INHIBITED (^{3}He, d) TRANSITIONS TO $3s_{1/2}$ ISOBARIC ANALOG STATES*

R. L. McGrath, N. Cue, W. R. Hering,† L. L. Lee, Jr., B. L. Liebler, and Z. Vager‡
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11790
(Received 6 July 1970)

The (^{3}He, d) reaction cross sections on ^{90,92,94}Zr and ^{92,94,96,98}Mo targets have been measured to unbound isobaric analog states. All expected transitions are observed except those to $3s_{1/2}$ analog states which are inhibited. Distorted-wave Born approximation calculations do not explain the anomaly. Other possible explanations are suggested.

Studies of (^{3}He, d) or (d, n) reactions which populate unbound isobaric analog states complement the more common resonance scattering data. Not only do direct proton-transfer reactions populate analog states which are undetectable as resonances due to small barrier penetrations, but also the data can provide additional tests of theories of analog states or reaction mechanisms. This Letter reports results of investigations of (^{3}He, d) cross sections for formation of a number of analog states on ^{90,92,94}Zr and ^{92,94,96,98}Mo targets. Analyses of (^{3}He, d) reactions leading to unbound analog states have not been published with the exception of a study by Blair and Armstrong[1] who observed transitions to several states (unbound by several hundreds of keV) in Co and Cu isotopes in which no unusual transition strengths were noted. In the present experiment, all expected analog-state transitions are observed with the exception of transitions to $3s_{1/2}$ analog states which are found to be inhibited. In contrast, previous studies[2-4] of these analog states populated in proton resonance scattering show no such anomaly. Since the analog states have lifetimes (typically, $\Gamma \lesssim 80$ keV) much longer than characteristic direct-interaction times, it is natural to consider these (^{3}He, d) reactions as simple single-nucleon transfer processes. However, preliminary distorted-wave Born approximation (DWBA) estimates of the (^{3}He, d) cross sections offer no explanation of the effect.

The single-particle spectroscopic factors S_n of the parent states in the mass-90 region have been determined in previous (d, p) experiments.[5-8] The 50-neutron configuration forms a closed core, with the next neutron shells corresponding to the $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, $1g_{7/2}$, and $1h_{11/2}$ orbitals. For example, the ground and 1.21-MeV states of ^{91}Zr carry most of the $2d_{5/2}$ and $3s_{1/2}$ strengths, whereas states at 2.06, 2.16, and 2.19 MeV have large $2d_{3/2}$, $1g_{7/2}$, and $1h_{11/2}$ components, respectively. The reaction ^{90}Zr(^{3}He, d)^{91}Nb

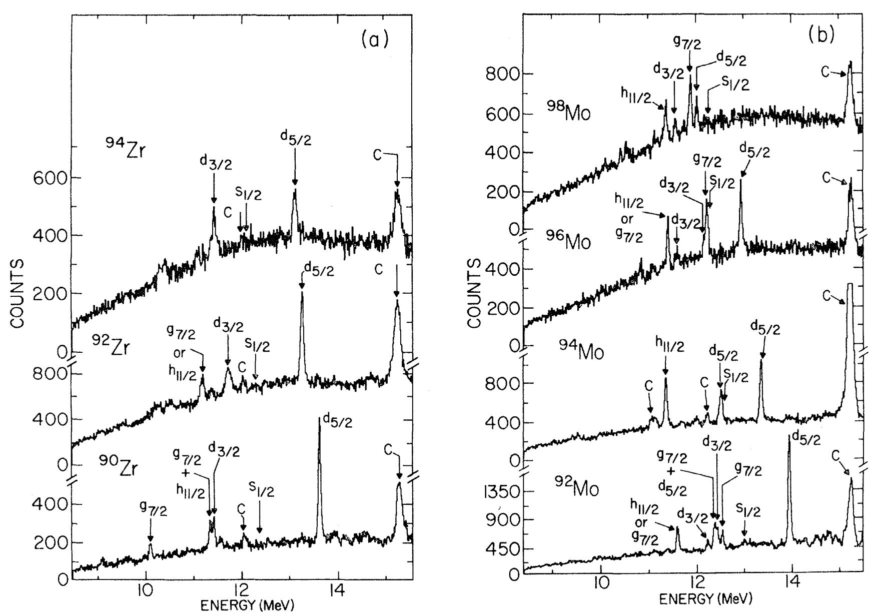

FIG. 1. Portions of energy spectra at 30° from (^{3}He, d) reactions on (a) ^{90,92,94}Zr and (b) ^{92,94,96,98}Mo targets. The peaks corresponding to analog states are identified by the parent-state spin assignments. Peaks due to target contaminants are labeled C.

populates the analogs of all except the 1.21-MeV state.

The data were collected at 24 MeV incident ^{3}He energy with two ΔE-E silicon detector telescopes. Thicknesses of the self-supporting foil targets ranged from 200 to 1000 μg/cm^2. Depending on the target, the overall deuteron energy resolution varied from 45 to 75 keV. Cross sections for ^{90}Zr were measured at intervals of 5° or less between 10° and 80°. Because these data revealed rather structureless angular distributions for the analog states (for example, the cross section of the $2d_{5/2}$ analog state in ^{91}Nb decreased approximately exponentially by a factor of 14 over the angular interval 10.8° to 85° c.m.), and also because the $3s_{1/2}$ transitions were not evident at any angles, reactions on the other targets were surveyed at only the two angles 30° and 35°.

Portions of 30° deuteron spectra are displayed in Fig. 1 where prominent analog-state peaks are labeled according to spin assignments taken from (d,p) analyses. The peaks are superimposed on a continuum arising primarily[9] from unresolved lower-isospin states; the analog-state cross sections were extracted assuming a smooth noninterfering background and these are tabulated in Table I. Upper limits for the $3s_{1/2}$ transitions on ^{90,92,94}Zr and ^{98}Mo were computed by taking three times the standard deviation of the number of events contained in the continuum interval corresponding to the expected peak position. (The interval equaled the expected $3s_{1/2}$ peak full width at half-maximum.) While no evidence for these transitions was found at any angle for the ^{90}Zr target, upper limits of about 70 μb/sr were obtained at 11°, 14°, 24°, 27°, and 30° c.m., where the average $2d_{5/2}$ cross section is about 900 μb/sr. Possible $3s_{1/2}$ transitions on ^{94,96}Mo are obscured by other states, so no limits are given. The S_n of the parent states are indicated in the first column for each shell-model configuration. Generally, peaks corresponding to resolved low-lying parent states with $S_n \gtrsim 0.3$ are listed. Because of similarities in (d,p) $L=4$ and $L=5$ angular distributions,

Table I. (^{3}He,d) analog-state cross sections and normalized ratios of observed cross sections to cross-section predictions based on the parent-state (d,p) spectroscopic factors S_n.

Target	$2d_{5/2}$			$2d_{3/2}$			$1g_{7/2}$			$1h_{11/2}$			$3s_{1/2}$	
	S_n	σ^*_{exp}	$\sigma_{exp}/\sigma_{pred}$	S_n	σ^*_{exp}	$\sigma_{exp}/\sigma_{pred}$	S_n	σ^*_{exp}	$\sigma_{exp}/\sigma_{pred}$	S_n	σ^*_{exp}	$\sigma_{exp}/\sigma_{pred}$	S_n	σ^*_{exp}
^{90}Zr	0.89[a]	640±30	1.0†	0.45[a]	143±14	1.0†	0.52[a,e]	143±14	0.85±.14				0.72[a]	<23
							0.33[a]	78±15	0.73±.17					
^{92}Zr	0.54[a]	288±16	0.82±.07	0.38[a]	181±18	1.78±.25	0.42[a]	94±14	0.82±.16 ↔	0.27[d]	94±14	1.12±.19	0.91[a]	<12
^{94}Zr	0.30[a]	150±22	0.92±.14	0.45[a]	159±29	1.51±.31							0.89[a]	<20
^{92}Mo	0.84[b]	744±20	1.00±.06	0.50[b]	138±18	0.70±.11	0.26[b]	102±13	1.0†				0.64[b]	50±25
				0.18[b]	56±12	0.80±.19	0.37[c]	170±15	1.18±.18 ↔	0.66[d]	170±15	0.59±.07		
^{94}Mo	0.59[b]	338±22	0.80±.06							0.68[d]	244±19	1.0†	0.37[b]	
	0.17[b]	222±20	1.58±.16											
^{96}Mo	0.42[c]	146±20	0.58±.08	0.28[c]	∿30±5**	∿0.40±.08	1.28[c]	∿140±20**	∿0.40±.08				0.55[c]	
				0.34[c]	40±13	0.45±.15	0.30[c]	96±14	1.18±.23 ↔	0.46[d]	96±14	0.68±.11		
^{98}Mo	0.21[b]	51±14	0.47±.13	0.43[b]	34±13	0.34±.13	0.42[b]	104±14	1.05±.19	0.30[d]	76±15	1.00±.21	0.67[b]	<16

*Center-of-mass cross sections in μb/sr averaged at 30° and 35° (lab). Only statistical uncertainties are included; absolute cross-section uncertainties ±20%.

†Normalized to unity for this transition.

**Peak includes three unresolved states ($\frac{7}{2}^+$, $\frac{1}{2}^+$, $\frac{3}{2}^+$) according to Ref. 7; relative yields were estimated using S_n together with (^{3}He,d) transition strengths obtained from the present work.

[a] See Ref. 5.

[b] See Ref. 6.

[c] See Ref. 7.

[d] See Ref. 8.

[e] According to Ref. 8 this peak actually consists of a $1g_{7/2}+1h_{11/2}$ doublet; however, the published data are insufficient to permit an estimate of their relative (d,p) strengths.

there exist several uncertain $1g_{7/2}$ or $1h_{11/2}$ spin assignments; hence, these states have been entered in both columns.

Assuming that these reactions proceed via the single-particle component of the analog states it might be expected that the cross sections are simply related to proton spectroscopic factors $S_p = S_n/(2T_0+1)$, where T_0 is the isospin of the target nucleus. This expectation can be tested by taking the ratios of experimental cross section to S_p for the $2d_{5/2}$, $2d_{3/2}$, $1g_{7/2}$, and $1h_{11/2}$ states. This is a meaningful procedure within the context of direct-reaction theories because the Q values for transitions to given orbitals are all similar, as can be seen in Fig. 1. The ratios, normalized to one particular state for each orbital, are presented in the table. Considering the well known uncertainties in extracting S_n, and the unbound nature of the analog states, the data indicate the observed cross sections are proportional to S_p. It remains, then, to understand why the $3s_{1/2}$ transitions corresponding to parent states with large S_n are inhibited.

The fact that the observed cross sections are roughly proportional to S_p suggests a direct reaction mechanism should describe the reaction. The difficulties in performing realistic DWBA calculations to unbound isobaric-analog states have been discussed elsewhere[10] and a detailed treatment is beyond the scope of this note. We have, however, performed calculations using two simplified models to assure that the inhibition of the $3s_{1/2}$ transitions is not due to some trivial cause such as momentum mismatch. In both cases optical-model parameters were taken from studies[11] of (^{3}He, d) reactions on ^{89}Y and ^{90}Zr at 25-MeV incident energy. First, calculations were performed using bound-state proton form factors calculated for a Woods-Saxon potential adjusted to yield the neutron separation energies of the parent states. Second, proton scattering-state form factors were generated in a real Woods-Saxon potential with depth adjusted to give a resonance, with appropriate quantum numbers, at the proton energy of the analog state. Since the shapes of the form factors of the bound and unbound states are nearly identical inside the well we adopted a normalization procedure requiring the wave functions to have the same maximum amplitude in this region. The procedure of Huby and Mines[12] was then used in performing the unbound state calculations.

Both of the above calculations produced similar angular distributions showing pronounced oscillatory structure for all l values in disagreement with the experimental result. The latter scattering-state calculations produce approximately the measured average (over angle) cross sections while the bound-state calculations produce cross sections about a factor of 5 lower. Both roughly predict the measured ratios of cross sections to the various spin states and predict transitions to the $3s_{1/2}$ states of strength comparable with those to the observed $2d_{3/2}$ states. Thus neither calculation describes the experimental angular distributions or the inhibited $3s_{1/2}$ transitions. It should also be noted that the inhibition does not exist for bound $T = T_z$ states; in the works cited above[11] Vourvopolous and Fox and Vourvopolous et al. observed several strong $l=0$ transitions to lower-lying states in ^{90}Zr and ^{91}Nb.

Preliminary inspection of additional (^{3}He, d) data[13] for the same targets studied here indicates that the inhibition of $3s_{1/2}$ transitions persists at 20 and 45 MeV incident energy. These results make it appear likely that the inhibition arises from the special structure of the isobaric analog states rather than from a particular reaction-mechanism feature. Work is now under way on an effort to find an explanation in terms of enhancements arising from fluctuations associated with lower-isospin states. The importance of such effects in proton scattering was first pointed out by Robson[14] and has been demonstrated experimentally.[15] Any successful explanations must, of course, explain not only the absolute cross sections but also the structureless angular distributions and the approximate dependence of the measured cross sections on S_p.

The authors are pleased to acknowledge the help of Mr. Harvey Rudolph and Mr. Patrick Cooney in the data-taking phase of this work.

---

*Work supported in part by the National Science Foundation.

†On leave of absence from the Max-Planck-Institut, Heidelberg, Germany.

‡On leave of absence from the Weizmann Institute of Science, Rehovot, Israel.

[1]A. G. Blair and D. D. Armstrong, Phys. Lett. 16, 57 (1965).

[2]C. F. Moore, thesis, Florida State University, 1964 (unpublished).

[3]C. F. Moore, P. Richard, C. E. Watson, D. Robson, and J. D. Fox, Phys. Rev. 141, 1166 (1966).

[4]W. J. Thompson, J. L. Adams, and D. Robson, Phys. Rev. 173, 975 (1968).

[5]B. L. Cohen and O. V. Chubinsky, Phys. Rev. 131,

2184 (1963).
[6]J. B. Moorhead and R. A. Moyer, Phys. Rev. 184, 1205 (1969).
[7]S. A. Hjorth and B. L. Cohen, Phys. Rev. 135, B920 (1964).
[8]W. Booth, S. M. Dalgliesh, K. C. McLean, R. N. Glover, and F. R. Hudson, Phys. Lett. 30B, 335 (1969).
[9]This conclusion is based on the ^{90}Zr(^{3}He, $d\tilde{p}$) data of R. Hoffswell, D. Jamnik, T. M. Noweir, and A. I. Yavin [(Phys. Rev. Lett. 19, 754 (1967)], and P. Cooney et al. [Bull. Amer. Phys. Soc. 15, 625 (1970)] in which few coincidence events are observed at $d+p$ energies corresponding to ^{91}Nb excitations above the neutron threshold.
[10]R. Coker and T. Tamura, Phys. Rev. 182, 1277 (1969); T. Tamura and C. E. Watson, Phys. Lett. 25B, 186 (1967).
[11]G. Vourvopoulous and J. D. Fox, Phys. Rev. 177, 1558 (1969); G. Vourvopoulous, R. Shoup, J. D. Fox, and J. B. Ball, in *Nuclear Isospin,* edited by J. Anderson *et al.* (Academic, New York, 1969), p. 205.
[12]R. Huby and J. R. Mines, Rev. Mod. Phys. 37, 406 (1965).
[13]R. McGrath, D. L. Hendrie, and N. Cue, to be published.
[14]D. Robson, Phys. Rev. B 137, 535 (1965).
[15]For example, see H. L. Scott, C. P. Swann, and F. Rauch, Nucl. Phys. A 134, 667 (1969).

ISOSPIN SPLITTING OF THE GIANT DIPOLE RESONANCE IN ^{64}Zn†

B. C. Cook, R. C. Morrison, and F. H. Schamber
Institute for Atomic Research, Department of Physics, Iowa State University, Ames, Iowa 50010
(Received 2 January 1970)

The (γ, np) reaction is discussed as a probable channel for observation of the $T=T_0+1$ component of the giant dipole resonance, and experimental evidence is presented in support of this conjecture in the case of ^{64}Zn.

Several years ago Fallieros, Goulard, and Ventner[1] predicted that the giant dipole resonance of the nuclear photoeffect should be split into two isospin components in all nuclei with ground state $T>0$. The lower-energy component ($T_<$) has the same isospin as the ground state (T_0), while the second component ($T_>$) has isospin $T=T_0+1$. Several authors[1-3] have reported model-dependent calculations of both the energy splitting and the relative dipole absorption strengths of the two components. Isospin selection rules allow proton decay of both components but prohibit ground-state neutron decay of the $T_>$ states, providing a possible experimental method of identifying the two components. Several experimenters[4-7] have searched for the predicted $T_>$ component by measuring (γ, p), (p, γ_0), and $(\gamma, n)+(\gamma, p)$ cross sections; however, the results of these measurements have not been conclusive. Shoda et al.[5] and Axel et al.[4] found (γ, p) resonances 4-5 MeV above the (γ, n) giant resonance in ^{90}Zr and ^{88}Sr; however, the measured cross section in both cases is much smaller than the predicted strength of the $T_>$ states. Measurements of the photoneutron yield of nickel[6] and the $(\gamma, n)+(\gamma, p)$ cross sections of molybdenum isotopes[7] show anomalous strength in the region above the giant resonance. While these results can be explained by isospin splitting, they do not give direct evidence for states of different T. A conclusive search for the predicted $T_>$ giant resonance requires a direct comparison between isospin-allowed and isospin-forbidden reactions in the energy region just above the $T_<$ giant resonance.

The major cross sections which can be expected to contribute to dipole absorption in this energy region are (γ, n), (γ, p), $(\gamma, 2n)$, (γ, pn), and (γ, np). Decay of the $T_>$ states through either the ground-state (γ, n) or $(\gamma, 2n)$ channels is isospin forbidden, while proton decay (to ground or excited states), as well as neutron decay to $T_>$ states in the residual nucleus, is allowed by the isospin selection rules. In medium and heavy nuclei the Coulomb barrier will strongly inhibit proton emission as long as neutron emission to residual $T_>$ states is energetically possible. In heavy nuclei these residual $T_>$ states are, in general, particle unstable and can decay by isospin-allowed proton decay or isospin-forbidden neutron decay.[8] Since the Coulomb barrier clearly favors the (γ, n) and $(\gamma, 2n)$ processes while selection rules favor (γ, p) and (γ, np), comparison of the relative strengths of these reactions provides a direct test of the strength of isospin selection rules. In particular, these arguments predict that the (γ, np) process should dominate the $T_>$ giant resonance, and in the energy region of expected $T_>$ strength, the (γ, np) cross section should be larger than the Coulomb-barrier favored (γ, n) and $(\gamma, 2n)$ strengths. [The (γ, pn) process is of course also isospin allowed