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^{176}Yb(t,p)^{178}Yb reaction

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Fourteen levels up to 3.1 MeV in ^{178}Yb have been identified using the ^{176}Yb(t,p) reaction. Measured angular distributions were compared with the results of distorted-wave Born approximation calculations. For six levels we make J^{π} assignments based on L values and the systematics of the lighter even Yb isotopes. The first three members of the ground-state band, the first two members of the excited $K^{\pi}=0^{+}$ band, and the 2^{+} γ-vibrational state are suggested by the systematics. Based only on L values, J^{π} assignments are made for two states and tentative assignments are suggested for four other states. The Q value for the ^{176}Yb(t,p)^{178}Yb reaction is also reported.

[NUCLEAR REACTIONS ^{176}Yb(t,p)^{178}Yb, $E_t=15$ MeV, $\sigma(\theta,E_p)$, DWBA analysis; ^{178}Yb deduced L, J, π, enriched target, magnetic spectrograph.]

I. INTRODUCTION

The most recent nuclear data compilation[1] for $A=178$ contains very little information on the structure of ^{178}Yb. No excited states or gamma rays have been reported for ^{178}Yb and its mass excess is known only to 50 keV.[2] As ^{178}Yb has two more neutrons than the heaviest stable ytterbium isotope, there are only a few reactions which can be used to populate this nucleus, one of which is the (t,p) reaction. This reaction has been used in the past to study deformed rare-earth nuclei with specific interest directed toward the investigation of the neutron-rich isotopes (see e.g., Refs. 3–5).

The purpose of the present work is to locate excited states in ^{178}Yb and to make spin-parity assignments by comparing angular distributions of reaction protons to DWBA predictions. The (t,p) spectra on rare-earth nuclei have, in particular, been shown to be dominated by $L=0$ transitions (see Refs. 3–5, and references therein). These (t,p) $L=0$ transitions have very characteristic angular distributions and therefore provide an excellent tool for locating 0^{+} states in even-even nuclei.

II. EXPERIMENTAL DETAILS

The ^{176}Yb(t,p)^{178}Yb experiment was performed with a 15-MeV triton beam from the University of Pennsylvania FN tandem Van de Graaff accelerator. The ^{176}Yb target, approximately 120 μg/cm^2 in areal density on a 20 μg/cm^2 carbon backing, was prepared from 96.2% isotopically enriched $^{176}Yb_2O_3$. The reaction protons were momentum analyzed with a multiangle spectrograph over a laboratory angular range from 3.75° to 86.25° in 7.5° steps. The reaction protons were detected in nuclear emulsion plates, which had Mylar foils directly in front of them in order to eliminate all other reaction particles. An energy calibration was obtained using groups from the ^{12}C(t,p)^{14}C and ^{16}O(t,p)^{18}O reactions. The experimental resolution was about 25–30 keV full width at half maximum (FWHM) in this experiment.

A solid-state monitor detector of known solid angle was positioned at 40° in the scattering chamber and used to record elastically-scattered tritons. The elastically-scattered triton yield, when normalized to optical-model calculations using parameters list-

TABLE I. Optical-model parameters.

Channel	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0 (fm)	a_W (fm)	$4W_D$ (MeV)	r_D (fm)	a_D (fm)
$t+{}^{176}$Yb	-161.1	1.20	0.72	-18.6	1.40	0.84			
$p+{}^{178}$Yb	-58.34 $-0.32E_x$	1.17	0.75				39.45 $-E_x$	1.32	0.66
$n+{}^{176}$Yb	a	1.30	0.67						

[a]Adjusted to give binding energy equal to 0.5 $(Q_0-E_x+8.482)$ MeV, i.e., $\frac{1}{2}$ of the $2n$ separation energy, where E_x is the excitation energy in MeV.

ed in Table I, was used to establish an absolute cross section. The uncertainty in the absolute cross section using this technique is estimated to be about 15%.

III. RESULTS AND DISCUSSION

Shown in Fig. 1 is a proton spectrum recorded at 18.75 deg from the ^{176}Yb$(t,p)^{178}$Yb reaction. Also apparent in Fig. 1 are groups from the ^{12}C and ^{16}O target contaminants. The Q value for the ^{176}Yb$(t,p)^{178}$Yb reaction was measured to be 3865 ± 10 keV, which is to be compared with the value of 3831 ± 50 keV from the 1977 Mass Tables.[2] Using all the analyzed spectra we observe 13 excited states below 3.1 MeV in ^{178}Yb at five or more angles. Three additional states were observed at only a few angles. All the excited states were previously unreported. Excitation energies are given in Table II.

Angular distributions have been extracted for all levels that were observed at five or more angles and are shown in Fig. 2. These experimental (t,p) angular distributions are compared to the predictions of distorted-wave Born approximation (DWBA) calculations which are also shown in Fig. 2. These DWBA calculations were made using the computer code DWUCK4 (Ref. 6) with the optical-model parameters listed in Table I. The optical-model parameters for both ^{176}Yb$+t$ and ^{178}Yb$+p$ channels were taken from the global parametrizations of Becchetti and Greenlees as tabulated in Ref. 7. L value assignments are given in Table II.

Whereas the $J^{\pi}=0^{+}$ ground state is reported to be the strongest state in the spectrum in various studies of other rare-earth nuclei,[3,5] this feature is not observed in the present work. The $L=0$ state at 1317 keV in ^{178}Yb is observed to have about the same strength as the ground state. The general shape of the angular distribution for both states is well reproduced by the $L=0$ DWBA calculation.

States at 82 and 1402 keV have very similar an-

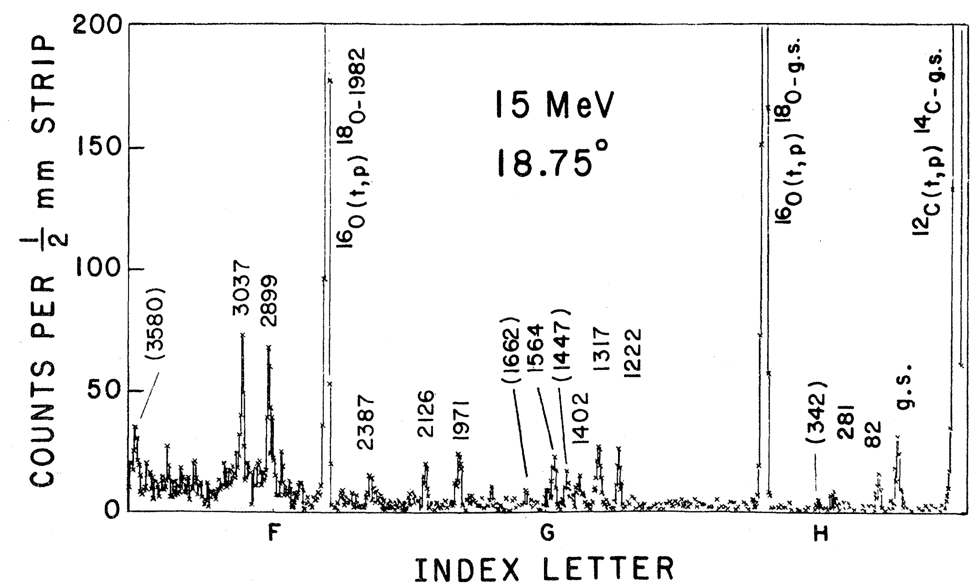

FIG. 1. Proton spectrum for the ^{176}Yb$(t,p)^{178}$Yb reaction. Excitation energies of states in ^{178}Yb are given in keV. Groups from ^{16}O and ^{12}C in the target are also labeled.

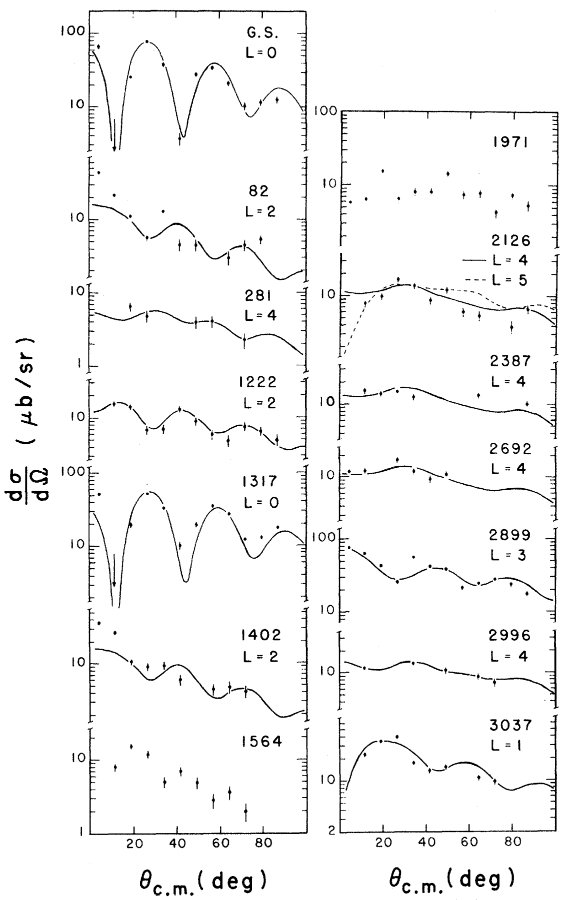

FIG. 2. Angular distributions for levels in ^{178}Yb. The excitation energy of each state is given in keV. The solid curves are the results of DWBA calculations using the code DWUCK4 for the L values shown.

gular distributions and are best fitted by $L=2$ DWBA calculations though they are not well reproduced by the calculation. We assign these states to have $J^{\pi}=2^{+}$ based on their angular distributions and following systematics: The spacing between the 0^{+} ground state (g.s.) and 82-keV 2^{+} state and the spacing between the 1317 0^{+} and 1402-keV 2^{+} states are very similar to the spacing between the 0^{+} and 2^{+} states for the ground state and excited $K^{\pi}=0^{+}$ bands observed by Riedinger *et al.*[8] in the lighter even-Yb isotopes (see Fig. 4 of Ref. 8). Similarly, based on the comparison of the 281-keV state's angular distribution to the DWBA calculation for $L=4$ and the systematics of the ground state band, we assign this state to be the $J^{\pi}=4^{+}$ member of the ground-state band. The 1222-keV state is assigned $J^{\pi}=2^{+}$ based on the comparison of its angular distribution to the DWBA $L=2$ prediction and the systematics of the energies of the 2^{+} γ-vibrational states in the lighter Yb nuclei.[8] It should be noted that there is a slight difference between the DWBA $L=2$ shape in Fig. 2 for the 82- and 1402-keV states and the shape of the calculation for the 1222-keV state. For the 82- and 1402-keV calculations, the transferred neutrons were put into the $1i_{13/2}$ shell-model orbital, while for the 1222-keV state the calculation corresponds to the neutrons being transferred to a lower angular-momentum orbital [the $(3p_{3/2})^2$ and $(2f_{5/2})^2$ configurations produced the same shape].

Other states for which we believe definitive J^{π} assignments can be made, based on how well their angular distributions are reproduced by the DWBA calculations and the strengths of the states, are those at 2899 and 3037 keV excitation which we assign $J^{\pi}=3^{-}$ and 1^{-}, respectively. Owing to the possibility of multiple step processes, the assignments for the following weaker states, also based on the DWBA fits to angular distributions, should be considered tentative: 4^{+} or 5^{-} for the 2126-keV state, 4^{+} for the 2387-keV state, and 4^{+} for the 2996-keV state. Angular distributions for states at 1564 and 1971 keV excitation in ^{178}Yb are presented in Fig. 2 but no comparison to DWBA calculations is made.

TABLE II. Energy levels of ^{178}Yb and L values for the ^{176}Yb$(t,p)^{178}$Yb reaction measured in the present experiment. J^{π} assignments are based on the assumption that for an even-even target the (t,p) reaction populates only natural-parity states, and a comparison to systematics for some states.

Level number	E_x (keV)	ΔE_x (keV)	number of angles	L	J^{π}
0	0		12	0	0^{+}
1	82	5	10	2	2^{+}
2	281	8	5	4	4^{+}
	(342)		2		
3	1222	5	11	2	2^{+}
4	1317	5	12	0	0^{+}
5	1402	9	9	2	2^{+}
	(1447)		2		
6	1564	8	9		
	(1662)		2		
7	1971	8	12		
8	2126	8	10	(4,5)	$(4^{+},5^{-})$
9	2387	12	7	(4)	(4^{+})
10	2692	10	6	(4)	(4^{+})
11	2899	10	12	3	3^{-}
12	2996	13	5	(4)	(4^{+})
13	3037	10	8	1	1^{-}

IV. CONCLUSIONS

The Q value for the ^{176}Yb$(t,p)^{178}$Yb reaction has been measured to be 3865 ± 10 keV, and the reaction has been used to populate states in ^{178}Yb: 14 states to just over 3 MeV excitation are observed. From the comparison of their angular distributions and systematics[8] of the lighter Yb isotopes, the g.s. and 1317-keV states are seen to have $J^{\pi}=0^{+}$ and are populated with about the same strength in the (t,p) reaction. In addition, the 2^{+} members of these bands (g.s. and $K^{\pi}=0^{+}$) are believed to be the states at 82 and 1402 keV, respectively; and the state at 281 keV is believed to be the 4^{+} member of the ground-state band. The 1222-keV state is assigned $J^{\pi}=2^{+}$ based on its angular distribution and the systematics of the energies of the 2^{+} γ-vibrational states in the lighter Yb nuclei.[8] Based solely on DWBA fits to the experimental angular distributions we make the following six (four tentative) assignments: $(4^{+},5^{-})$ for 2126 keV, (4^{+}) for 2387 keV, (4^{+}) for 2692 keV, 3^{-} for 2899 keV, (4^{+}) for 2996 keV, and 1^{-} for 3037 keV. Angular distributions for the states at 1564- and 1971-keV excitation are presented.

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