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Depletion of the $2f_{7/2}$ neutron hole state in ^{207}Pb

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Spectroscopic factors of six low-lying neutron hole states in ^{207}Pb were measured with a (p,d) reaction at 65 MeV. The results are compared with previous (p,d) reaction data as well as recent escape width ones of isobaric analog states in ^{208}Bi into the neutron hole states in ^{207}Pb. The spectroscopic factor for the $2f_{7/2}$ hole state shows a strong quenching (about 50% of the sum-rule limit), which suggests the existence of considerable strengths in higher excitation energy region. The appearance of the fragmentation or quenching in neutron hole strength distribution observed in the $2p$-$1f$ and $3p$-$2f$ shell regions is discussed. [S0556-2813(97)00406-8]

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It has been known that the distribution of some single-hole states shows an explosive fragmentation in several MeV excitation energy region [1–4]. For example, the $1f_{7/2}$ hole state in ^{59}Ni and ^{61}Ni observed with high-resolution (p,d) reactions at 65 MeV splits to over 20 levels in the excitation energy region of 1–6 MeV, while the low-lying $2p_{1/2}$, $1f_{5/2}$, and $2p_{3/2}$ hole states to 2–4 levels [3,4]. A similar level sequence in the p-f shell nuclei is found in lead isotopes. For the ^{207}Pb nucleus, the ground $1/2^-$, 0.570 MeV $5/2^-$, 0.900 MeV $3/2^-$, and 2.340 MeV $7/2^-$ states are strongly excited with one neutron transfer reactions [5–10], and are assigned to be the $3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, and $2f_{7/2}$ hole states, respectively. There is no fragmentation around the principal peaks of these hole states. Van der Werf *et al.* compiled escape width data of isobaric analog states in ^{208}Bi into these hole states in ^{207}Pb and evaluated carefully one-neutron-transfer spectroscopic factors for these four-hole states [11]. They have concluded that three low-lying $3p_{1/2}$, $2f_{5/2}$, and $3p_{3/2}$ hole states consume almost full strengths (~90%) for the shell-model sum-rule limit, but the $2f_{7/2}$ hole state consumes a half (~50%). They have also shown that the geometrical parameters of the Woods-Saxon well to calculate the single-particle bound-state wave function in the escape width analysis affect more weakly on the final results than in a one-nucleon-transfer reaction analysis. And average values of the parameters determined in the analysis of $(e,e'p)$ reaction data were adopted. Recently, Majumdar analyzed the ^{207}Pb hole states with a particle-vibration coupling model which considered the giant quadrupole and octupole resonances and showed a strong quenching of the principal $2f_{7/2}$ hole state [12]. The strength of the low-lying $2f_{7/2}$ hole state of 50% for the sum-rule limit is interpreted in terms of core polarization accompanying many residual strengths located in 4–18 MeV excitation energy region.

To confirm the above interesting fact, it is desired to compare spectroscopic factors with those from one-nucleon-transfer reactions because there is a great number of data with these reactions for target nuclei over the Periodic Table. It is also suggestive to analyze the data using the parameters for calculating the single-particle bound-state wave function adopted in the escape width analysis. Unfortunately, spectroscopic factors for the concerned states which were measured previously by neutron pickup reactions were distributed between 50 and 200% strengths for the sum-rule limit [5–9]. It is natural that there is a severe problem in absolute determination of the spectroscopic factor originated in the calculation of the bound-state wave function for the transferred nucleon in the distorted-wave Born approximation (DWBA) analysis.

However, the (p,d) reaction with a several tens MeV polarized proton beam has been proved to provide clear identification of the transferred angular momenta and reasonable values of spectroscopic factors for hole states in a relatively wide angular-momentum transfer range [1–4,13]. It is desired to reinvestigate the above-mentioned problem with the (p,d) reaction using several tens MeV energy protons.

Then, the (p,d) reaction on ^{208}Pb was studied at 65 MeV. The experiment was performed using a high-resolution polarized proton beam from the AVF cyclotron of the research center for nuclear physics (RCNP), Osaka University. The experimental procedure has been described in detail in our previous works [1–4,13–16]. The target is a metallic ^{208}Pb foil 0.800 mg/cm^2 thick enriched to higher than 99%. Absolute values of cross sections were determined with the aid of an optical-model calculation of elastic-scattering data with standard parameters [17] and the resultant value was checked with a standard method from measurements of the target weight and area, solid angle, and integrated beam current. Emitted deuterons were analyzed with the spectrograph RAIDEN [18,19]. The energy resolution was 35 keV.

The analyzed states are the ground $1/2^-$, 0.570 MeV $5/2^-$, 0.900 MeV $3/2^-$, 1.633 MeV $13/2^+$, 2.340 MeV $7/2^-$, and 3.413 MeV $9/2^-$ ones. The measured angular distributions of cross sections and analyzing powers for these hole states are shown in Fig. 1 together with DWBA predictions. The DWBA curves are calculated using the code DWUCK [20] in zero-range approximation with finite-range and nonlocal corrections. The proton and deuteron optical potentials are of standard type of Menet *et al.* [17] and of

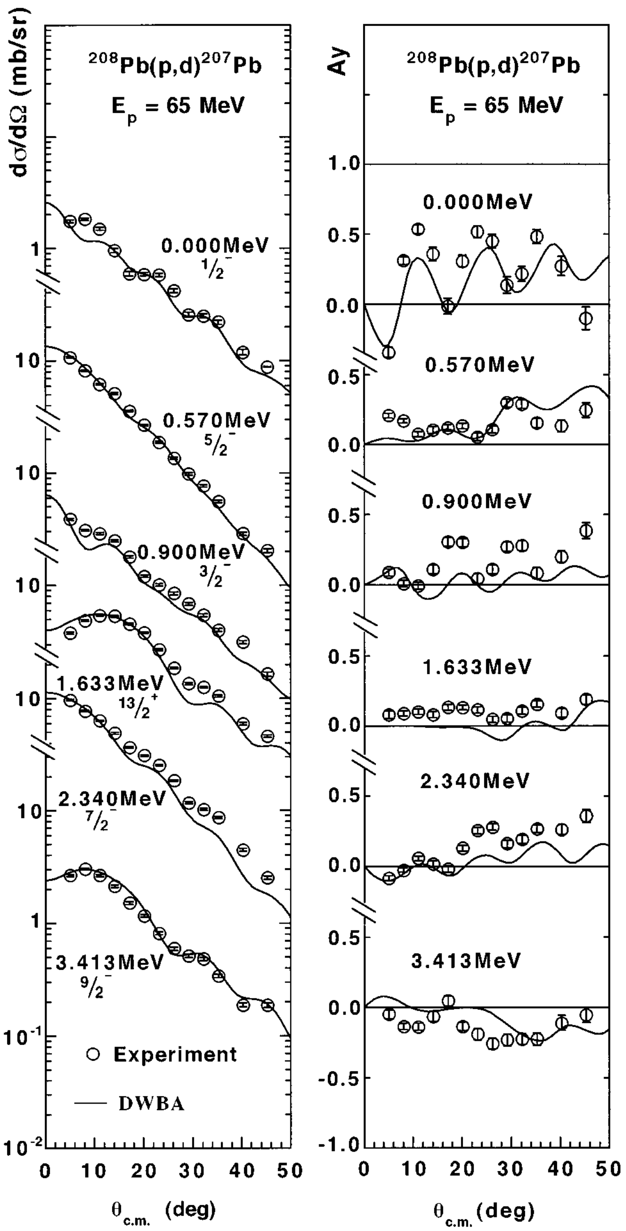

FIG. 1. Angular distribution data of cross sections (left) and analyzing powers (right) for low-lying states in the ^{208}Pb (p,d) ^{207}Pb reaction at 65 MeV. The solid curves show the predictions of the DWBA theory.

adiabatic type reduced from neutron and proton potentials of Becchetti and Greenlees [21], respectively. The neutron bound-state wave functions are calculated using the set of geometrical parameters determined in the escape width analysis, $r_n = 1.268$ fm and $a_n = 0.65$ fm with a Thomas spin-orbit term of $\lambda = 25$ [11]. The resultant spectroscopic factors for the observed hole states are tabulated in Table I together with those from previous typical (p,d) reactions [5,6], escape width measurements of van der Werf *et al.* [11], and the theoretical prediction of Majumdar [12]. As data of (p,d) reactions, those of a relatively high-resolution ($\leqslant 50$ keV) study for peak separation in several tens MeV bombarding energy [5,6] are cited.

It is found from Table I that the results at 35, 41, and 65 MeV bombarding energies are in good agreement with each other. Besides, average values of these data agree well with the escape width data, although the absolute values are slightly larger. It is noted that the difference of the present data from the escape width ones are always within their errors. The geometrical parameters for calculating a one-nucleon bound-state wave function in DWBA analysis are recommended usually to use $r_n = 1.25$ fm and $a_n = 0.65$ fm with a Thomas spin-orbit term of $\lambda = 25$. van der Werf *et al.* have chosen $r_n = 1.268$ fm by fixing the a_n and λ values to the standard ones. The present result shows that the choice of the parameters of van der Werf *et al.* is reasonable also for the (p,d) reaction analysis at several tens MeV energy region. The present result confirms again the strength of the 2.340 MeV $2f_{7/2}$ hole state to be about 50% for the sum-rule limit, while those of the $3p_{1/2}$, $2f_{5/2}$, and $3p_{3/2}$ hole states to be about 90%. Of course, there are no clear fragmentations around the principal peaks for four-hole states [5–10]. The energies and the spectroscopic factors for $3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, and $2f_{7/2}$ hole states are consistent with the predictions of the particle-vibration coupling model of Majumdar [12]. It is noted also that the 1.633 MeV $1i_{13/2}$ and 3.413 MeV $1h_{9/2}$ hole states have about 50% strength for the sum-rule limit.

The successive $2f_{7/2}$ hole states may exist at 4.52 and 5.47 MeV with about 16% of the strength of the 2.34 MeV states [6]. This feature agrees well with the prediction of Majumdar, in which the $2f_{7/2}$ hole state splits to 3 levels below 6 MeV excitation energy, and the $3p_{1/2}$, $2f_{5/2}$, and $3p_{3/2}$ hole states do not [12]. However, the assignment of the 5.47 MeV level in [6] is ambiguous. In (d,t) reaction data at 200 MeV [10], for example, this level does not exist at 5.47 MeV, but splits to 3–4 levels in this energy region. Since no spectroscopic factor data are reported for these states, further discussions on them are not performed here.

Finally, the $f_{7/2}$ hole state does not split largely in the $3p$-$2f$ shell nucleus ^{207}Pb, while in case of the $2p$-$1f$ nuclei, i.e., nickel isotopes, it splits explosively. The fragmentation of a single-particle state or a hole state is caused by the interaction with the mean field and the mixing to a large number of one-particle–two-hole states in the background region. The results for ^{207}Pb are understandable because the level density in the double magic nucleus region is quite low and the mixing is very weak.

Although the global feature of the prediction of Majumdar is reasonable, it results in a rather large spreading width Γ of about 6 MeV for the $2f_{7/2}$ hole state, which is considerably larger than the mean-field predictions in this excitation energy region [22,23]. Bertsch *et al.* showed a sudden increase of the spreading width of the ^{208}Pb$+n$ system above the 4–6 MeV excitation energy region [24]. This is caused by the strong coupling of one-particle motion with the surface vibration. This fact may also relate to a strong depletion of the principal single-particle or hole state in several MeV excitation energy regions.

In summary, spectroscopic factors of six low-lying neutron hole states in the ^{207}Pb nucleus were measured with the (p,d) reaction at 65 MeV. The results agree well with those from (p,d) reactions at several tens MeV bombarding energy and also from the escape width data of isobaric analog states in ^{208}Bi into the neutron holes states in ^{207}Pb. The

TABLE I. Spectroscopic factors $[C^2S/(2j+1)]$ of low-lying hole states in ^{207}Pb obtained by (p,d) reactions at several tens MeV bombarding energy region. Those from escape width data of isobaric analog states in ^{208}Bi into neutron hole states in ^{207}Pb and a theoretical prediction are also shown.

	Orbit	$3p_{1/2}$	$2f_{5/2}$	$3p_{3/2}$	$1i_{13/2}$	$2f_{7/2}$	$1h_{9/2}$	E_p (MeV)
Experiment	E_x (MeV)[a]	0.0	0.570	0.900	1.633	2.340	3.413	
(p,d) reactions	C^2S[b]	0.9	0.86	0.8	0.67	0.55	0.49	35
	C^2S[c]	1.1	1	0.95	0.61	0.64	0.64	41
	C^2S[a]	1.1	0.88	0.96	0.49	0.55	0.56	65
Average of (p,d) reaction data	C^2S[d]	1.00±0.11	0.90±0.10	0.89±0.09	0.56±0.15	0.56±0.09	0.55±0.10	
Escape width	C^2S[e]	0.87±0.06	0.88±0.12	0.92±0.08	—	0.50±0.11	—	
Theory	E_x (MeV)[f]	0.0	0.850	0.633	—	2.128	—	
	C^2S[f]	0.945	0.815	0.805	—	0.627	—	

[a] Present work.

[b] Reference [5].

[c] Reference [6].

[d] The errors are estimated from the standard deviations of three data and 5% systematical ones.

[e] Reference [11].

[f] Reference [12].

spectroscopic factor for the $2f_{7/2}$ hole state shows a strong quenching (about 50% for the sum-rule limit), which suggests the existence of considerable strengths in higher excitation energy region. The energies and the spectroscopic factors of low-lying $3p_{1/2}$, $2f_{5/2}$, $3p_{3/2}$, and $2f_{7/2}$ hole states are interpreted well with the particle-vibration coupling model with giant resonances.

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