HIGH RESOLUTION MEASUREMENT OF THE ^{91}Zr$(p,t)^{89}$Zr REACTION*

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The ^{91}Zr$(p,t)^{89}$Zr reaction has been studied in a high resolution experiment at an incident energy of 25 MeV. Angular distributions for transitions to the levels of ^{89}Zr up to an excitation energy of $\sim$ 3.400 MeV have been measured. The data are compared with the DWBA predictions.The energy levels of ^{89}Zr has been studied in the framework of shell model.

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1. Introduction

A study of the ^{91}Zr$(p,t)^{89}$Zr reaction was performed to improve the information on the ^{89}Zr by means of an accurate measurement of the differential cross sections and in comparison with the angular distributions of the ^{90}Zr$(p,t)^{88}$Zr reaction [1] measured at the same incident energy.

The level structure of ^{89}Zr nucleus has been evidenced by different kinds of experimental measurements. Mainly radioactivity investigations and in beam γ - ray spectroscopy has been applied, using the reactions ^{86}Sr$(\alpha$,n$\gamma)$, ^{83}Sr$(\alpha,2n\gamma)$, ^{88}Sr$(\alpha,3n\gamma)$ and (HI,$xn\gamma$). Further, levels in ^{89}Zr have been studied using (p,n), $(p,n\gamma)$ and $(^3$He$,t)$ reactions and one and two nucleon transfer reactions ^{90}Zr(p,d), ^{90}Zr(d,t), ^{90}Zr$(^3$He$,\alpha)$ and ^{91}Zr(p,t) [2,3].

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The experimental results are summarized in the NDS compilation [4], where more complete collection of references can be found.

2. Experimental results

A 25 MeV proton beam from the Munich University MP tandem accelerator, bombarded a 50 μg/cm^2 thick ^{91}Zr enriched target (94.59%), on a 12 μg/cm^2 carbon foil. Outgoing tritons have been detected in the focal plane of the Q3D magnetic spectrometer by the light-ion focal plane detector with periodic readout [5]. Absolute cross sections are estimated with an uncertainty of $\pm$15% and the energy accuracy is $\pm$3 keV.

In Table I the integrated cross section values and the attributed spins and parities are given together with the energies, spins and parities of ^{89}Zr levels adopted so far [4] and with the energies, spins and parities of the levels observed in previous (p,t) reactions [2, 3].

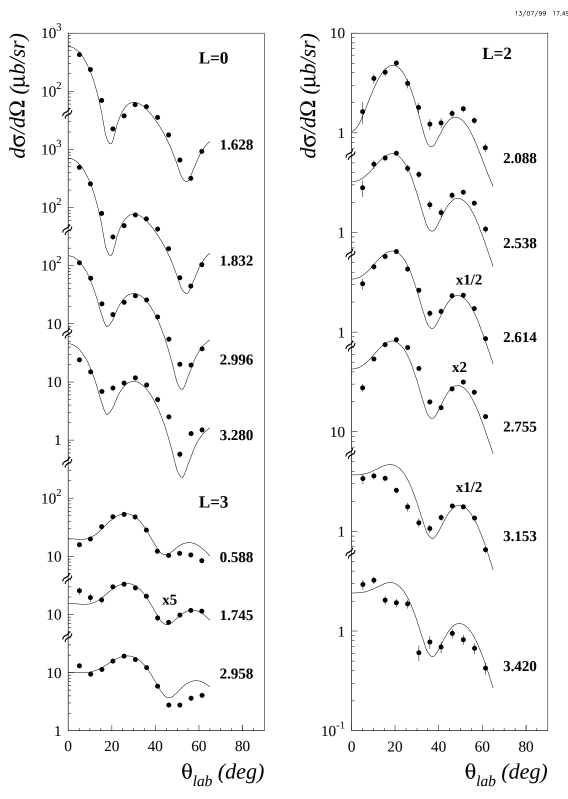

Fig. 1. Experimental angular distributions for some triton groups observed in the ^{91}Zr$(p,t)^{89}$Zr reaction, compared with the DWBA calculations for the indicated L-transfer values.

TABLE I

$^{91}\mathrm{Zr}(p,t)^{89}\mathrm{Zr}$

Adopted levels [4]		Previous (p,t) [2]			Present Experiment			
E_x(keV)	J^π	E_x	J^π	L	E_x	J^π	L	$\sigma_{\rm int}(\mu$b)
0.0	9/2+	0.0		2+4+6	0.0	9/2+	2+4+6	309.026
587.82	1/2−	588		3	588	-	3	75.409
1094.9	3/2−	1094		1+3	1094	-	1+3	94.981
1451.3	5/2−	1450		1+3+5	1452	-	1+3+5	28.909
1511.8	(9/2)+	1512		2+4+6	1512	9/2+	2+4+6	16.960
1627.29	5/2+	1626	5/2+	0	1628	5/2+	0	123.718
1742.6	1/2−	1743		1+3	1745	-	3	11.278
1833.7	5/2+	1832	5/2+	0	1832	5/2+	0	156.494
1864.6	3/2−	1864		1+3	1864	-	1+3	31.860
1943.72	(13/2)+				1941	+	4	2.566
2086.0	(5/2)+	2088		2+4+6	2088	+	2	6.522
2099.9	5/2−				2101	+	2+4+6	8.727
2101.4	(7/2, 11/2)							
2128.6	(7/2+)				2130			11.331
2132.3	(7/2, 9/2, 11/2)							
2297.8	(7/2)				2300			2.056
2390		2390			2391			1.345
2533	(−)	2533		(3)	2538	+	2	8.405
2567.3	(≤ 7/2)				2563	+	2	1.104
2572.4	(7/2, 9/2+)	2570		1+3	2575	+	2+4	2.382
2612.1	9/2+	2610		2	2614	+	2	17.659
2710		2710			2713	+	6	7.047
2732	(+)	2725			2732	+	0+4	9.729
2750		2750		2	2755	+	2	57.739
2782	5/2−, 7/2−				2783			2.503
2784	(5/2+, 7/2+)							
2889.6	(7/2, 9/2, 11/2)				2887	+	2	3.574
2926.0	7/2+, 9/2+							
2926.52	(19/2)				2927	-	3	5.385
2959.8	(7/2+, 9/2+)				2958	-	3	28.164
2995.3	(21/2)+				2996	5/2+	0	47.887
3016.1	7/2−				3019	+	2+4+6	6.053
3092.69	(7/2+)				3090	+	2	5.720
3141.3	9/2+				3144	+	2	3.905
					3153	+	2	11.302
					3181	+	0+4	14.305
					3269	+	2	3.242
3281.0	7/2+, 9/2+				3280	5/2+	0	16.041
3330	1/2−, 3/2−				3339	-	1+3	1.679
3383	9/2+				3372	+	2	2.798
					3420	+	2	3.566

Most of the (p,t) reaction measurements are concentrated on even-target nuclei. The situation for (p,t) reaction from non zero-spin target, as in the case of ^{91}Zr(p,t)^{89}Zr, is rather complex. In general more than one L-transfer value contributes for the given final state angular distribution.

The measured differential cross sections display two kinds of shape.

One exhibits significant angular structure, prominent enough to allow a distinction among different L-transfers. The second one, rather featureless, is distinctive of more L-transfer contributions.

The DWBA analysis has been carried out in the frame of a semi-microscopic dineutron pick-up theory, using the TWOFNR code [6].

The proton entrance channel parameters are deduced from ref. [7] and for the triton exit channel from ref. [8], slightly adjusted in order to have a better agreement with the shape of the experimental data. Examples of good quality fits obtained by DWBA calculations, with a dominant L-transfer value, are given in Fig. 1.

A significant number of transitions with a little angular structure are reproduced well in terms of a mixing of L transfers allowed by a non zero-spin target, weighted by a $(2L{+}1)$ factor [2]. In Fig. 2 a sample of these fits is reported. The DWBA differential cross section is obtained combining the $L{=}2$, 4 and 6 contributions for the G.S.; $L{=}1$ and 3 for the 1.094 MeV level; $L{=}2$, 4, and 6 for the 1.512 MeV level; $L{=}1$ and 3 for the 1.864 MeV level; $L{=}2$ and 4 for the 2.575 MeV level; $L{=}1$ and 3 for the 3.339 MeV level.

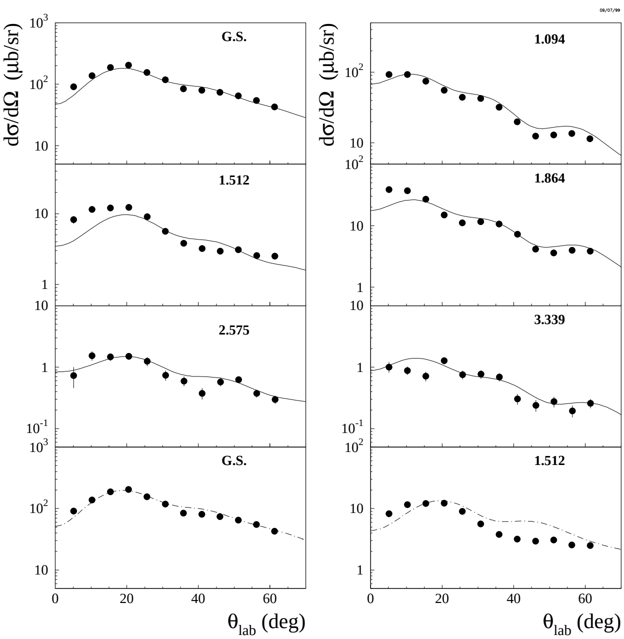

Fig. 2. Angular distributions for some ^{89}Zr levels compared with the DWBA calculations in terms of mixed L-transfer values weighted by $(2L+1)$ (*solid line*), and using the two-particle parentage amplitudes obtained in the shell model calculations (*dotted-dashed line*).

3. Shell model calculations

The structure of low-lying levels of ^{89}Zr has been studied in the framework of the shell model with the code OXBASH [9]. The calculations have been performed for both nuclei ^{88}Zr [1] and ^{89}Zr, using the same residual interaction PMM90, introduced by Brown [9].

The allowed occupation numbers, in squared brackets, for each orbital and the corresponding single particle energies used to generate both positive (PPS) and negative (NPS) parity states are given in the following:

PPS: $\pi 1f_{5/2}$[6 6] 1.00 MeV, $\pi 2p_{3/2}$[4 4] 3.60 MeV, $\pi 2p_{1/2}$[0 2] 5.13 MeV, $\pi 1g_{9/2}$[0 2] 3.15 MeV, $\nu 1f_{5/2}$[4 6] -2.30 MeV, $\nu 2p_{3/2}$[2 4] 0.30 MeV, $\nu 2p_{1/2}$[0 2] 1.83 MeV, $\nu 1g_{9/2}$[8 10] -0.15 MeV, $\nu 2d_{5/2}$[0 1] 2.97 MeV

NPS: $\pi 1f_{5/2}$[4 6] 1.00 MeV, $\pi 2p_{3/2}$[2 4] 3.60 MeV, $\pi 2p_{1/2}$[0 2] 5.13 MeV, $\pi 1g_{9/2}$[0 2] 3.15 MeV, $\nu 1f_{5/2}$[5 6] -2.30 MeV, $\nu 2p_{3/2}$[3 4] 0.30 MeV, $\nu 2p_{1/2}$[1 2] 1.83 MeV, $\nu 1g_{9/2}$[9 10] -0.15 MeV.

For its relevance in connection with the (p,t) reaction, in addition to the energy spectra we have also calculated the two-neutron parentage amplitudes with respect to the ground state in ^{91}Zr($5/2^+$). From the shell model calculations the wave function for this state is given by the coupling of the extra neutron in the $d_{5/2}$ orbital with the ^{90}Zr ground state, namely about 80% of $\nu(1p(d_{5/2}))$ nature with respect to the $N=50$, $Z=40$ core, and 20% corresponding to two-particle-two-hole proton excitation, namely of $\pi(2p-2h)\nu(1p)$ nature. The former component is expected to populate, via (p,t) reactions, components in ^{89}Zr of $\nu(1h)$ and $\nu(1p-2h)$ nature, while the latter leads to $\pi(2p-2h)\nu(1h)$ and $\pi(2p-2h)\nu(1p-2h)$ components.

The calculated level energies are shown in Fig. 3 in comparison with the experimental values. The overall agreement is reasonable.

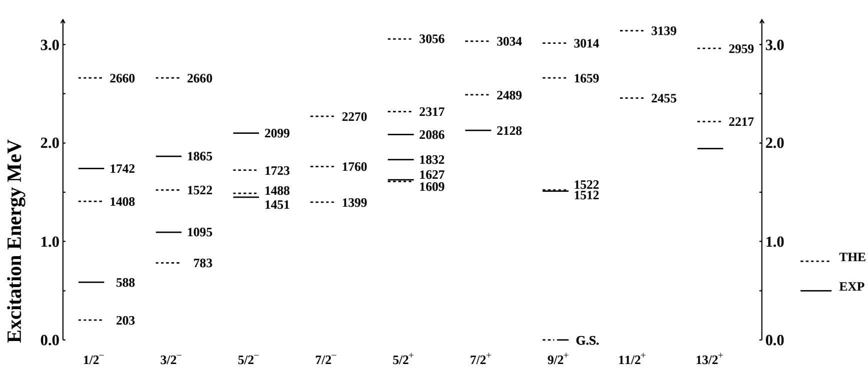

Fig. 3. Energy level scheme comparing shell model and experimental results.

Let us consider the positive parity states. The first two $9/2^+$ levels have both as major component of the state corresponding, for the neutron part, to a single hole in the $1g_{9/2}$ orbital, with prevalent (close to 80% of probability) proton closure for the ground state, while for the excited state with $\pi(2p-2h)$ nature. As a consequence the ground state has large two-particle parentage amplitudes associated with the transfer of one neutron of the pair in the $d_{5/2}$ shell and of the second neutron in $g_{9/2}$ shell, with all possible momentum transfer, while for the ${9/2^+}_2$ state the corresponding parentage amplitudes are smaller, although appreciable, with consistency with the experimental data. Using these two-particle parentage amplitudes, the DWBA calculations for the angular distributions of the G.S. $9/2^+$ and of the 1512 keV $(9/2)^+$ state of the ^{89}Zr are shown in Fig. 2. The agreement obtained between experimental and theoretical data for the 1512 keV state allows to remove the uncertainty on spin assignment reported in [4].

As for the $5/2^+$ states, the lowest state mainly corresponds (more than 85%) to neutron $(1p-2h)$ configuration, with the particle in the $\mathrm{d}_{5/2}$ orbital and two holes, coupled to $L=0$, in the $g_{9/2}$ orbital. As a consequence the state has a large two-particle parentage amplitude associated with $L=0$ pair of neutrons in the $g_{9/2}$. The second $5/2^+$ state is instead associated with a single neutron hole in the $g_{9/2}$ state, coupled to a $L=2$ proton $(2p-2h)$ excitation, with consequent small two-particle parentage amplitudes.

Finally the third state has a structure similar to ${5/2^+}_1$, but the two holes in the $g_{9/2}$ are coupled to $L=2$. In this case there is a large two-particle parentage amplitude associated with a pair of neutrons in the $g_{9/2}$ orbital, but with $L=2$ coupling.

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