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(^{3}He, d) Stripping to Unbound Analog States in Tc Isotopes

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A systematic study of 14 unbound analog states in Tc isotopes was performed via the ^{92,94,96}Mo(^{3}He, d) reactions. Proton form factors were calculated using a simple single-particle resonance model. The proton spectroscopic factors deduced with the distorted-wave Born approximation agree well with the known neutron spectroscopic factors for the parent states obtained from (d, p) reactions. We conclude that this simple model is adequate for the calculation of spectroscopic factors to unbound analog states in these isotopes.

Recently there has been a growing interest in the problem of proton-stripping reactions to unbound analog states. The conclusions obtained by McGrath *et al.*[1] suffered from the lack of distorted-wave Born-approximation (DWBA) calculations for unbound states. Since then, a few approaches to the problem were suggested by several authors,[2-6] and some experimental results are available from both (^{3}He, d) and (d, n) studies.[1,2,7] It is the purpose of this letter to report the results of a systematic study of 14 unbound analog states in Tc isotopes, which were populated via the (^{3}He, d) reaction. A simple method for the analysis of the results, which takes into account the unbound nature of these states, is proposed and tested against all our experimental results with very good agreement.

A 30.2-MeV ^{3}He beam from the Saclay cyclotron

was used to bombard self-supporting isotopically enriched ^{92,94,96}Mo targets. The outgoing deuterons were detected using ΔE-E silicon detector telescopes together with Chaivre-type[8] identification systems. Angular distributions were measured over an angular range of 9–70°. The spectra obtained were analyzed using the code AUTOFIT,[9] which unfolds peaks and carefully subtracts the background. The angular distributions of the deuterons leading to the $d_{5/2}$ analogs of the ^{93}Mo, ^{95}Mo, and ^{97}Mo ground states are shown in Fig. 1.

In the calculation of the cross section for a nucleon-transfer reaction in the zero-range DWBA analysis, it is necessary to evaluate the radial integral:

$$\int \chi^{(b)}_{L_b J_b}\left(k_b, \frac{M_A}{M_B}r\right) F_{lsj}(r)\chi^{(a)}_{L_a J_a}(k_a, r)dr\,, \qquad (1)$$

where $\chi^{(a)}_{L_a J_a}$ and $\chi^{(b)}_{L_b J_b}$ are partial waves in the entrance and exit channels, respectively.[10] The function $F_{lsj}(r)$ is the radial form factor for the transferred particle. In the analysis presented here we treat the isobaric analog resonance (IAR) as a single-particle resonance. This approach does not take into account the relation between the IAR and its parent state. We also neglect the fine structure of the IAR that results from the interference between the compound states and the single-particle resonance. However, the approximation used in calculating the form factor may be justified because the stripping reaction proceeds through the single-particle component of the IAR wave function, and the contribution to the cross section from the interference terms is small.[6]

The procedure we used for calculating the proton form factor was the following: the code ABACUS[11] was used to generate a proton scattering wave function $U_{lj}(r) = rF_{lj}(r)$, which resonates at an energy equal to the resonance energy of the proton with the right l and j in the proton-plus-target system. The optical potential used was

$$V(r) = V_0(r) + V_{so}\frac{1}{r}\left|\frac{d}{dr}V_0(r)\right|\vec{\sigma}\cdot\vec{l}\,, \qquad (2)$$

where $V_0(r)$ is a real potential of a Woods-Saxon form. With the code ABACUS we searched for a real potential depth, which corresponds to an imaginary phase shift equal to unity, and obtained the corresponding form factor. A typical result for $F_{lj}(r)$ is given in Fig. 2 together with the form factor for the parent bound state. It is evident that the main difference between the two form factors is in the surface region, where the reaction is expected to take place. For the normalization we require

$$\int_0^{R_0} F_{lj}^2(r)r^2dr = 1, \qquad (3)$$

where R_0 is the first zero of $F_{lj}(r)$ outside the nucleus. The function $F_{lj}(r)$ was then read into the code DWUCK,[12] which was modified to allow for 800 integration points. The numerical evaluation of Eq. (1) was performed according to the procedure suggested by Huby and Mines.[13] The upper radial cutoff was extended to 100 fm. (The con-

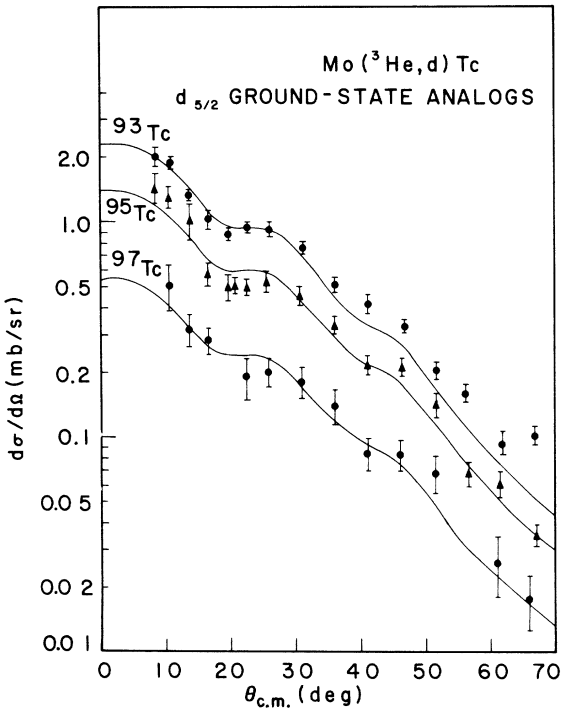

FIG. 1. Angular distributions of the deuterons leading to the analogs of the $d_{5/2}$ ground states of ^{93}Mo, ^{95}Mo, ^{97}Mo in ^{93}Tc, ^{95}Tc, and ^{97}Tc, respectively. The lines represent DWBA calculations for the unbound analog states

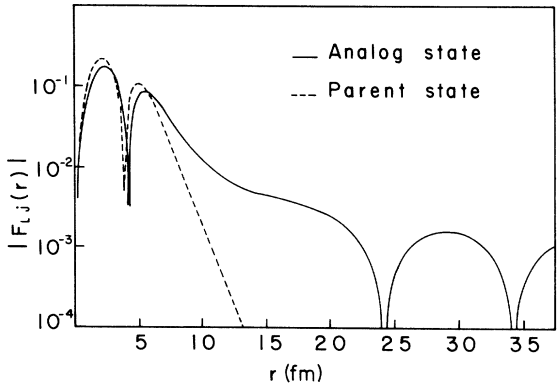

FIG. 2. Form factors for the ^{93}Mo ground state (dashed line) and its analog state (solid line) in ^{93}Tc.

TABLE I. Proton spectroscopic factors S_p for analog states obtained from the analysis of the (^{3}He, d) reaction; and neutron spectroscopic factors S_n, obtained from the analysis of the (d, p) reactions to the corresponding parent states.

Nucleus	Parent excitation energy (MeV)	J^π	S_p (analog)	S_n (parent)
^{93}Tc	0.0	$\frac{5}{2}^+$	0.72	0.87 [a]
	1.37	$\frac{7}{2}^+$	0.28	0.26 [a]
	1.50	$\frac{3}{2}^+$	0.55 [b]	0.50 [a]
	1.53	$\frac{7}{2}^+$	0.15 [b]	0.14 [a]
	1.70	$\frac{3}{2}^+$	0.32	0.18 [a]
	2.32	$\frac{11}{2}^-$	0.33	0.33 [a] 0.66 [c]
^{95}Tc	0.0	$\frac{5}{2}^+$	0.6	0.59 [a]
	0.77	$\frac{7}{2}^+$	0.30 [b]	0.18 [a]
	0.82	$\frac{5}{2}^+$	0.30 [b]	0.17 [a]
	1.95	$\frac{11}{2}^-$	0.33	0.26 [a] 0.68 [c]
^{97}Tc	0.0	$\frac{5}{2}^+$	0.38	0.42 [d]
	0.70	$\frac{7}{2}^+$	0.51 [b]	1.28 [d]
	0.70	$\frac{3}{2}^+$	0.11 [b]	0.28 [d]
	1.44	$\frac{11}{2}^-$	0.21	0.46 [c]

[a] From Ref. 16.

[b] Unresolved doublets; S_p calculated using relative strengths implied by S_n and normalizing to the (^{3}He, d) data.

[c] From Ref. 15.

[d] From S. A. Hjorth and B. L. Cohen, Phys. Rev. 135, B920 (1964).

tribution to the magnitude of the cross section was found to be negligible beyond $r \sim 50$ fm.) The optical-potential parameters for the ^{3}He particles and the deuterons were taken from the work of Kozub and Youngblood,[2] and Perey and Perey.[14] Figure 1, which shows only three of the analog states studied, illustrates the kind of agreement found for all states between the shapes of the experimental and calculated angular distributions. The comparison between the experimental and theoretical angular distributions yields the proton spectroscopic factors S_p through the relation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = (2J+1)\, C^2 S_p \left(\frac{d\sigma}{d\Omega}\right)_{\text{calc.}} .$$

Table I lists the values of S_p obtained for the various analog states studied, together with the corresponding spectroscopic factors S_n obtained from (d, p) reactions populating the parent states. As can be seen, the agreement between the S_p and S_n values is generally very good. The main cases for which there is not good agreement are the unresolved doublets in ^{95}Tc and ^{97}Tc. The S_p values for the $\frac{11}{2}^-$ states in the three nuclei show a trend similar to that observed by Booth *et al.*,[15] although the absolute values agree better with those given by Moorhead *et al.*[16] We conclude that the calculation of the cross section for (^{3}He, d) stripping to unbound analog states in Tc isotopes can be reliably done using a simple model of a single-particle resonance. The basic agreement between our results and those found recently using a more rigorous theory[6] is most gratifying and lends further confidence and validity to our simple approach.

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Nuclear Matrix Elements in the First-Forbidden Beta Decay of ^{203}Hg†

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Nuclear matrix elements in the $\frac{5}{2}^-$(210-keV β)$\frac{3}{2}^+$(279-keV γ)$\frac{1}{2}^+$ β-γ cascade in ^{203}Hg have been extracted, and comparison has been made with conserved-vector-current (CVC) theory predictions for the vector-matrix-element ratio $\int\vec{\alpha}/(\int i\vec{r}/R)$. This ratio was found to be significantly smaller than the CVC prediction based on the assumption that the Coulomb Hamiltonian is diagonal. Reasonably good limits have been placed on the matrix elements in spite of the fact that the Coulomb-enhanced matrix element combination tends to dominate the transition. The nuclear matrix elements do not support a strict single-particle picture of this β decay, in agreement with the current knowledge of the structure of the initial and final states.

I. INTRODUCTION

A. General Considerations

In recent years a number of first-forbidden β transitions have been studied with the objective of determining the nuclear matrix elements. The majority of first-forbidden β transitions are well described by the so-called ξ approximation.[1-3] In these instances the Coulomb-enhanced terms dominate the formulas, and the observables look like their counterparts in allowed decay. Furthermore, when a first-forbidden β transition is governed by the ξ approximation, the extraction of *all six* primary nuclear matrix elements is, at best, extremely difficult.

However, when certain observables show values different from those predicted by the ξ approximation, this usually means that the Coulomb-enhanced matrix elements are no longer dominant, and that the other matrix elements are playing a more significant role in determining the observables.[4] A more complete matrix-element extraction is therefore possible, and the determination of the matrix elements of many different operators between the same two nuclear states makes the investigation of such a first-forbidden β transition particularly attractive in nuclear-structure studies. In addition, knowledge of the six primary nuclear matrix elements makes it possible to obtain experimental limits on the vector-matrix-element ratio $[\int\vec{\alpha}/(\int i\vec{r}/R)]$. This ratio is of interest because it can be compared with the theoretical prediction based on the conserved-vector-current (CVC) theory for β decay.[5-7]

B. Experimental Considerations

In view of the relatively low logft value (6.4), the large size of the Coulomb parameter ($\xi = \alpha Z/2R = 16.2$), and the low β-end-point energy ($W_0 = 1.41$) of the 210-keV first-forbidden nonunique β transition in ^{203}Hg, one should expect all of the observables of this decay to be consistent with the ξ approximation.[1-4] [Throughout this discussion natural units (i.e., $\hbar = m_e = c = 1$) are used. Hence energies are in units of $m_e c^2$.] On the other hand, several observables for this β transition have been measured, and some of the results deviate slightly from the values predicted by the ξ approximation.

The β-γ directional correlation has been measured by several authors, with a diversity of results. Steffen[8] and Wyrick *et al.*[9] have reported small negative β-γ anisotropies. On the other hand, Bashandy and El-Nesr,[10] as well as Collin *et al.*,[11] found a *large* negative anisotropy. A recent precision measurement by Cipolla and Steffen[12] has removed this ambiguity and confirmed the small-negative-anisotropy result.

The β-γ circular-polarization correlation has been measured by Daniel *et al.*[13] and, more recent-