Explanation of Some Stripping Transitions to Unbound Isobaric Analog States

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Several (^{3}He,d) and (d,n) transitions on Zr and Mo targets leading to unbound isobaric analog states, which had previously been reported anomalous in comparison with distorted-wave Born-approximation predictions, have been recalculated using a different form-factor prescription. Broad overall agreement with experiment is obtained, indicating that both the nuclear structure and the reaction mechanism are normal.

Two recent Letters[1,2] have reported stripping reactions on isotopes of Mo and Zr which led by proton capture to unbound isobaric analog states, the reactions being respectively (^{3}He, d) and (d,n). Both reported preliminary distorted-wave Born-approximation (DWBA) calculations which could not explain all the observed features, some of the observed regularities being so far out as to be designated anomalies. Much is known about the spectra of analog states in the residual nuclei (e.g., from proton resonances) and their parents [e.g., from (d,p) reactions], and from this strong transitions were expected by proton capture into $3s_{1/2}$, $2d_{3/2}$, and $2d_{5/2}$ orbits. The major anomaly reported in Ref. 1 was the absence of the $3s_{1/2}$ transitions from the observed spectra. In Ref. 2 the most pronounced anomaly was the enhancement by a factor ~4 of the observed d-state transitions above the predicted magnitudes. The present Letter reports DWBA stripping calculations for these transitions (omitting only those nuclei for which there was inadequate spectral data) assuming a quite normal reaction mechanism and structure model, which result in broad overall agreement with experiment. Although there are some discrepancies in detail, the apparent anomalies have been resolved.

These final analog states present difficulties greater than those of other unbound levels for which we have done stripping calculations[3,4] because of their high excitation, more than one decay channel being open, and because they are not simple resonances. We have consequently modified the procedure as follows: We start by finding a real Woods-Saxon proton well of such depth as to give a resonance of the relevant l and j at the energy of the observed final level. This continuum wave function (normalized in the energy scale) was substituted in the basic DWBA matrix elements to yield a single-particle cross section $[d\sigma(\theta)/dE]_{\text{s.p. max}}$ per unit energy at the resonance maximum, the convergence of the radial integrals being expedited by the method of contour integration due to Vincent and Fortune.[5] If the corresponding single-particle width is $\Gamma_{\text{s.p.}}$, then the single-particle cross section integrated over the resonance is approximately $\frac{1}{2}\pi\Gamma_{\text{s.p.}}[d\sigma(\theta)/dE]_{\text{s.p. max}}$. If the actual level has a proton spectroscopic factor θ_p^2, its integrated cross section is $\frac{1}{2}\pi\theta_p^2[d\sigma(\theta)/dE]_{\text{s.p. max}}$.

In order to predict from this formula the absolute magnitude of the cross section, we have used two alternative methods which invoke, respectively, the independent observation of the analog level by proton scattering and the production of its parent by the (d,p) reaction. In method 1 we equate the <u>observed</u> partial width Γ_p of the level for proton elastic scattering to $\theta_p^2\Gamma_{\text{s.p.}}$. Our final formula for the predicted stripping cross section is then $\frac{1}{2}\pi\Gamma_p[d\sigma(\theta)/dE]_{\text{s.p. max}}$. In method 2 we assume that the <u>observed</u> neutron spectroscopic factor θ_n^2 of the parent level yields θ_p^2 as $\theta_n^2/(2T_0+1)$, so that the final formula for the predicted cross section is $\frac{1}{2}\pi\theta_n^2(2T_0+1)^{-1}\Gamma_{\text{s.p.}} \times [d\sigma(\theta)/dE]_{\text{s.p. max}}$. A test of our analysis is the agreement of the predictions of methods 1 and 2.

Table I sets out, against the various targets (column 1) and the analog states in the residual nuclei (column 2), the experimental differential cross sections at a fixed angle for the respective reactions (^{3}He,d) and (d,n), in columns 3 and 6, together with our predictions by methods 1 and 2. The internal agreement between our predictions by methods 1 and 2 is reasonably good except in the case of the $d_{5/2}$ transition from ^{94}Mo. In this instance the result of method 1 is suspect because it derives from a value of Γ_p from Ref. 6, where difficulties and anomalies concerning this state had been remarked, associated with the (p,n) threshold.

Regarding the reported anomaly[1] of the absence of the $3s_{1/2}$ transition except for the target ^{92}Mo, the table shows that by and large these transitions are consistent with our predictions (but see below for ^{96}Mo). In dealing with the experimen-

Table I. A comparison of measured (^{3}He,d) and (d,n) cross sections with DWBA calculations. In method 1 the observed proton widths of Refs. 6 and 7 are used; in method 2 computed single-particle widths and the neutron spectroscopic factors of Ref. 8 have been used.

		(^{3}He,d) Reaction			(d,n) Reaction		
		Experimental Cross-section[a]	Theoretical Cross-section[b] µb/sr		Experimental Cross-section[c]	Theoretical Cross-section[d] µb/sr	
Target Nucleus	J^π	µb/sr	Method 1	Method 2	µb/sr $\theta n = 25^{\circ}$ (lab.)	$\theta_n = 25^{\circ}$ (c.m.) Method 1	Method 2
^{92}Mo	$5/2^+$	744 ± 20	-	800	1200 ± 200	-	2200
	$1/2^+$	50 ± 25	25	40	100 ± 30	75	130
	$3/2^+$	138 ± 18	60	140	300 ± 50	320	750
^{94}Mo	$5/2^+$	338 ± 22	90	380	1300 ± 150	320	1350
	$(3/2^+)^e$	222 ± 20	100	90	360 ± 50	420	360
^{96}Mo	$5/2^+$	146 ± 20	150	160	300 ± 50	550	590
	$1/2^+$				< 40	80	80
	$3/2^+$	about 30 ± 5	50	40	$\lesssim 40$	250	220
^{90}Zr	$5/2^+$	640 ± 30	-	600			
	$1/2^+$	<23	15	20			
	$3/2^+$	143 ± 14	50	80			
^{92}Zr	$5/2^+$	288 ± 16	-	340			
	$1/2^+$	<12	15	25			
	$3/2^+$	181 ± 18	-	80			
^{96}Zr	$1/2^+$	-	-	-	≤ 60	-	110

[a] Ref. 1, averaged at 30° and 35° (lab).

[b] Averaged at 30° and 35° (c.m.). Optical-model parameters of Ref. 1.

[c] Ref. 2.

[d] Optical-model parameters of Ref. 2.

[e] Spin uncertain.

tal upper limits placed on the cross sections of unobserved transitions in spectra, such as those of Fig. 1 in Ref. 1, it should be borne in mind that the measured stripping spectrum does not represent directly the cross section integrated over the peak, but the peak itself in the continuum, $d\sigma/dE$. The height of the peak is inversely proportional to the total width Γ, and so for a given integrated cross section it must be more difficult to resolve the relatively wider $3s_{1/2}$ peaks from the background fluctuations.

The measured $2d_{3/2}$ and $2d_{5/2}$ cross sections are by no means larger generally than the predicted ones, thus removing the principal anomaly of Ref. 2.

For the ^{96}Mo target, the analog levels above the $d_{5/2}$ ground-state analog present a puzzle experimentally. They are a multiplet of $s_{1/2}$, $d_{3/2}$, and $g_{7/2}$ transitions, the aggregate cross section for which was actually larger than that for the $d_{5/2}$ level in the (^{3}He,d) experiment,[7] whereas nothing of the multiplet could be detected at all in the (d,n).[2] Our predictions agree in the (^{3}He, d) case, and therefore disagree with the (d,n).

We have calculated some angular distributions and obtained good agreement with the data of Refs. 1 and 2.

The large differences between our DWBA results and those of Refs. 1 and 2 stem from the use of different prescriptions for the proton form factor in the various calculations. For instance, in Ref. 2 the form factor used is that of the parent analog state. The large increase of our d-state predicted cross sections over theirs, which results in our obtaining agreement with experiment, can be understood by a comparison of the form factors of the two prescriptions. We have found that, while the shapes are very similar in the interior of the well, ours has a very much larger tail representing greater barrier penetration.

While we would not claim too much for our calculations, they indicate clearly that there is nothing particularly anomalous about these reactions.

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$^{15}\mathrm{N}(p,\gamma_2\gamma)^{16}\mathrm{O}$ and the Deformed Giant Resonance in $^{16}\mathrm{O}$†

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The cascade γ-ray decay of states at 19.9 and 20.4 MeV in ^{16}O has been observed using the reaction $^{15}\mathrm{N}(p,\gamma_2\gamma)^{16}\mathrm{O}$. These states appear to have the properties expected of giant dipole states based on the $J^\pi = 3^-$ state at 6.13 MeV. Together with earlier work, the result implies that giant dipole states based on the $J^\pi = 0^+$ state at 6.05 MeV are displaced significantly from the energies expected from a simple weak-coupling model.

In a recently published paper[1] Barnett and Tanner reported on the (unresolved) $\gamma_1+\gamma_2$ decay from states in the giant resonance region of ^{16}O reached by proton capture on ^{15}N. They found that there were very strong resonances present in the $\gamma_1+\gamma_2$ yield and that these did not branch to the ground state. The strongest transition, from the resonance at 20.4 MeV, and that from the 19.9-MeV resonance are of special interest as they have the properties expected[1] of known[2] giant-resonance states built by simple p-h (particle-hole) excitations out of either the deformed $0_2{}^+$ state at 6.05 MeV or the more nearly spherical (but strongly collective) $3_1{}^-$ state at 6.13 MeV. The experiment of Ref. 1 measured the direct cascade γ ray and could not distinguish between these possibilities; in the present study we undertook to determine whether the basis state was the $3_1{}^-$ alternative by a direct γ_2-γ coincidence study. Since the $0_2{}^+$ state decays entirely by pair emission it will not influence the γ-γ yield.

The coincidence γ rays were observed from a gas target containing 97% $^{15}\mathrm{N}_2$ at a pressure of 3000 mm Hg and enclosed by a 1-μm nickel foil. The approximate target thickness was 1.7 mg/cm^2 (about 65 keV at $E_p = 8.8$ MeV). The proton beam (<0.3 nA) of the University of Minnesota's MP tandem was focused on the target and was stopped on gold. Two NaI crystals, 7.6 cm diam ×7.6 cm and 10 cm diam×13 cm, were placed 7 cm on opposite sides of the target and were well shielded by lead from nontarget background. A single-channel gating window was set around the 6.13-MeV region of the spectrum from the 10-cm-diam×13-cm crystal (see insert of Fig. 1), and both singles and coincidence spectra from the other crystal were recorded. Crossover timing discriminators gave a coincidence resolving time of $2\tau = 50$ nsec and simultaneous accumulation of the random spectrum showed that the real-to-random ratio was better than 10 : 1 (with singles deadtimes of up to 5 %).

Figure 1 shows the spectra for the decay of the 20.4-MeV state ($E_p = 8.83$ MeV at the target center), accumulated for a total charge of 11.2 μC. A direct comparison of the 14.3-MeV peak in both spectra (as indicated) leads to the required $\gamma_2/(\gamma_1+\gamma_2)$ branching ratio independently of the efficiency of the 7.6-cm-diam×7.6-cm crystal, the gas-target thickness, and the accuracy of the beam-current integration. A coincidence background spectrum, measured above the resonance at $E_p = 9.2$ MeV, is shown in Fig. 1. There is no indication of a 14.3-MeV γ ray in this spectrum. The decay of the 19.9-MeV resonance ($E_p = 8.30$ MeV) is shown in Fig. 2. Corrections to the coincidence peak counts for background were estimated to be (25 ± 10) % for the 14.3-MeV γ ray and (25 ± 25) % for the 13.8-MeV γ ray.

The fraction of the 6.13-MeV spectrum appearing at the single-channel analyzer window (insert of Fig. 1) was measured to be 0.43 ± 0.02 by using the reaction $^{16}\mathrm{O}(p,p_2\gamma_{6.13})^{16}\mathrm{O}$ at $E_p = 6.9$ MeV with O_2 gas in the target. A pure spectrum of 6.13-MeV γ rays above 4 MeV was obtained. The ef-