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NUCLEAR STATES OF ^{98}Zr[†]

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By means of the reaction ^{96}Zr(t,p), we have achieved the first reported production of excited states of ^{98}Zr. Comparison of the experimental proton angular distributions with the predictions of a distorted-wave calculation has yielded spin and parity assignments for many of the states. Possible identification of neutron configurations with some of the states is discussed.

Except for half-life measurements,[1] there exists no published experimental information on the nucleus $^{98}_{40}$Zr$_{58}$. Since the ground state of ^{96}Zr appears to be approximately described by a closed $2d_{5/2}$ neutron subshell,[2] naive considerations suggest that the ^{98}Zr ground state might be approximately described by coupling two neutrons in the next $3s_{1/2}$ shell-model orbital to the ^{96}Zr ground state. However, the following two neutron orbitals, $2d_{3/2}$ and $1g_{7/2}$, lie fairly close (1 to 2 MeV) to the $3s_{1/2}$ orbital,[3] and their proximity might complicate the ^{98}Zr ground state. To the extent that neutron configuration mixing appears in the ground state, excited 0^+ states will also, of course, be described by wave functions which include mixed configurations.

We have studied the ^{98}Zr nucleus by means of the reaction ^{96}Zr$(t,p)^{98}$Zr. The experimental techniques have been described elsewhere.[4] The present experiment was conducted with a 20-MeV triton beam from the Los Alamos tandem Van de Graaff facility. A preliminary run was made with a thin self-supporting target[5] of Zr enriched to 57.4% in ^{96}Zr. Later runs were made with a target prepared in the same way, but with 82.25% enrichment in ^{96}Zr. Angular distributions were obtained with semiconductor ΔE-E telescope counters, and, in addition, spectrograph nuclear emulsion exposures were made at three angles, $\theta_{\rm lab} = 12$, 24, and 36°. The energy resolution of the counter spectra was approximately 45 keV; the resolution of the emulsion spectra was limited by the target thickness to approximately 25 keV.

The Q value of the ground-state transition was measured to be 3.508 ± 0.020 MeV. The calibration for this measurement was obtained from the positions of the ground-state and first-excited-state peaks of ^{18}O, obtained from the (t,p) reaction on the contaminant ^{16}O in the target, and the measured energy calibration curve of the spectrograph.

Table I shows the states observed in ^{98}Zr, with their differential cross sections at $\theta_{\rm c.m.} \approx 37°$ ($\theta_{\rm lab} = 36.6°$). The excitation energies up to 4.0 MeV are considered accurate to ±5 keV, while the levels above 4.0 MeV have associated errors of ±10 keV.

Distorted-wave (DW) calculations were performed for all of the neutron configurations considered to lie in the first few MeV of excitation of ^{98}Zr. The principal purpose of these calculations was to establish the L transfer for the various states observed and to obtain an estimate of the relative strength of different configurations. The DW program used for this purpose is due to Bayman and Kallio.[6] The optical-model parameters for the triton incident channel were obtained from a computer program,[7] which adjusted the parameters until a best fit to the measured elastic data was obtained.[8] The proton parameters are from the work of Perey.[7] The parameters

Table I. Levels in ^{98}Zr observed with the reaction ^{96}Zr$(t,p)^{98}$Zr.

Excitation Energy (MeV)	$d\sigma/d\Omega$ (mb/sr) at $\theta_{c.m.}\approx 37°$	J^π assigned
0	2.19×10^{-1}	0^+
1.224	4.14×10^{-2}	2^+
1.591	3.32×10^{-2}	2^+
1.745	1.37×10^{-1}	2^+
1.807	1.02×10^{-1}	3^-
1.852	2.00×10^{-2}	
2.047	1.34×10^{-1}	4^+
2.798	1.32×10^{-1}	5^-
3.035	4.11×10^{-2}	
3.063	6.88×10^{-2}	
3.160	2.28×10^{-2}	
3.271	2.40×10^{-2}	4^+
3.354	7.14×10^{-2}	5^-
3.435	2.20×10^{-2}	2^+
3.506	2.37×10^{-2}	
3.539	3.55×10^{-2}	
3.739	2.40×10^{-2}	
3.763	1.25×10^{-2}	
3.825	1.81×10^{-2}	
3.855	1.49×10^{-2}	
3.886	2.08×10^{-2}	(7^-)
4.005	1.07×10^{-1}	$(5^-,6^+)$
4.061	5.42×10^{-2}	6^+
4.097	2.22×10^{-2}	
4.225	2.45×10^{-2}	
4.365	3.98×10^{-2}	
4.387	2.98×10^{-2}	
4.450	3.80×10^{-2}	7^-
4.608	4.57×10^{-2}	

used are given in Table II.

In Fig. 1 experimental angular distributions are compared to DW predictions for a number of the low-lying states. Except for the 1.807-MeV distribution, where there is some disagreement between the $L=3$ prediction and the data in the neighborhood of 40°, the correspondence between predicted and experimental distributions is good. In general, for those states which are strongly excited there seems to be little ambiguity in L-transfer assignments. Since the target nucleus has zero spin and the (t,p) reaction proceeds primarily with the two neutrons in a relative s state, the spins and parities of the final states are also determined, i.e., $J=L$, $\pi=(-1)^L$.

Table II. Optical-model parameters used in the DW calculations.

	V (MeV)	W (MeV)	r_r (F)	r_i (F)	a_r (F)	a_i (F)	r_c (F)
Proton	48.4	15.4[a]	1.25	1.25	0.65	0.47	1.25
Triton	171.3	16.8[b]	1.16	1.48	0.735	0.885	1.25

[a] Saxon derivative well form.

[b] Saxon well form.

Table I lists the J^π values for all states for which we could make L-transfer assignments. The lowest three excited states are seen to be 2^+ states; they are, on the average, excited with relative cross sections in the ratio of 1.3:1.0:4.5. According to the DW calculation, the neutron configurations $(2d_{3/2}{}^2)_2$, $(2d_{3/2}1g_{7/2})_2$, and $(3s_{1/2}2d_{3/2})_2$ would yield cross sections in the ratio 1.13:1.00 :6.09, suggesting that these configurations could be the principal ones for these three observed states. Of course, the actual 2^+ states are not

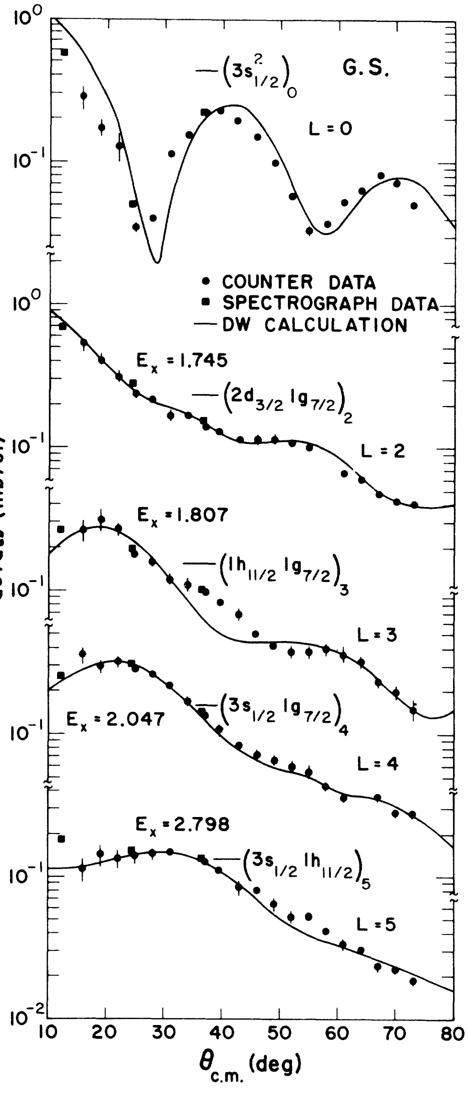

FIG. 1. Proton angular distributions for several low-lying states in ^{98}Zr.

single configurations, and since the coherent two-nucleon transfer process is quite sensitive to configuration mixing, small amounts of mixing among the three closely spaced 2^+ levels could have a large effect on their observed relative cross sections. A fourth 2^+ state would be expected from the $(g_{7/2}{}^2)_2$ configuration, but it is predicted to have a cross section an order of magnitude smaller than that for the $(d_{3/2}g_{7/2})_2$ configuration. There is a possible 2^+ state at 3.435 MeV, but it has a cross section too large to be identified simply with the $(g_{7/2}{}^2)_2$ configuration.

Three $L=4$ transitions are to be expected in the energy range examined. These are based on the configurations $(3s_{1/2}1g_{7/2})_4$, $(2d_{3/2}1g_{7/2})_4$, and $(g_{7/2}{}^2)_4$. The last of these would yield a cross section an order of magnitude smaller than the others and thus would be difficult to observe. However, the first two configurations appear to describe the states seen at 2.047 and 3.271 MeV, respectively. The 2.047-MeV angular distribution is shown in Fig. 1 where it is compared with the results of the DW calculation. The $g_{7/2}{}^2$ configuration also couples to $J^\pi = 6^+$; states for which the 6^+ assignment is either probable or possible are indicated in Table I.

The observation of odd-L transfers is dependent upon the availability of negative-parity single-particle neutron states. The nearest expected single-particle state of this character in ^{98}Zr is the $1h_{11/2}$ state, but its actual energy is unknown in this mass region.[3] It seems likely that a major component of the 3^- state at 1.807 MeV is the $(1h_{11/2}1g_{7/2})_3$ configuration. However, for collective 3^- states the coherency of the two-nucleon stripping interaction is similar to that of inelastic scattering, and constructive interference for a large number of small components of the wave function is possible, leading to a large cross section for this state. Coupling of an $n_{11/2}$ particle to the $3s_{1/2}$, $2d_{3/2}$, and $1g_{7/2}$ particles will give several states of 5^-, 7^-, and 9^- spin and parity. The levels at 2.798 and 3.354 MeV appear to have $L=5$ distributions, and the 4.005-MeV state may also have $J^\pi = 5^-$. States with probable 7^- assignments are also shown in Table I.

It is of interest that no $L=0$ transitions were observed other than to the ground state. Up to an excitation energy of 3.2 MeV, any such transition whose strength was larger than 2% of the ground-state transition strength at 12° or 36° would have been seen. Above this excitation energy the density of states and the background begin to be somewhat troublesome, and the limiting value of additional $L=0$ strength is larger. The appearance of only the ground-state $L=0$ transition is in marked contrast to the results of (t,p) reaction on ^{90}Zr, ^{92}Zr, and ^{94}Zr, where in each case several $L=0$ transitions above the ground state were observed.[9] On the basis of orbital positions alone, one might expect low-lying 0^+ states in ^{98}Zr formed by the $(2d_{3/2})_0$ and $(1g_{7/2})_0$ neutron configurations. The absence of $L=0$ transitions to excited states suggests that the ground state of ^{98}Zr is better described as a superconducting state, with a wave function comprised of an in-phase sum of $(3s_{1/2}{}^2)_0$, $(2d_{3/2}{}^2)_0$, and $(1g_{7/2}{}^2)_0$ configurations coupled to the ^{96}Zr ground state. Transitions to the excited 0^+ states would then be inhibited by destructive interference among the various components of the spectroscopic amplitude. This behavior would place ^{98}Zr in company with nuclei such as those in the Sn region, where close-lying shell-model orbitals permit strong ground-state correlations.[10]

In order to investigate the sensitivity of the transition strengths to configuration mixing in the 0^+ states, DW calculations were performed for the (t,p) reaction to the ^{98}Zr ground state and to a 0^+ state assumed to lie at an excitation energy of 1.5 MeV. For a pure $s_{1/2}{}^2$ ground state and a pure $d_{3/2}{}^2$ excited state, the transition strength to the excited state is calculated to be 0.67 times that to the ground state. Small amounts of $d_{3/2}{}^2$ and $g_{7/2}{}^2$ neutron configurations mixed into the predominantly $s_{1/2}{}^2$ ground-state wave function have a relatively small effect on its predicted strength, but the strength of the transition to the complementary state at 1.5 MeV is strongly reduced as the mixing is introduced. For example, for a ^{98}Zr ground-state wave function of $0.90(s_{1/2}{}^2)_0 + 0.43(d_{3/2}{}^2)_0$, the transition strength is predicted to be 1.35 times larger than for a pure $s_{1/2}{}^2$ configuration. For the excited state having the complementary wave function $0.90(d_{3/2}{}^2)_0 - 0.43(s_{1/2}{}^2)_0$, however, the transition strength is calculated to be only 0.04 times that of the ground-state transition strength.

An alternative explanation for the lack of additional low-lying $L=0$ transitions in the present spectra is that there are one or more unresolved doublets. In particular, the discrepancy between the predicted $L=3$ distribution and the experimental distribution for the 1.807-MeV state could be alleviated by postulating an accompanying $L=0$ distribution whose cross section was approximately 16% of the ground-state cross section. Even this result, however, would still imply considerable configuration mixing in the ground-state wave function. Furthermore, a careful examination of the spectrograph data indicates that the doublet members at this energy would necessarily lie within 10 keV of each other.

A full account of the present experiment will be given in a forthcoming paper. We wish to acknowledge helpful discussions with R. Broglia and to thank B. Bayman for the use of his DW code.

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ENERGY DEPENDENCE OF THE ISOSPIN-NONCONSERVING REACTIONS ^{12}C(d, α)^{10}B(0^+, $T=1$) AND ^{16}O(d, α)^{14}N(0^+, $T=1$)†

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The resonancelike excitation function and strong forward peaking of the isospin-nonconserving ^{12}C(d,α)^{10}B(0^+, 1) and ^{16}O(d,α)^{14}N(0^+, 1) cross sections can be reconciled by an appropriate choice of reaction mechanism interpreted in the strong-absorption model.

The isospin-nonconserving reactions ^{12}C(d, α)^{10}B(1.74, 0^+, 1) and ^{16}O(d, α)^{14}N(2.31, 0^+, 1) recently have been found to proceed via some direct mechanism at incident deuteron energies above 11 MeV.[1-3] The major features of the data are the following: (1) The angular distributions are strongly forward-peaked (at about 20°) and vanish at 0° [Fig. 1(a)]. (2) The peak differential cross sections are large in magnitude, about 100 μb/sr, or 1% of typical T-allowed cross sections. (3) The excitation function for the reaction ^{12}C(d, α)^{10}B* is strongly energy dependent, exhibiting two large resonancelike maxima at E_d(lab) = 12.8 and 14.5 MeV, with widths on the order of 1 MeV [Fig. 1(b)]; similar behavior has been reported for the ^{16}O reaction.[3]

The comparatively large magnitude of the T-forbidden cross sections rules out mechanisms based on single-photon exchange, of which several have been proposed.[4-6] Since direct reactions involve relatively simple, low-order matrix elements of the interactions, large T-nonconserving cross sections suggest large isospin impurities in certain nuclear levels. There is thus need to reexamine previous estimates of isospin mixing in low-lying levels of light nuclei, which have mostly been based on first-order perturbation treatment of the electromagnetic interaction (i.e., on single-photon exchange).[7,8]

The strong forward peaking of the angular distribution indicates the presence of many partial waves in the amplitude and so precludes the compound nucleus mechanism. The data thus present a dilemma: how to reconcile an excitation function like that of a compound nucleus in the region of giant resonances with an angular distribution which unequivocally indicates a direct mechanism.

What can we learn from the general features of these reactions? Since the entrance- and exit-channel spins are respectively 1 and 0, first-order direct two-nucleon pickup is forbidden by spin and parity conservation, as well as by isobaric symmetry[1,9]; so we must consider mechanisms of second or higher order in perturbation theory. (The vanishing of the angular distribu-