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Strength function of the $d_{5/2}$ hole state in ^{39}Ca

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The strength function of the $d_{5/2}$ hole state in ^{39}Ca has been determined from the $(\vec{p},d)$ reaction at 65 MeV. The $d_{5/2}$ hole state consists of three strongly excited states at the excitation energies of 5–6 MeV with strengths of 41% of the sum-rule limit and a group of several tens of weakly excited states instead of six or seven peaks as in previous data, distributed in the excitation-energy region from 6 to 10 MeV with 38% of the sum-rule limit. This is evidence for the general feature of the fragmentation of deeply bound hole states, proved by peak-by-peak analysis. The strength quenching of the stretched 6^- state in ^{40}Ca(p,n) reaction is discussed with the strength fragmentation of the $d_{5/2}$ hole state.

Strength functions of the deeply bound hole states and highly excited states excited by transfer reactions supply a better understanding of the damping phenomena in the single-particle picture of nuclei.[1,2] Detailed strength functions of $1g_{9/2}$ and $2p$ hole states in the tin isotopes have been determined[3–5] and the comparisons between experiment and theory have revealed that the fragmentation in the excitation-energy region of ~4–10 MeV arises from a coupling of the single-hole state to the collective phonon motion in the core nucleus.[6–8] Reasonable agreement for the average energy and the width between experiment and theory has been obtained.[5] In these results, the shape of the strength function of the single-hole state is generally classified into two parts, one a narrow bump with a width of about 0.5–1 MeV existing near the rising region of the continuum (about 4-5 MeV in tin isotopes) and the other a broad bump with a width of about 2–3 MeV located 2–3 MeV higher in the excitation region. This feature may correspond to the coupling of the hole state to collective phonon motion.[6–8] The experimental data receive, however, severe criticism for the subtraction of the physical background and the deconvolution of mixed l,j components. It is desirable to obtain the strength function in the wide energy region with low level density and lower physical background and to investigate the fragmentation of a single-hole state in a peak-by-peak analysis. Double-magic nuclei are good candidates. In double-magic nuclei, ^{40}Ca is interesting because, in the shell-model concept, the nuclear surface of ^{40}Ca consists of $1d_{3/2}$, $2s_{1/2}$, and the slightly deeper $1d_{5/2}$ shells and the deepest major $(1p,1s)$ shells may exist in a much higher excitation-energy region. In excitation energy lower than 10 MeV, it is sufficient to assume that the levels arising from the $1d_{3/2}$, $2s_{1/2}$, and $1d_{5/2}$ shells are mainly excited.[9] If one uses a high-resolution polarized beam, the $1d_{5/2}$ and $1d_{3/2}$ components can be identified in a peak-by-peak analysis. Unfortunately, there are no high-resolution transfer reaction experiments with polarized beams on ^{40}Ca in the wide excitation energy region.

Recently, the Indiana group has shown the fragmentation of the stretched 6^- states excited by the ^{40}Ca$(p,n)^{40}$Sc reaction and the data are used for discussion of the quenching phenomena of pure shell-model states.[10] In the mass region of $2s$-$1d$ and $1f$-$2p$ shell nuclei, stretched 6^- states arising from $1f_{7/2}$-$1d_{5/2}^{-1}$ configuration are strongly excited and the normalization factors of ~0.3–0.4 are reported. The stretched 6^- state excited in the ^{40}Ca$(p,n)^{40}$Sc reaction splits to a number of states in the 5–10 MeV excitation-energy region and a normalization factor of 0.35 is determined for the sum of the bump of these states. The fragmentation of 6^- stretched states is interpreted by comparison with the ^{39}K$(p,n)^{39}$Ca and ^{40}Ca$(p,d)^{39}$Ca neutron pickup reactions to $d_{5/2}$ hole states in the excitation-energy region of ~5–10 MeV. To discuss the quenching phenomena in stretched states, it is important that the assignment of j is correct and the deduced spectroscopic factors are quantitative.

With this viewpoint, the ^{40}Ca$(p,d)^{39}$Ca reaction to the excitation energy up to about 14 MeV has been investigated in a high-resolution polarized-beam experiment.

The experiment was done with the Osaka University AVF Cyclotron. A polarized proton beam of 65 MeV was accelerated, analyzed, and made to bombard a natural calcium metallic foil target 1.1 mg/cm^2 thick. The emitted deuterons are analyzed with the high-resolution spectrograph RAIDEN (Ref. 11) and viewed with the focal plane detector system KYUSHU.[12] A typical energy spectrum of emitted deuterons is shown in Fig. 1. The energy resolution is typically 30 keV [full width at half max-

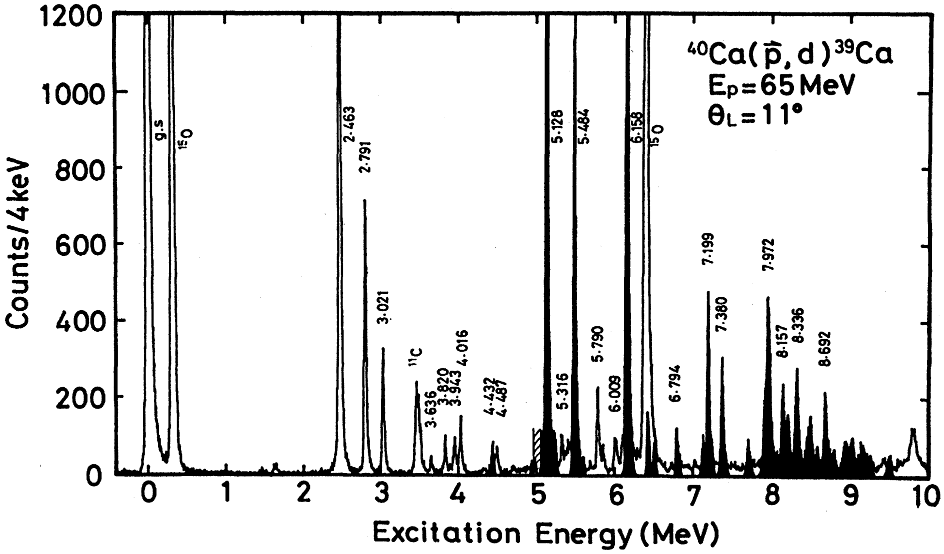

FIG. 1. Typical energy spectrum of deuterons from ^{40}Ca(p,d) ^{39}Ca reaction at 65 MeV. The darkened parts correspond to the $l=2, j=\frac{5}{2}$ transitions (see text).

imum (FWHM)], mainly due to the target thickness and the beam width. The normalization of the cross sections was performed by comparing the elastic scattering data with the optical-model analysis, which agreed within an error of 10% with those independently calculated using the target thickness, beam charge, and solid angle.

The discrete levels distribute in the excitation energy region up to about 10 MeV. In the excitation energy region higher than 10 MeV, clear peaks were not found. The continuum background under the peaks has no effect in the excitation energy region below 8 MeV. From 8 to 10 MeV, a weak background which shows monotonic decreasing angular distribution exists. The subtraction of this background did not severely affect the results because this was relatively small compared with the net peak yield.

For the discrete levels, the data were processed with peak-by-peak analysis. Seventy-nine peaks were found in the excitation energy region of 0–9.5 MeV. The angular distributions of strongly excited states show clear diffraction patterns. In the energy region of ~4–10 MeV, there are forty-one peaks having $l=2$ patterns. Two recent experimental results should be commented on. Källne and Fagerström measured the ^{40}Ca$(p,d)^{39}$Ca reaction at 185 MeV with an energy resolution of 260 keV,[13] and Martin *et al.* at 40 MeV with an energy resolution of 65 keV.[14] There only six $l=2$ excited states were found in the former, and seven in the latter $E_x=4$–10 MeV region. Furthermore, the beams were unpolarized and the resolutions were relatively worse.

In Fig. 2, angular distributions of analyzing power distribution for the ground state and nine strongly excited states with the $l=2$ angular distribution are shown. There are three very strongly excited states in the excitation energies, 5.128, 5.484, and 6.158 MeV. Transferred orbital angular momenta of these states have been already assigned to be $l=2$ and the total angular momenta tentatively to be $j=\frac{5}{2}$.[13,14] The j assignments were definitely established with the present polarized-beam experiment with the experimental angular distribution of analyzing power of known levels[15] and the distorted-wave Born approximation (DWBA) prediction described below. Almost all the transitions in the excitation energy above 5 MeV arise from $l-2$, $j=\frac{5}{2}$ transition. In Fig. 1, the darkened parts of $E_x=5$–10 MeV are all $d_{5/2}$ hole contributions. The $d_{5/2}$ hole strength splits to two parts: (1) three strongly excited states in the excitation energy region of 5–6 MeV; and (2) a group of weakly excited states located in the excitation-energy region from 7 to 10 MeV instead of its smooth splitting around the main strong peak. This feature is consistent with the experimental and theoretical results of the deeply bound hole states in medium-weight nuclei.[1–8]

The zero-range DWBA analysis in the local-energy approximation were performed with the distorted-wave Born-approximation code (DWUCK).[16] For the optical potentials of incident and outgoing channels, Menet's[17] and the adiabatic type[18] constructed from Becchetti-Greenlees's[19] respectively, were used. The standard corrections for the finite-range effect of 0.621 and nonlocalities of 0.85 and 0.54 for protons and deuterons, respectively, were taken into account. The spin-orbit potential of deuterons was weakened from about 6.2 to 2.06 MeV in order to reproduce the analyzing power data. With this reduction, the differential cross section did not change meaningfully. For the calculation of neutron bound states, the effective binding-energy method and the separation-energy method were used. To obtain reasonable spectroscopic factors in a wider excitation energy range the former results will be adopted as discussed in Ref. 14. The bound-state parameters were determined to normalize the sum of the strengths for the surface shells $1d_{3/2}^{-1}$ and $2s_{1/2}^{-1}$ to almost full occupation (~90%),[20] and $r_0=1.27$ fm and $a_0=0.70$ fm with 25 times the standard spin-orbit Thomas term were determined. Under these

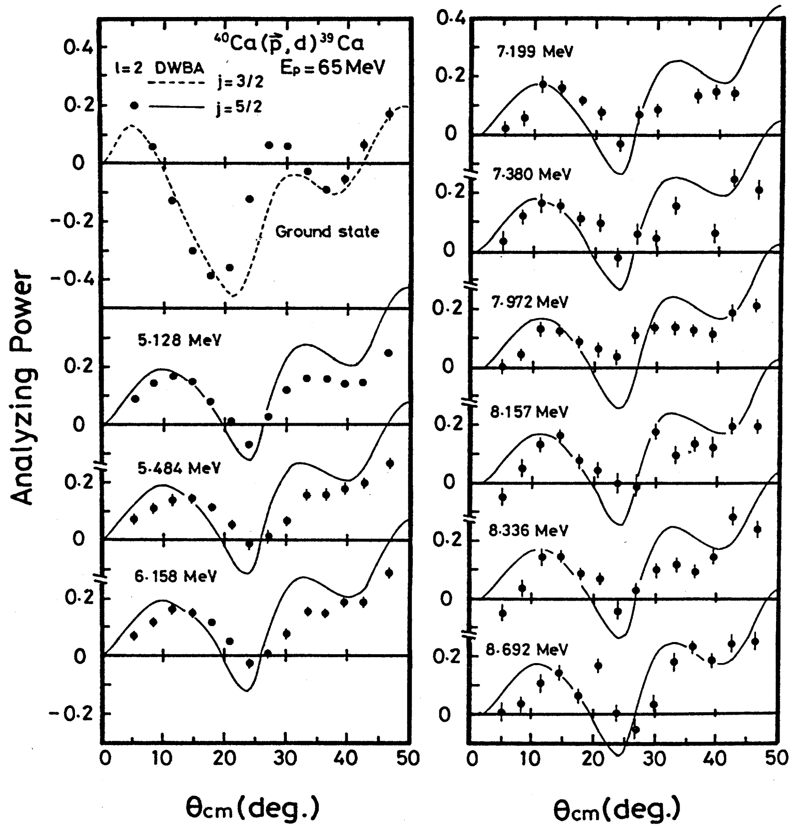

FIG. 2. Analyzing power data with $l=2$ patterns. Those of ten strongly excited states are shown. Solid and dashed lines show, respectively, the DWBA predictions with $l=2$, $j=\frac{5}{2}$, and $\frac{3}{2}$ transitions.

conditions, the DWBA calculation predicts well the angular distributions of the cross section and analyzing power data for $1d_{3/2}$, $2s_{1/2}$, and $1d_{5/2}$ transfers. The sum of the deduced spectroscopic factors of $1d_{3/2}^{-1}$ and $2s_{1/2}^{-1}$ transitions were, respectively, 3.74 ± 0.2 and 1.64 ± 0.15.

With DWBA calculations, it was confirmed that the $d_{5/2}$ strengths are distributed in the excitation-energy region of $\sim$5–10 MeV. The spectroscopic factors C^2S for the $d_{5/2}$ hole state are displayed in Fig. 3 as a spectroscopic strength function. Spectroscopic factors for three strongly excited 5.128, 5.484, and 6.158 MeV states are 1.03, 0.49, and 0.94, respectively, which correspond to 41% strength of the sum-rule limit. The spectroscopic factors for the ground states, and these strongly excited states are in good agreement with the previous result at 40 MeV.[14] The total spectroscopic factor for the $d_{5/2}$ transfer from 4.432 to 10 MeV is 4.72 ± 0.4, then about 79% of strength exist in this excitation-energy region. The average excitation energy and the spreading width estimated with the 1st and 2nd moments of the strength function are, respectively, $E_x=6.61$ MeV and $\Gamma_{\downarrow}=2.35\times\sigma=3.17$ MeV. The spreading width is slightly smaller than those obtained from the analysis of the continuum spectra of deeply bound hole states at a similar excitation energy. This may be due to the closed-shell characteristics of the target nucleus.

The normalization factor of 0.35–0.48 has been determined for the 6^- stretched state excited by ^{40}Ca(p,n) reactions to 4–10 MeV excitation-energy region.[10] This value was consistent with the theoretical consideration of the higher-shell configuration mixing effects.[21] The present result confirmed the strength fragmentation of the 6^- stretched state quantitatively.

In summary, the strength function of the $d_{5/2}$ hole stat :

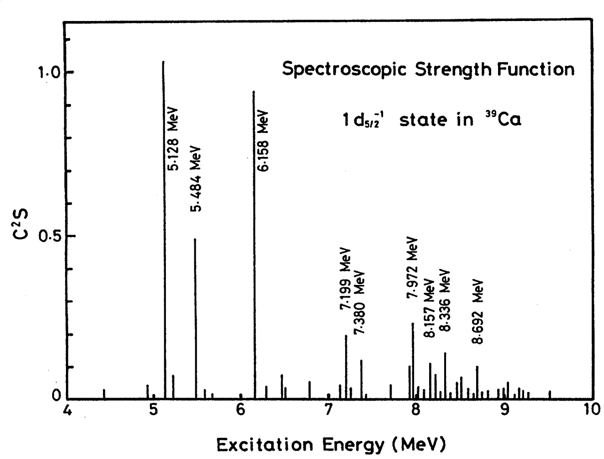

FIG. 3. Spectroscopic strength function of $1d_{5/2}$ hole state in ^{39}Ca.

in ^{39}Ca has been determined with a high-resolution polarized-beam experiment. This result is a precise and careful determination of almost the full structure of the strength function of a deeply bound hole state in peak-by-peak analysis with unambiguous l and j assignments. The general feature of two group distributions of the strength function of the deeply bound hole state has been confirmed. The data have also quantitatively confirmed the strength fragmentation of the stretched 6^- state in ^{39}Ca excited by ^{40}Ca(p,n) reaction at 135 MeV.

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[1]M. Sakai and K. Kubo, Nucl. Phys. **A185**, 217 (1972); T. Ishimatsu *et al.*, *ibid.* **A185**, 273 (1972), and many references therein; see, for example, S. Galès, J. Phys. (Paris) Colloq. **45**, Suppl. No. 3, C4-39 (1984), and references therein.
[2]G. F. Bertsch *et al.*, Rev. Mod. Phys. **55**, 287 (1983).
[3]S. Galès *et al.*, Nucl. Phys. **A381**, 40 (1982).
[4]M. Matoba *et al.*, Phys. Lett. **149B**, 50 (1984).
[5]M. Matoba *et al.*, Nucl. Phys. **A456**, 235 (1986).
[6]T. Koeling and F. Iachello, Nucl. Phys. **A295**, 45 (1978).
[7]V. G. Soloviev *et al.*, Nucl. Phys. **A342**, 261 (1980); T. D. Thao *et al.*, Yad. Fiz. **34**, 43 (1983) [Sov. J. Nucl. Phys. **34**, 77 (1983)].
[8]P. F. Bortignon and R. A. Broglia, Nucl. Phys. **A371**, 405 (1981).
[9]J. W. Watson *et al.*, Phys. Rev. C **26**, 961 (1982).
[10]T. Chittrakarn *et al.*, Phys. Rev. C **34**, 80 (1986).
[11]H. Ikegami *et al.*, Nucl. Instrum. Methods **175**, 33 (1980).
[12]M. Matoba *et al.*, Nucl. Instrum. Methods **180**, 419 (1981).
[13]J. Källne and B. Fagerström, Phys. Scr. **11**, 79 (1975).
[14]P. Martin *et al.*, Nucl. Phys. **A185**, 465 (1972).
[15]K. Hosono *et al.*, Nucl. Phys. **A343**, 234 (1980).
[16]P. D. Kunz, DWUCK Program, University of Colorado (unpublished).
[17]J. J. H. Menet *et al.*, Phys. Rev. C **4**, 1114 (1971).
[18]R. C. Johnson and P. J. R. Soper, Phys. Rev. C **1**, 976 (1970).
[19]F. D. Becchetti, Jr. and G. W. Greenlees, Phys. Rev. **182**, 1190 (1969).
[20]S. Nishizaki (private communication).
[21]A. Yokoyama and H. Horie, Phys. Rev. C **36**, 1657 (1987).