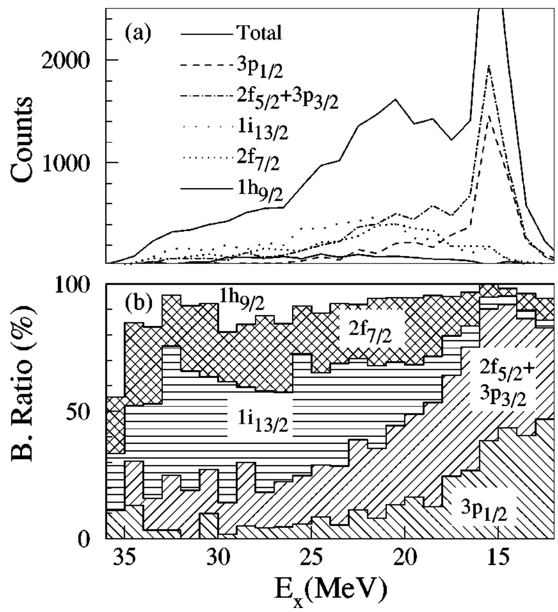

FIG. 3. (a) Total decay spectrum (relative units) measured at 1°, and decomposition into contributions for proton-decay to the various low-lying neutron-hole states in ^{207}Pb (i.e., $3p_{1/2}, 2f_{5/2}, 3p_{3/2}, 1i_{13/2}, 2f_{7/2}, 1h_{9/2}$), and (b) relative branching ratios for the decays to these neutron-hole states as a function of excitation energy in steps of 1 MeV. The spectrum overlaps with the resonances (IAS at 15.165 MeV, GTR at 15.6 MeV, and SDR at 21.1 MeV).

width is connected with the microscopic, proton-particle–neutron-hole structure of the resonance. It comprises the sum of the partial escape widths due to proton decays to single-neutron-hole states in the final daughter nuclei. The escape width can thus be written as

$$\Gamma^{\uparrow}=\Gamma_{p}^{\uparrow}=\sum_{i}\Gamma_{p_i}^{\uparrow}, \tag{1}$$

where $\Gamma_{p_i}^{\uparrow}$ is the partial escape width associated with decay to the ith neutron-hole state in the residual nucleus, e.g., ^{207}Pb in the present case. The ratio of $\Gamma^{\uparrow}$ to the total width Γ can be obtained from the ratio of the coincidence double-differential cross section to the singles cross section,

$$\frac{\Gamma_{p_i}^{\uparrow}}{\Gamma}=\frac{\int (d^2\sigma_{p_i}/d\Omega_t d\Omega_p)d\Omega_p}{d\sigma/d\Omega_t}. \tag{2}$$

Here, it is implicitly assumed that the double-differential and singles cross sections have been integrated over the excitation energy of the resonance.

The measured branching ratios and the partial escape widths of the GTR and IAS have been published earlier [2]. In Table I, the deduced branching ratios and partial escape widths for the summed SDR strength composed of 0^-, 1^-, and 2^-, are given in columns 5 and 6, respectively. The partial escape widths have been determined using Eq. (2). First, the singles cross section for the SDR has been obtained from fitting the singles spectra. The partial double-differential cross sections for the SDR have been determined from fitting the final-state spectra in Fig. 2(b) to obtain the cross sections for populating the ground state and low-lying neutron-hole states in ^{207}Pb (i.e., $3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, $1i_{13/2}$, $2f_{7/2}$, $1h_{9/2}$). These were then integrated over the full solid angle assuming an angular correlation given by $1+a_2P_2$, where P is a Legendre polynomial. This is justified for excitations with intermediate $\Delta L=1$ transfer. The coefficients a_2 for the proton decay from the SDR to the different neutron-hole states in ^{207}Pb were determined from fitting the 132° and 157° data points. The ratio of the integrated double-differential cross section to the singles cross section yields the branching ratio. Note that in this ratio, the target thickness, collected charge, and spectrometer (triton) solid angle cancel out.

TABLE I. Theoretical and experimental partial escape widths and branching ratios for the decay of SDR in ^{208}Bi into the neutron-hole states in ^{207}Pb. The branching ratios are given in % and the widths in keV.

		Theory[b]		Exp.[c]	
Decay channel	E_x [a] (keV)	$\Gamma_{p_i}^{\uparrow}/\Gamma$	$\Gamma_{p_i}^{\uparrow}$	$\Gamma_{p_i}^{\uparrow}/\Gamma$	$\Gamma_{p_i}^{\uparrow}$
$3p_{1/2}$	0	1.05	88.4	0.95 ± 0.28	79.8 ± 23.5
$2f_{5/2}$	570	1.94	163.2	2.10 ± 0.61	176.4 ± 51.2
$3p_{3/2}$	898	2.18	183.1	2.79 ± 0.81	234.4 ± 68.0
$1i_{13/2}$	1633	3.80	318.8	3.41 ± 0.98	286.4 ± 82.3
$2f_{7/2}$	2340	4.02	337.3	3.14 ± 0.91	263.8 ± 76.4
$1h_{9/2}$	3413	1.17	98.6	0.97 ± 0.27	81.5 ± 22.7
$\Sigma_i\Gamma_{pi}^{\uparrow}/\Gamma$		14.2	1190	13.4 ± 3.9	1122 ± 324
Γ			8400[d]		8400[d]

[a]Nuclear Data Sheet.
[b]Moukhai *et al.* [7]. A small contribution to deep-hole states of 1.94% is not listed.
[c]Present experiment.
[d]Total width is taken from the present experimental results.

The three spin components of the SDR are expected to have excitation energies $E_x(2^-)<E_x(1^-)<E_x(0^-)$ with the strength ratio of 5:3:1. It was not possible in the present experiment to disentangle the various spin components (2^-, 1^-, and 0^-) of the SDR on the basis of their angular correlation patterns, which were not characteristic. Possible weak contributions from the 1^- GDR could also not be identified. The total proton decay branching ratio for the SDR has been determined from the coincidence spectra to be 13.4 ± 3.9% after correcting for observed angular correlation effects. Because of this correction this number differs slightly from the number published earlier, i.e., 14.1 ± 4.2% [2]. If the SDR is assumed to be one single resonance with the total width of 8.4 ± 1.7 MeV, a total proton escape width of 1.12 ± 0.32 MeV is deduced using Eq. (2). Even if one assumes that the observed total proton escape width should be divided among the three components, the resulting proton escape width per component is still considerably larger than that for the GTR [2].

Results of recent theoretical calculations by Moukhai *et al.* [7] for the branching ratios and the partial escape widths to the various neutron-hole states in ^{207}Pb are listed in columns 3 and 4 of Table I, respectively. These calculations were performed in a semi-microscopical approach based on continuum RPA (CRPA), i.e., with coupling to the continuum, and with the strengths of the Landau-Migdal force f' and g' chosen to be 1.0 (to reproduce the experimental difference of the neutron and proton separation energies in ^{208}Pb) and 0.76 (to describe the GTR excitation energy in ^{208}Bi), respectively. Furthermore, the mean-field depth has been increased slightly to describe better the nucleon separation energies in ^{208}Pb. With these adjustments of the parameters to reproduce the global properties of single particles in ^{208}Pb and GTR in ^{208}Bi, the theoretical results are found to reproduce the experimental partial escape widths very well. The new calculations of Moukhai *et al.* [7] reproduce also the experimental branching ratios and partial escape widths of the IAS and GTR published earlier [2].

In conclusion, we have reported the results of proton decay from the spin-dipole resonance (SDR) in ^{208}Bi performed with the ^{208}Pb(^{3}He,tp) reaction at $E(^3\mathrm{He}) = 450$ MeV. The total and partial branching ratios for direct proton decay of the SDR have been determined, and the relative partial branching ratios for proton decay from the IAS, GTR, and SDR resonance region to the neutron-hole states in ^{207}Pb have been deduced as a function of excitation energy. The deduced partial escape widths of the SDR are in good agreement with the theoretical calculations based on continuum RPA. The present results will serve to establish a good understanding of the microscopic structure of the SDR and other collective spin-isospin excitations in ^{208}Bi.

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