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Study of ^{95}Nb by Means of the ^{94}Zr(^{3}He, d) Reaction*

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The ^{94}Zr(^{3}He, d)^{95}Nb reaction was studied with 35.6-MeV ^{3}He particles from the Argonne cyclotron. Experimental angular distributions are compared with distorted-wave Born-approximation calculations to determine l values and spectroscopic factors. The results are compared with the previous data on (^{3}He, d) and (d, ^{3}He) reactions and β decay. The proton configurations of ^{95}Nb are discussed in terms of this data and recent theoretical results.

I. INTRODUCTION

The proton structure of $N \approx 50$ nuclei has been studied extensively. In the case of ^{95}Nb, only four states have been observed[1] from ^{95}Zr decay. The reported results[2-4] of pickup and stripping reactions reveal the existence of several unresolved doublets, and the spin assignments are consequent-

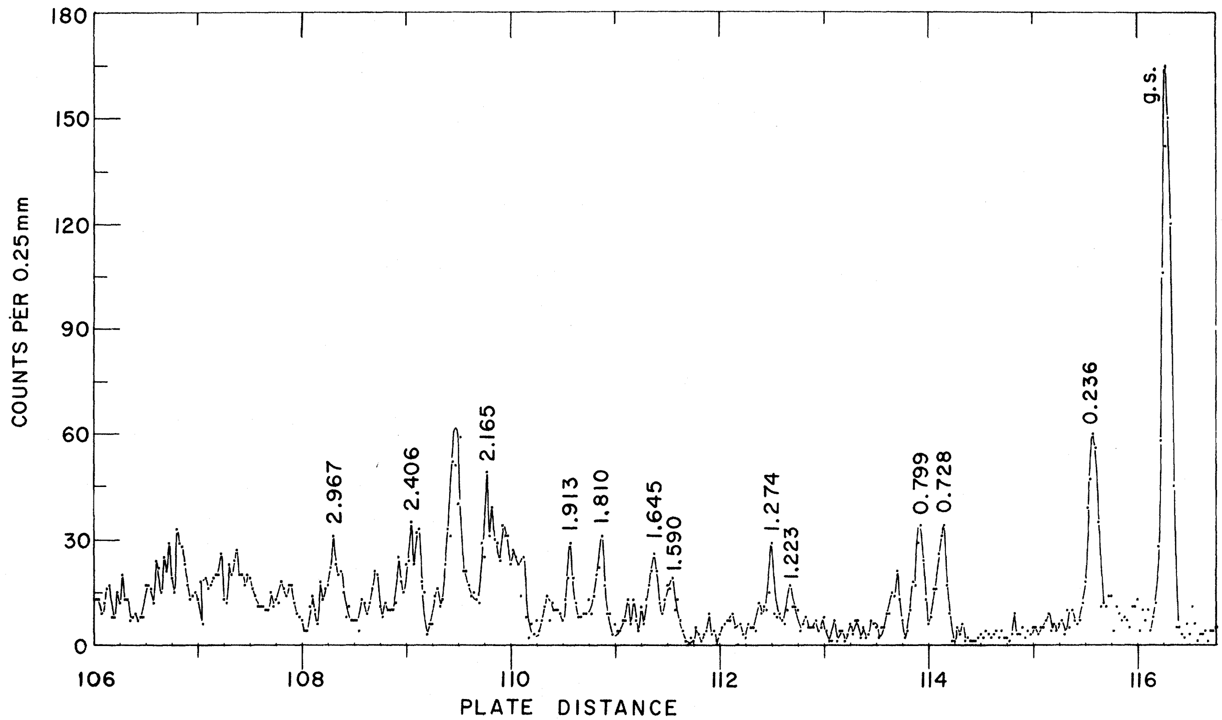

FIG. 1. Typical deuteron spectrum from the ^{94}Zr(^{3}He, d)^{95}Nb reaction at $\theta_{lab} = 19°$.

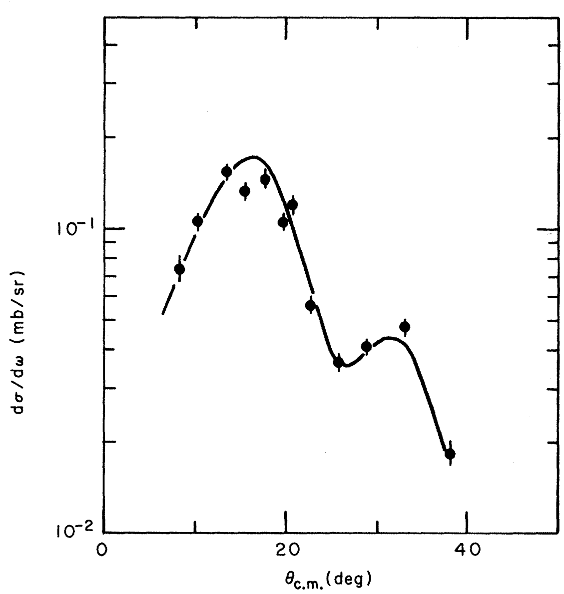

FIG. 2. Angular distribution of the deuterons leading to the ground state in the ^{94}Zr(^{3}He, d)^{95}Nb reaction. The solid line is the DWBA calculation for an $l = 4$ transfer.

ly uncertain. It seems of value, then, to reexamine ^{95}Nb by means of the (^{3}He, d) reaction with improved energy resolution. More definite spin assignments and a more accurate determination of spectroscopic factors should facilitate the study of shell-model systematics in the regions away from the $N=50$ closed shell.

II. EXPERIMENTAL PROCEDURE

The 35.6-MeV ^{3}He beam from the Argonne cyclotron was used to obtain deuteron spectra at 12 angles between 8 and 37°. The outgoing deuterons were momentum-analyzed with a split-pole magnetic spectrograph, and spectra were recorded on Kodak NTB emulsion plates. The exposed plates were scanned by a computer-controlled plate scanner.[5] The target, which was made by evaporation onto a carbon backing, had a thickness of 100 μg/cm^{2} and was enriched to 96.28% in ^{94}Zr. The over-all resolution of the system was 35 keV full width at half maximum (FWHM). A typical spectrum is shown in Fig. 1.

The data were analyzed with the program AUTOFIT[6] in order to obtain excitation energies (±0.008 keV) and relative cross sections. The measured angular distributions were compared with distorted-wave calculations in which the optical-model parameters listed in Table I were used

TABLE I. Optical-model parameters used in DWBA calculations of $^{94}Zr(^{3}He, d)^{95}Nb$.

	^{3}He	d	Bound-state particle
V (MeV)	172	97.2	
r_0 (fm)	1.14	1.12	1.2
a (fm)	0.72	0.8	0.65
W (MeV)	17	0	
W_D (MeV)	0	12.8	
r'_0 (fm)	1.55	1.31	
a' (fm)	0.8	0.79	
r_c (fm)	1.4	1.3	1.4
V_{so} (MeV)	0	7	$\lambda=25$

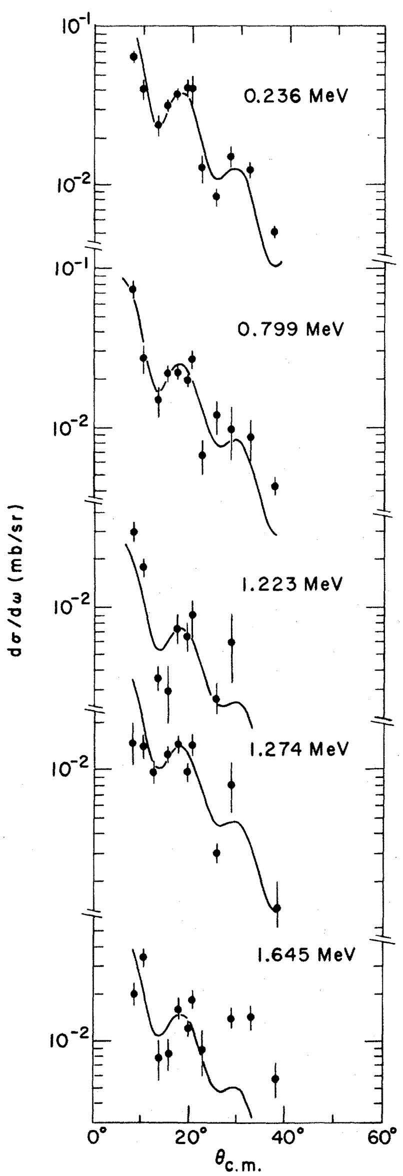

FIG. 3. Angular distributions for five levels excited by $l=1$ transfer in the $^{94}Zr(^{3}He, d)^{95}Nb$ reaction. The solid curves are results of the DWBA calculations.

in the program DWUCK.[7] The spectroscopic strengths $G_{lj} = [(2J_f+1)/(2J_i+1)]C^2S_{lj}$ were derived from the differential cross sections by use of the expression

$$d\sigma/d\Omega = 4.42\, G_{lj}\, \sigma_{\text{DWUCK}}/(2j+1),$$

where J_i, J_f, and j are the total angular momenta of the target nucleus, the residual nucleus, and the transferred proton, respectively. The measured angular distributions were normalized to the calculations by requiring that $G_{lj} = 7.8$ for the ground-state transition, as previously measured.[4]

III. RESULTS AND DISCUSSION

With the improved energy resolution obtained in the present experiment, l values were assigned to the angular distributions of previously unresolved levels and of several newly reported levels. The results for all of the well resolved levels are shown in Figs. 2–4 and Table II.

The ground state and the first excited state at 0.236 MeV are reached by strong $l=4$ and $l=1$ transfers, respectively. This is consistent with shell-model systematics if the $1g_{9/2}$ and $2p_{1/2}$

TABLE II. Levels observed in ^{95}Nb with the $^{94}Zr(^{3}He, d)$ reaction. The uncertainty in the excitation energies is ±0.008 MeV.

E_{exc} (MeV)	l	J^π	G_{lj}
0	4	$\frac{9}{2}^+$	7.8
0.236	1	$\frac{1}{2}^-$	0.6
0.728	2	$(\frac{1}{2}, \frac{5}{2})^+$	0.84
0.799	1	$(\frac{1}{2}, \frac{3}{2})^-$	0.24
1.223	1	$(\frac{1}{2}, \frac{3}{2})^-$	0.08
1.274	1	$(\frac{1}{2}, \frac{3}{2})^-$	0.10
1.590	2	$(\frac{3}{2}, \frac{5}{2})^+$	0.18
1.645	(1)	$(\frac{1}{2}^-, \frac{3}{2}^-)$	(0.14)
1.810	2	$(\frac{3}{2}, \frac{5}{2})^+$	0.36
1.913	2	$(\frac{3}{2}, \frac{5}{2})^+$	0.24
2.070	2	$(\frac{3}{2}, \frac{5}{2})^+$	0.36
2.121	2	$(\frac{3}{2}, \frac{5}{2})^+$	0.42
2.165	2	$(\frac{3}{2}, \frac{5}{2})^+$	0.72
2.373	(0)	$(\frac{1}{2}^+)$	(0.06)
2.406	(0, 2)	$(\frac{1}{2}^+, \frac{5}{2}^+)$	(0.06, 0.12)
2.431	(2)	$(\frac{3}{2}^+, \frac{5}{2}^+)$	(0.18)
2.967	2	$(\frac{3}{2}, \frac{5}{2})^+$	0.30

orbitals are being filled. This result was also found from earlier (^{3}He, d), (d, ^{3}He), and ^{95}Zr-decay experiments. No evidence for another $l=4$ transition was found in the present measurement. The remaining $l=1$ strength is found to be distributed among four states at 0.799, 1.223, 1.274, and 1.645 MeV. These $l=1$ angular distributions are shown in Fig. 3. From previous (d, ^{3}He) studies,[2] the 0.77- and 1.22-MeV levels were assigned $\frac{3}{2}^-$ on the basis of $l=1$ pickups of $2p_{3/2}$ protons.

Nine levels below 3 MeV were excited by means of $l=2$ transitions. The angular distributions of all except the weak state at 2.431 MeV are shown in Fig. 4. Most of the $l=2$ strength is divided between the 0.728- and 2.165-MeV levels.

Evidence for $l=0$ transfers was found for weak states at 2.373 and 2.406 MeV. Because only a few data points were obtained, the angular distributions are not shown.

The results of the present work modify several conclusions from previous experiments. No evidence was found for the possible $\frac{7}{2}^+$ states at 0.726 and 0.757 MeV reported from ^{95}Zr decay. These states may have a more complex configuration not expected to be observed with the (^{3}He, d) reaction. However, a $\frac{5}{2}^+$ assignment for the 0.726-MeV level is consistent with both the β decay and

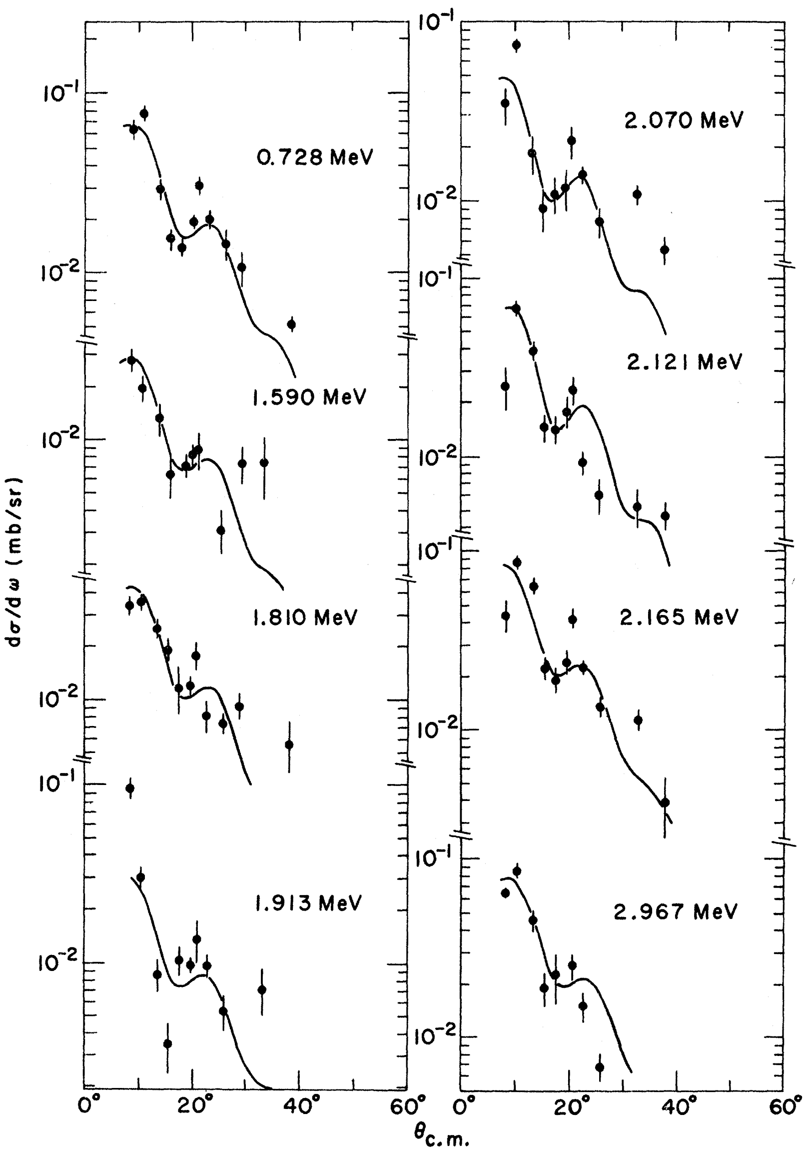

FIG. 4. Angular distributions for eight levels excited in the ^{94}Zr(^{3}He,d)^{95}Nb reaction. The solid curves are results of the DWBA calculations for $l=2$ transfers.

the present results. No evidence was found for the 0.98-MeV $\frac{5}{2}^-$ level reported from previous (^{3}He, d) and (d, ^{3}He) experiments. The (d, ^{3}He) results indicate that this state arises from the filled $1f_{5/2}$ orbital in ^{94}Zr and therefore should not be strongly excited in the (^{3}He, d) reaction.

The levels observed in β decay, (d, ^{3}He), and the present (^{3}He, d) experiments are compared in Fig. 5 along with the shell-model level scheme calculated recently[8] on the assumption that ^{95}Nb consists of an ^{88}Sr core plus two protons and five neutrons. The matrix elements for the residual interactions were derived by use of fits to data for neighboring nuclei. Some of these levels were also predicted in earlier calculations.[9,10] Although this method has proved reasonably effective for nuclei near the $N=50$ closed shell, the accuracy of the model might be expected to deteriorate for ^{95}Nb. The calculations show that this nucleus is indeed quite complex because of the interactions of the five neutrons outside the closed shell. In particular, the prediction of thirteen states with $J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$ is consistent with the present experimental observation that the $l=1$ strength is divided among at least five states. Likewise, 18 states with $J^\pi = \frac{3}{2}^+$ or $\frac{5}{2}^+$ are predicted, while ten states are reached by $l=2$ transfers in the present work.

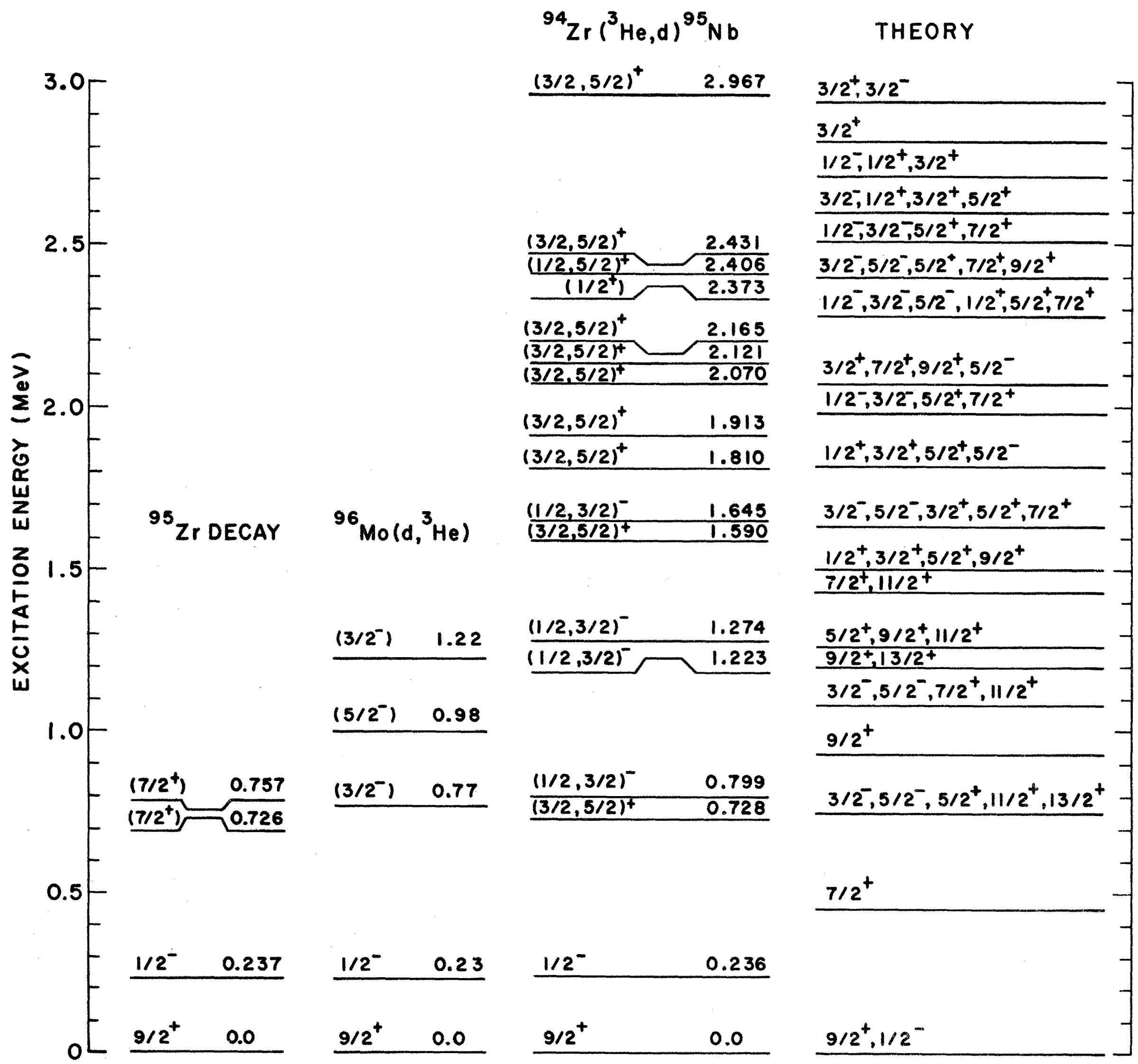

FIG. 5. Energy-level schemes of ^{95}Nb as deduced from β decay, (d, ^{3}He), and (^{3}He, d) experiments. These results are compared to the predictions from shell-model calculations.

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Study of ^{93}Nb Levels with the ^{96}Mo(p, α)^{93}Nb Reaction

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Levels of ^{93}Nb have been studied with the ^{96}Mo(p,α) reaction at 15-MeV incident energy. Angular distributions for transitions to a dozen prominent levels below 2 MeV have been measured with 30- to 40-keV experimental resolution over $15° \leq \theta_L \leq 150°$, and they have been compared with distorted-wave Born-approximation (DWBA) calculations. Angular distributions for p-^{96}Mo and α-^{93}Nb elastic scattering have also been measured, and proton and α-optical-model potential parameter sets have been determined by a search procedure. Of the three sets of α-potential parameters, the one which best reproduced the measured (p,α) angular distributions of known low-lying levels in ^{93}Nb was chosen as the standard set for the rest of the (p,α) calculations. The conventional triton-cluster form factor was used exclusively for the (p,α) DWBA calculations which lead to J^π assignments. A semimicroscopic form factor was used in a few test cases in order to check the sensitivity of calculations to the choice of form factor. Reliable J^π assignments have been made for levels below 1.5 MeV based on the j dependence for $l=1(p,\alpha)$ transfers, as well as for higher angular momentum transfers observed in the present work; and they are in excellent agreement with those determined from recent Coulomb-excitation and ^{90}Zr(α,$p\gamma$) works. Dominant three-nucleon shell-model configurations to which the levels of interest belong have been proposed.

I. INTRODUCTION

Low-lying levels in ^{93}Nb have been studied extensively in recent years by a number of authors with ^{93}Nb(n, $n'\gamma$) inelastic scattering.[1,2] Owing to the complex scheme inherent to γ-decay modes, however, only a few consistent J^π assignments are found among these works. Recently a major discrepancy in spin assignments for low-lying positive-parity states has been resolved by Stelson *et al.*[3] via Coulomb excitation, the results of which are well described within the framework of a weak-coupling model in which ^{92}Zr is treated as a core. The more recent Coulomb-excitation work by Kreger and Seaman,[4] however, proposed tentative spin assignments for levels at 809, 950, and 979 keV which differ from those made by Stelson *et al.*[3]

The level scheme of ^{93}Nb has been studied extensively in the past by several theoretical groups[5] on the basis of a shell model in which ^{88}Sr is treated as the core. On the other hand, experimental spectroscopic studies of the levels via direct reactions have been limited to a few proton