High-Lying Proton Strengths Observed in Stripping Reactions

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Strong transitions to high-lying proton states are observed for the first time in the study of the (α, t) and $(^3\mathrm{He}, d)$ reactions on ^{144}Sm at 80- and 240-MeV incident energy, respectively. The excitation energies, angular distributions, and strengths of these states suggest that they arise from proton stripping to high-spin outer subshells, e.g., $1h_{9/2}$ and $1i_{13/2}$.

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The spreading of simple states into an underlying background remains one of the important questions in nuclear physics. One method of studying this problem is by transfer reactions, in particular at high excitation energies where the level density is large. During the past few years, the neutron hole state response function has been extensively studied by pickup reactions.[1-5] The theoretical models developed to explain the empirical systematics suggest that the hole states mix extensively with phonon states.[6-9] On the other hand, practically no information is available about the highly excited particle states.[10] A search in the literature shows that neutron strength functions have been studied by using (d, p) reactions at low bombarding energy in the lead[11] and in the rare-earth region[12] up to 5-MeV excitation energy. However, here the excited levels correspond to stripping within the same major shell, in contrast with neutron pickup experiments where broad "bumps" due to the removal of nucleons from inner subshells show up as "giant resonance" structures superimposed on a continuous background.[1-5]

In this Letter, we report the study of the reaction $^{144}\mathrm{Sm}(\alpha, t)^{145}\mathrm{Eu}$ at 80 MeV, complimented by an investigation of the $(^3\mathrm{He}, d)$ process at 240 MeV. In the (α, t) experiment, two broad peaks at $E_x = 5.9$ and 7.6 MeV dominate the high-energy part of the residual energy spectra. These features display striking similarities with those observed in the early experiments on deeply bound states in the Sn isotopes.[1-5,13] One plausible explanation for these peaks is that they arise from proton states in the next major shell consisting of closely spaced high-spin orbitals, e.g., $2f_{7/2}$, $1h_{9/2}$, and $1i_{13/2}$. Such high-lying proton strengths could be strongly enhanced in the (α, t) process due to the known selectivity of this reaction for large momentum transfers $(l = 5, 6)$.

The (α, t) experiment was performed with α particle beams at 80 MeV delivered by the Grenoble University isochronous cyclotron. We used isotopically enriched ^{144}Sm target (96%) of 6 mg/cm^2. With the beam transport system set in an achromatic mode, we obtained a current of 50 nA and an overall resolution of 230 keV, mainly determined by the target thickness. Reaction products were detected by a gas delay-line counter backed by two plastic scintillators in the focal plane of the quadrupole single dipole spectrometer. An excitation energy range of 22 MeV was explored in two successive exposures at different magnetic fields. Angular distributions were measured from 1.75° to 18° (laboratory angle) in 3° steps. The ^{145}Eu energy spectrum from the (α, t) reaction is presented in Fig. 1(a). A previous study of the reaction[14] $^{144}\mathrm{Sm}(^3\mathrm{He}, d)^{145}\mathrm{Eu}$ at 40 MeV has established the distribution of valence proton strengths in the *sdhg* shell $(50 < Z < 82)$. No information was available for proton states located above 2.5 MeV. In Fig. 1(a), one observes the low-lying states with a selective population of the $1h_{11/2}$ state due to the matching conditions. At high excitation energy, two broad bumps are strongly excited above a continuous background. Their spacing in energy, their respective widths, and in particular, the fact that the second bump [B in Fig. 1(a)] appears as a shoulder of the main structure (A) recall the similar features observed in the study of deeply bound $1g_{9/2}$ and $2p$ hole states in tin isotopes.[1-5,13] Around 14 MeV, a sharp peak ($\Gamma < 200$ keV) is also populated. Simple Coulomb displacement energy calculations predict that the $T_>$ part of the $1h_{9/2}$ and $1i_{13/2}$ proton strengths should be located around 14 MeV in ^{145}Eu in very good agreement with the observed peak.

Following the method employed in the study of deep hole states, namely varying the incident energy and/or the reaction process in order to fulfill different matching conditions, the same range of excitation in ^{145}Eu was studied at few angles by means of the reaction ^{144}Sm(^{3}He,d) at 240 MeV. The reaction ^{144}Sm(^{3}He, d)^{145}Eu was observed at 240 MeV by using the ^{3}He beam from the Orsay University synchrocyclotron and a large magnetic spectrometer. The emerging particles were detected by two multiwire proportional chambers working in the charge induction mode and backed by two plastic scintillators. The energy resolution, mainly limited by the target thickness (6 mg/cm^2), was of about 130 keV. The resulting energy spectra is shown in Fig. 1(b). The broad structures A and B are also observed in the present (^{3}He, d) study, their positions and widths being consistent with the (α, t) results [see Figs. 1(a) and 1(b)]. The relative yields of the two structures are quite different in the two spectra due to the different selectivity in momentum of the two processes.

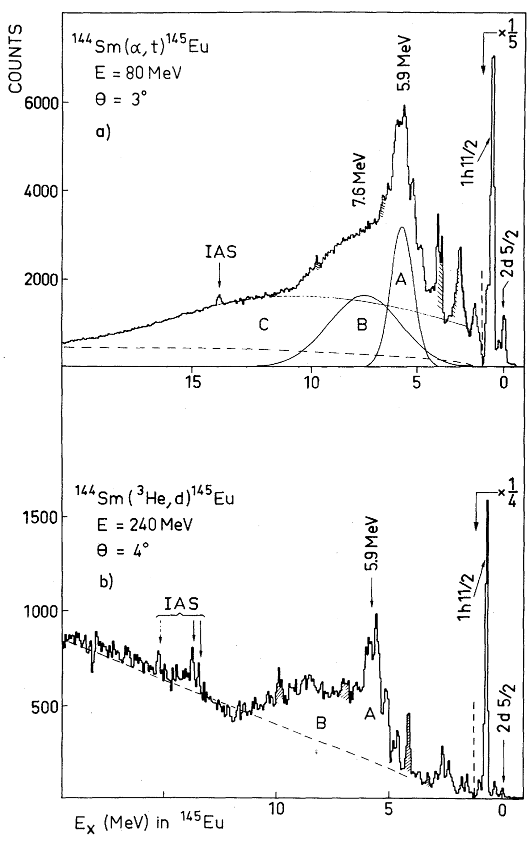

FIG. 1. (a) Triton energy spectrum from the reaction ^{144}Sm(α,t)^{145}Eu at a laboratory angle of 3°. The dashed line indicates the background line shape calculated within the plane-wave breakup model. The solid curves show the results of the fitting procedure (background region C and the two Gaussian peaks A and B). The hatched areas refer to the position of contaminant peaks. (b) Deuteron energy spectrum from the reaction ^{144}Sm(^{3}He,d)^{145}Eu at a laboratory angle of 4°. The symbols have the same meaning as in (a).

In contrast to the low-energy part, the high-energy parts of the two spectra have quite different behaviors. Since the spectral shapes of α and ^{3}He particle breakup process at incident energy ranging from 20 to 40 MeV/nucleon are well explained by a simple plane-wave breakup model,[15-16] similar calculations including corrections due to the Coulomb force were carried out in order to have a consistent description of the background. The theoretical predictions were normalized to the experimental data at forward angles ($\theta < 6°$) and at high excitation energy ($E_x \cong$ 18–20 MeV) to minimize contributions from other mechanisms (direct and/or multistep). The results are shown as dashed lines in Figs. 1(a) and 1(b). This simple model was not able to reproduce the line shape of the continuum cross section in the case of the (α,t) reaction at 80 MeV on heavy nuclei, whereas for the (^{3}He,d) reactions the predictions are in reasonable agreement with the data.

A detailed analysis of the data has been made for the ^{144}Sm(α,t) experiment. The extraction of the centroid energies, widths, and differential cross sections of the "peaks" A and B implies an assumption on the background line shape. The solid line which smoothly connects the structureless part of the energy spectra to the minima of cross sections near 3.5 MeV has been adopted as an empirical line shape. At all angles, this line shape is well fitted by a Gaussian peak [C in Fig. 1(a)] with a centroid energy E_c located at 12.1 ± 1 MeV and a total width Γ_c of 16.7± 2 MeV. The remaining part of the cross section was fitted by two Gaussian peaks having different widths. The results of this fitting procedure are presented in Fig. 1(a) and the deduced centroid energies and widths are listed in Table I. The centroid and width of the Gaussian peak assumed for the background contribution (C) disagree by several megaelectronvolts with the values predicted by the plane-wave model. However, our assumption

TABLE I. Characteristics of high-lying proton strengths in ^{145}Eu.

Bump	$\tilde{E}$ [a]	Γ [a]	l	J^{π}	C^2S [b]
A	5.9	1.23	5	$(9/2)^-$	0.97
	± 0.1	± 0.15	or		
			5 + 3	$(9/2)^- + (7/2)^-$	0.75, 0.19
			(6)	$(13/2^+)$	(0.36)
B	7.6	4.00	6	$(13/2)^+$	0.94
	± 0.4	± 0.45	(5)	$(9/2)^-$	(2.36)
C	12.1	16.7			
	± 1.2	± 2.00			
	(16)[c]	(22)[c]			

[a]Centroid energies and total widths of the observed structures A, B, and C in Fig. 1(a).

[b]The C^2S values listed in parenthesis correspond to l transfers which do not reproduce the experimental data. The adopted values are indicated without parenthesis.

[c]The values of the centroid energy and widths listed in parenthesis are the predictions of the plane-wave breakup model for the background line shape (region C).

that the cross section lying in region C is mainly due to the breakup of the α particle is reinforced by the fact that the assumed line shape is quite similar to the one observed in the case of the ^{208}Pb and ^{116}Sn in the same study of the (α, t) reaction at 80 MeV. The weak dependence of the background yield versus the atomic number A is one of the characteristics of the breakup process.

In order to test further the assumption that the observed structures A and B arise from proton stripping to high-spin orbitals, a number of distorted-wave Born approximation (DWBA) calculations were carried out.

The optical potential parameters for the entrance and exit channels were the same as the ones employed in the analysis of the reaction ^{208}Pb$(\alpha, t)^{209}$Bi at 81.4 MeV.[17] This combination of optical parameters was found to reproduce quite well the shape and the strengths of the well-known low-lying $2d_{5/2}$, $1h_{11/2}$, $1g_{7/2}$, and $2d_{3/2}$ proton states in ^{145}Eu using the code DWUCK[18] within the zero-range approximation (ZR). Exact finite range (EFR) calculations were also carried out for the same transitions using the code MARY[19] and lead to nearly identical shapes. Therefore ZR-DWBA calculations were performed by using a ZR normalization constant $N = 36$ which is consistent with the results of EFR calculations reported by Perry *et al.*[17] and Friedman *et al.*[20] and agrees with recent determinations of the volume integral D_0 for the (α, t) reaction.[20,21]

Moreover, the observed gross structures being located above the proton threshold ($S_p = 3.26$ MeV), a series of calculations were made by using Gamov functions as form factors of the unbound proton.[22] This method has been successfully applied in the analysis of proton stripping to isobaric analog states in medium-heavy nuclei.[23] The program GAMOV was used to compute the proton form factor which was introduced in the code VENUS[24] to produce ZR-DWBA cross sections. The DWBA calculations were made under the assumption of an $l = 3$ ($2f_{7/2}$), $l = 5$ ($1h_{9/2}$), and $l = 6$ ($1i_{13/2}$) proton transfer since these subshells are the first ones to be considered for proton stripping above the $Z = 82$ shell closure. Because Coulomb and centrifugal barriers are dominant, the calculations with an unbound proton form factor and the ones assuming a quasi bound state give identical results in both shape and magnitude up to 6 MeV but strongly differ at higher excitation energy. The experimental data and DWBA curves for the peaks A and B are displayed in Fig. 2. A very good agreement is found between the experimental results and DWBA calculations if one assumes an $l = 5$ transfer for the bump A and an $l = 6$ transfer for the bump B. Although the observed difference between $l = 5$ and 6 transfers is rather small, the normalization of the two curves at forward angles allows with some degree of confidence an l assignment. For completeness one should mention that an $l = 3$ transfer does not reproduce the trend of the experimental data but a 20% mixing of $l = 3$ strength in the bump A will not change significantly the quality of the fit for the bump A. On the contrary, no $l = 3$ mixing is consistent with the angular distributions of the peak labeled B. The deduced spectroscopic strengths for the different transfers are listed in Table I and reinforce the l assignments proposed above. A pure $l = 5$ transfer for the $E_x = 7.6$-MeV peak leads to a total amount of strength which is much larger than the sum-rule limit. Furthermore, the results of the DWBA analysis indicate that the full $l = 5$, $1h_{9/2}$ strength is observed in the bump A with a possible 20% admixture of $l = 3$, $2f_{7/2}$ strength and that the $l = 6$, $1i_{13/2}$ is mainly concentrated in the region B. We would like to point out that the energy difference between the two structures A and B is nearly equal to the spacing between the low-lying $1h_{9/2}$ and $1i_{13/2}$ proton states in ^{209}Bi. Finally, the angular distributions obtained for the background

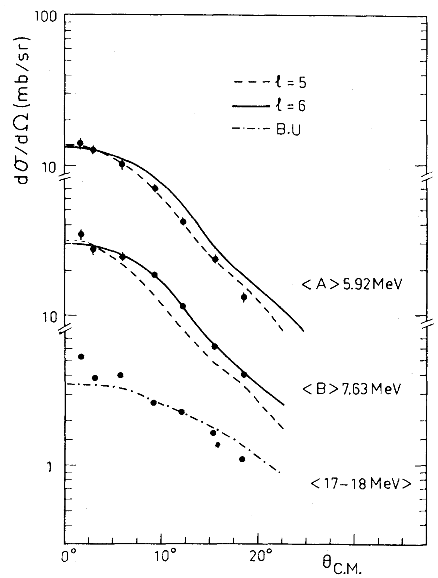

FIG. 2. Angular distributions from the reaction $^{144}Sm(\alpha,t)^{145}Eu$ to high-lying proton states. The centroid energy of the bumps are indicated. Solid and dashed lines are DWBA calculations (bound state, region A; Gamov function, region B) for the indicated l values. Error bars are statistical errors only. The dot-dashed curve corresponds to the theoretical prediction of the breakup model for the indicated energy bin in region C.

in the structureless part of the spectra (region C) is compared to the theoretical predictions from the plane-wave breakup model. Although the predictions failed for the spectral shape, the agreement here is rather good, especially at large angles.

In summary, two broad structures (1.2 and 4.0 MeV wide) have been observed at $E_x = 5.9$ and 7.6 MeV in ^{145}Eu. The measured excitation energies, angular distributions, and deduced strengths support strongly the assumption that these peaks arise from proton stripping to the next upper shell, namely to the $1h_{9/2}$ and $1i_{13/2}$ orbitals located well above the Fermi sea. It is remarkable that the full strength is still concentrated in a narrow energy range providing a first experimental evidence for a small damping of proton particle states in heavy nuclei.

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