PHYSICAL REVIEW C VOLUME 33, NUMBER 5 MAY 1986

Collective aspects of ^{91}Zr by (d,d′) scattering at 17 MeV

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(Received 31 December 1985)

The ^{91}Zr(d,d′)^{91}Zr* reaction has been investigated at 17 MeV incident energy. Up to 4.8 MeV excitation, 73 levels, some of them new, were identified. Angular distributions associated to ~40 levels were attributed to pure $L=2$, 3, or 5 excitations, concentrated in energy regions where the ^{90}Zr core exhibits 2^+, 3^-, and 5^- states. The partial deformation parameters β'_L obtained show agreement with those from low energy proton scattering for $L=2$, but there is a systematic difference for $L=3$ and $L=5$, which is discussed. Attention is drawn to the high excitation probability of the first excited state of ^{91}Zr, as measured by the $\beta_2 \simeq 0.18$ value obtained, a factor of ~2 above all other values for nuclei with $A=90\pm2$.

I. INTRODUCTION

The nuclei with mass number around $A=90$ have been subject to considerable interest, both from theoretical[1-7] and experimental[8-26] points of view, since the neutron shell closure at $N=50$ seems to be accompanied by semiclosures at $Z=38$ and $Z=40$, as is evidenced by the high-lying first excited states in ^{88}Sr and ^{90}Zr. Such features should make it possible to understand those nuclei and their neighbors on relatively simple terms.

Inelastic scattering studies have in the past been used to put into evidence collective aspects of even-even nuclei, but experiments on odd-A nuclei have been relatively less frequent. The number of basis states necessary for a good description of an odd nucleus in terms of its even neighbors is a measure of the interweaving of particle and collective degrees of freedom. Microscopic calculations for inelastic scattering[17,27,28] indicate that valence transitions contribute relatively little to the measured cross section, especially for low multipole excitations, particularly in the $A=90$ region. Inelastic scattering could then be used to also put into evidence collective aspects of the wave functions for odd-A nuclei. As long as simple patterns emerge, this type of experiment could then help to unravel the structure of odd-A nuclei. Following this line of ideas, the nucleus ^{91}Zr, which is just one neutron above a closed shell, was chosen as an interesting study case, the more so since other inelastic scattering data,[29-35] in particular from a precise (p,p′) study,[8] exist for this target.

II. EXPERIMENTAL PROCEDURE

A self-supporting target of 540 μg/cm^2 enriched to 89% in ^{91}Zr was bombarded by 17 MeV deuterons from the three-stage Van de Graaff accelerator of the University of Pittsburgh. The scattered deuterons were detected at seven angles from $\theta_{\text{lab}}=25°$ to 80° with nuclear emulsion plates (Kodak-type NTB, 50 μm thick) placed in the focal surface of an Enge split-pole magnetic spectrograph. During the experiment elastically scattered deuterons were continuously monitored by two NaI scintillators fixed symmetrically at $\theta_{\text{lab}}=38.7°$ relative to the incident beam. The emulsion plates were scanned at the University of São Paulo in steps of 0.2 mm along the plate. An energy resolution (FWHM) of ~15 keV was obtained for all spectra.

A typical spectrum, obtained at a laboratory scattering angle of 35°, is shown in Fig. 1. Deuteron groups corresponding to transitions to ^{91}Zr levels are indicated by the calculated excitation energies of ^{91}Zr states expressed in keV and, when corresponding to transitions to levels of contaminant isotopes, by the name of the isotope. Peaks of larger widths labeled by t are associated to triton groups from the (d,t) reaction on ^{91}Zr and correspond to levels above 5 MeV excitation energy in ^{90}Zr. The peak labeled p at the left-hand side of Fig. 1 corresponds to the proton group from the ^{91}Zr(d,p)^{92}Zr(g.s.) reaction. A description of the procedures used for the identification of peaks corresponding to states in ^{91}Zr has been given in detail elsewhere.[36,37]

The excitation energies presented in Table I represent the average of the excitation energies calculated at each angle, making use of the calibration of the spectograph and taking the energy of the state at (1204.8 ± 0.4) keV, as measured by gamma decay,[38] as a reference. The rms deviation of the energy measurements at six angles was in most cases less than 2 keV. Indicated in Table I by parentheses are those levels, with only tentative assignments, that presented a rms deviation of the energy measurements of more than 3 keV, but always smaller than 6 keV. The absolute excitation energy scale is estimated to be uncertain by $\pm0.15\%$, corresponding to an absolute uncertainty of less than ±7 keV in the tabulated excitation energies.

Relative normalization of the (d,d′) cross sections was obtained from the number of elastically scattered deuterons detected by the monitors during each exposure. The absolute normalization was obtained from the deuteron elastic cross section given by the optical model prediction using the potential parameters given in Table II. The use of five different sets of optical model parameters (see the next section) resulted in differences $\lesssim 8\%$ in the absolute normalization. The absolute cross section is estimated to be uncertain by at most 25%, due essentially to uncertainties in beam alignment and definition of the solid angles

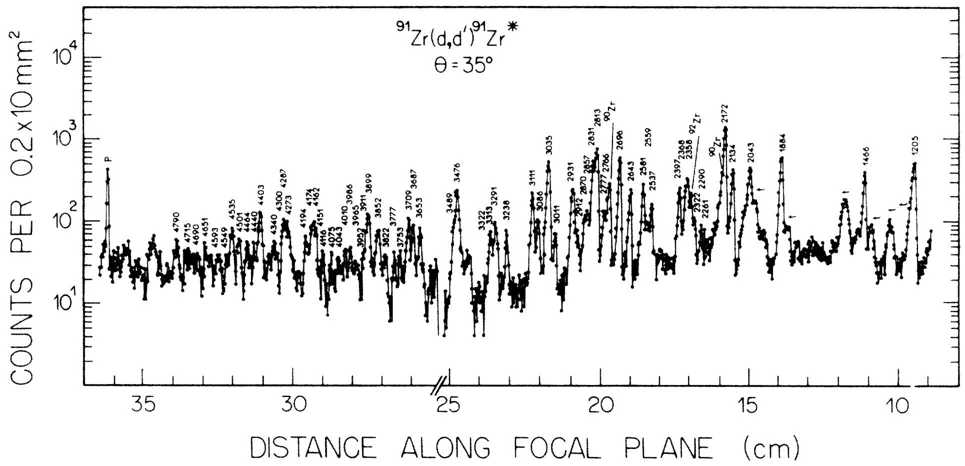

FIG. 1. Deuteron spectrum from the ^{91}Zr(d,d′)^{91}Zr* reaction at $\theta = 35°$. Peaks corresponding to transitions to ^{91}Zr states are labeled by the excitation energies of the states expressed in keV. The peaks due to the presence of contaminant zirconium isotopes in the target are identified by the name of the isotope. The peaks labeled by t or by p are associated to triton or proton groups from the reactions (d,t) or (d,p) on the ^{91}Zr target.

of the monitors.

The experimental angular distributions of 42 levels are shown in Figs. 2 and 3. The error bars show the combined effect of statistical deviations and uncertainties due to plate scanning, background subtraction, and relative normalization.

III. DWBA ANALYSIS

The angular distributions were compared with predictions of distorted-wave Born approximation (DWBA) calculations, performed by means of the code DWUCK,[39] with a macroscopic collective form factor using complex coupling. Coulomb excitation was considered in the usual way[39] and a nonlocality correction parameter $\beta = 0.54$ fm was employed. The optical model parameters were taken from the systematics of Childs, Daehnick, and Spisak[40] for 17 MeV deuterons and are shown in Table II. For the optical parameters of the exit channel the same energy dependence suggested by Perey and Perey[41] was supposed. Calculations employing the optical parameters of Perey and Perey[41] predicted angular distributions practically coincident with the former in the angular range of interest to this experiment.

The fits to the angular distributions are shown in Figs. 2 and 3 in comparison with the data, whenever an assignment of L was attempted. In the fitting procedure the aim was to match the average behavior of the experimental angular distribution. Partial deformabilities β'_L were extracted in the fitting procedure. If only one L value is important in each transition, the relation between experimental and predicted cross sections is written as

$$\sigma^{\mathrm{exp}}(\theta) = \beta'^2_L \sigma^{\mathrm{DW}}_L(\theta)$$

with β'_L related to the usual deformation parameter β_L by

$$\beta'_L = \left[\frac{(2j_f+1)}{(2j_i+1)(2L+1)} \right]^{1/2} \beta_L ,$$

where j_i and j_f are the spins of the initial and final states.

In the present analysis equal deformation parameters for the real and imaginary part of the potential were assumed. Calculations with equal deformation length $\delta_r = \delta_i$ ($\delta = \beta R$) were also done and would lead to values of the deformation parameters which are between 5% to 7% larger.

The values of L and the squares of the partial deformabilities β'_L are listed in Table I. The errors associated to the values of β'^2_L, also listed in Table I, do not include uncertainties in the absolute cross sections or DWBA formalism.

IV. RESULTS

In Table I, the present results are compared with those of other experiments performed with good energy resolution.[8,38] It is worth noting that, for most of the levels above ~3 MeV excitation energy, the information presented by the Nuclear Data compilation[38] is heavily based on the experiments performed by Blok *et al.*[8] Within the attributed errors, there is very good agreement between the reported values and the present results for level energies, although there seems to be an indication for an increasing systematic difference above 3.5 MeV of excitation.

The nucleus ^{91}Zr has been studied by inelastic scattering of various projectiles by several authors.[29–35] Only the detailed results of Blok *et al.*[8] for ^{91}Zr(p,p′) are presented in Table I since poor resolution affected most other work. Where comparison is possible with those older measurements there is general agreement. A previous inelastic deuteron scattering experiment,[29] performed at 15 MeV incident energy, did only obtain data at two scattering angles, with an energy resolution of 40 keV. All levels above 4.5 MeV excitation have not been reported before in inelastic scattering studies. As may be appreciated, by inspection of Table I, only some weak transitions reported

TABLE I. Summary of the results for ^{91}Zr(d,d')^{91}Zr* inelastic scattering and comparison with other experiments. Assignments given in parentheses are tentative.

Present experiment ^{91}Zr(d,d')						Blok *et al.*[a] ^{91}Zr(p,p')			Nuclear data[b]	
E_{exc} (keV)	$\left[\frac{d\sigma}{d\Omega}\right]_{\max}$[c] (mb/sr)	L	$\beta_L'^2\times 10^2$	β_L	$G(L)$ (W.u.)	E_{exc} (keV)	L	$\beta_L'^2\times 10^2$	E_{exc} (keV)	j_f^π
1205	0.35±0.11	2	0.21±0.03	0.18	22	1205	(2)		1204.8	$\frac{1}{2}^+$
1466	0.21±0.05	2	0.13±0.02	0.081	4.5	1468	2	0.09	1466.3	$\frac{5}{2}^+$
1884	0.53±0.07	2	0.27±0.02	0.101	7.0	1884	2	0.30	1882.1	$\frac{7}{2}^+$
2043	0.22±0.03	2	0.13±0.02	0.099	6.9	2041			2042.2	$\frac{3}{2}^+$
2134	0.45±0.06	2	0.23±0.01	0.083	4.8	2131	2	0.22	2131.3	$(\frac{9}{2})^+$
2172	0.63±0.08	3	0.75±0.06	0.162	24	2170	3	1.15	2170.0	$(\frac{11}{2})^-$
						2189	5	0.082	2189.9	
(2203)						2201			2200.7	$(\frac{7}{2})^+$
2261						2261	5	0.051	2259.7	$(\frac{13}{2})^-$
2290	0.016±0.004	5	0.050±0.014	0.045	5	2289	5	0.105	2287.6	$(\frac{15}{2})^-$
2322[d]	0.022±0.007	5	0.072±0.023	0.063	9	2322	5	0.165	2320.1	$(\frac{11}{2})^-$
2358	0.12±0.03	(3)	0.12±0.04	0.16[a]	23	2358	3	0.18	2355.8	$\frac{1}{2}^-,\frac{3}{2}^-$
2368	0.040±0.014	(4)	0.088±0.021			2369	(3+5)		2366.9	$(\frac{7}{2}^-)$
2397	0.074±0.010	(3)	0.11±0.02	0.068	4.3	2397	3	0.22	2394.9	$(\frac{9}{2})^-$
2537	0.060±0.011	(2)	0.043±0.008	0.046[a]	1.5	2534	(2)	0.045	2534	$(\frac{3}{2}^+,\frac{5}{2}^+)$
2559	0.023±0.006[f]					2557			2556.0	$\frac{1}{2}^+$
2581	0.098±0.010	3	0.137±0.014	0.098[a]	9.0	2578	3	0.20	2577.5	
2643	0.081±0.009	3	0.106±0.016	0.105	10.4	2641	3	0.15	2641.0	$(\frac{3}{2})^-$
2696	0.21±0.02	3	0.29±0.04	0.142[a]	19	2695	3	0.44	2694.0	$(\frac{3}{2}^-)$
2766	0.016±0.005	(5)	0.048±0.014	0.048[a]	5	2766	5	0.09	2764.8	
2777	0.038±0.006	(3)	0.045±0.013	0.069	4.3	2777	3	0.082	2775.0	$(\frac{3}{2})^-$
2813	0.29±0.04	3	0.37±0.03	0.139[a]	18	2813	3	0.55	2810.9	$\frac{5}{2}^-,\frac{7}{2}^-$
2831	0.17±0.03	3	0.23±0.03	(0.155)[g]	(22)	2832	3	0.32	2826.0	
2857	0.027±0.010	(4)	0.055±0.016	0.046	3	2859	4	0.077	2856.8	$(\frac{13}{2})^+$
2870	0.041±0.007	(2)	0.032±0.007	0.049[h]	1.7	2874			2874	$\frac{3}{2}^+,\frac{5}{2}^+$
						2905				
2912	0.012±0.007[f]					2915			2914.1	$(\frac{9}{2})^+$
2931	0.15±0.02	2	0.100±0.008			2931			2932	
3011	0.018±0.004	3	0.025±0.005	(0.036)[i]	(1.2)	3008	3	0.040	3009.1	$\frac{5}{2}^-,\frac{7}{2}^-$
3035	0.20±0.02	3	0.27±0.04	0.106[a]	11	3032	3	0.39	3033	
						3053			3053	
3086[d]	0.029±0.004	(3)	0.037±0.006			3082	4	0.072	3085.1	$\frac{3}{2}^+,\frac{5}{2}^+$
3111	0.16±0.02	2	0.100±0.008	0.055[a]	2.1	3108	2	0.11	3108.1	$\frac{7}{2}^+,\frac{9}{2}^+$
						3143			3146.6	$(\frac{17}{2}^+)$
						3170			3167.0	$(\frac{21}{2}^+)$
3238	0.047±0.008	(2)	0.034±0.005			3235	(2)	0.047		
						3262			3262	$\frac{3}{2}^+$
						3283			3283	
3291	0.041±0.012	(2)	0.031±0.006	0.048[h]	1.6	3290			3290	$\frac{3}{2}^+,\frac{5}{2}^+$
3313[d]	0.018±0.008	(2)	0.014±0.005			3309			3309	

TABLE I. (*Continued*).

Present experiment ^{91}Zr(d,d')						Blok *et al.*[a] ^{91}Zr(p,p')			Nuclear data[b]	
E_{exc} (keV)	$\left[\frac{d\sigma}{d\Omega}\right]_{\max}$[c] (mb/sr)	L	$\beta_L'^2\times10^2$	β_L	$G(L)$ (W.u.)	E_{exc} (keV)	L	$\beta_L'^2\times10^2$	E_{exc} (keV)	j_f^π
3322	0.011±0.006[f]					3317			3317	
						3335			3334	$\frac{1}{2}^+$
						3356			3356	
						3375			3375	
						3410			3410	
						3452	3		3455	$\frac{9}{2}^-,\frac{11}{2}^-$
						3466			3468	$\frac{7}{2}^+,\frac{9}{2}^+$
3476[e]	0.15±0.03	(2)	0.13±0.03			3474			3476	
3489	0.035±0.024[f]					3489			3489	
						3553			3554	$(\frac{7}{2})^+$
						3570			3576	$(\frac{3}{2})^-$
						3597			3597	$\frac{5}{2}^-,\frac{7}{2}^-$
						3635			3635	$\frac{3}{2}^+,\frac{5}{2}^+$
3653	0.022±0.004	(5)	0.069±0.015			3648	(5)		3648	
						3660			3666	
3687	0.059±0.007	2	0.040±0.005	0.055[h]	2.1	3683			3681	$\frac{3}{2}^+,\frac{5}{2}^+$
3709	0.098±0.010	2	0.072±0.011	0.046[j]	1.5	3704	2		3704	$\frac{7}{2}^+,\frac{9}{2}^+$
						3725			3725	
3753	0.019±0.004	(2)	0.017±0.003	(0.036)[k]	(0.9)	3749			3748	$\frac{3}{2}^+,\frac{5}{2}^+$
3777	0.011±0.003	(2)	0.010±0.003			3775			3774	
3822	0.021±0.005	(2)	0.019±0.006	0.027[j]	0.5	3817			3818	$(\frac{7}{2}^+,\frac{9}{2}^+)$
						3829			3829	$(\frac{5}{2}^+)$
3852	0.042±0.009	(2)	0.036±0.008	0.042[h]	1.3	3847			3848	$\frac{3}{2}^+,\frac{5}{2}^+$
						3884			3883	$(\frac{1}{2}^-,\frac{3}{2}^-)$
3899	0.076±0.013	(2)	0.065±0.013	0.049[j]	1.7	3893			3897	$\frac{7}{2}^+,\frac{9}{2}^+$
3911	0.020±0.011[f]					3903			3905	$\frac{9}{2}^-,\frac{11}{2}^-$
						3922			3924	$\frac{3}{2}^+,\frac{5}{2}^+$
3952						3944			3944	
3965						3959			3958	$\frac{7}{2}^+,\frac{9}{2}^+$
3986	0.013±0.003[f]					3980			3982	$\frac{3}{2}^+,\frac{5}{2}^+$
4010	0.021±0.005[f]					4003			4004	$\frac{7}{2}^+,\frac{9}{2}^+$
						4027			4024	
4043						4035			4036	$(\frac{3}{2}^+,\frac{5}{2}^+)$
4075						4065			4067	$\frac{9}{2}^-,\frac{11}{2}^-$
4116						4111			4111	$\frac{7}{2}^+,\frac{9}{2}^+$
4151						4145			4145	$(\frac{3}{2}^+,\frac{5}{2}^+)$
(4162)						4161			4163	
(4174)										
4194						4187			4195	
						4230			4230	
						4245			4245	
4273						4265			4263	$(\frac{1}{2}^-,\frac{3}{2}^-)$

TABLE I. (*Continued*).

Present experiment ^{91}Zr(d,d′)						Blok *et al.*[a] ^{91}Zr(p,p′)			Nuclear data[b]	
E_{exc} (keV)	$\left[\frac{d\sigma}{d\Omega}\right]_{\text{max}}^{c}$ (mb/sr)	L	$\beta_L'^2\times10^2$	β_L	$G(L)$ (W.u.)	E_{exc} (keV)	L	$\beta_L'^2\times10^2$	E_{exc} (keV)	j_f^π
(4287)						4273			4272	$\frac{7}{2}^+,\frac{9}{2}^+$
(4300)						4291			4293	$\frac{1}{2}^-,\frac{3}{2}^-$
						4323			4322	$\frac{3}{2}^-$
4340						4335			4335	
						4357			4353	$\frac{3}{2}^+,\frac{5}{2}^+$
						4376			4379	$\frac{7}{2}^+,\frac{9}{2}^+$
4403	0.039±0.006	(3)	0.076±0.011			4395			4398	
(4413)									4415	$\frac{9}{2}^-,\frac{11}{2}^-$
4440						4433			4433?	
						4450			4450	
(4464)						4459			4459	
4501									4511	$(\frac{1}{2}^-,\frac{3}{2}^-)$
4535									4535	$\frac{3}{2}^+,\frac{5}{2}^+$
4549										
4593									4582	
(4651)									4656	$(\frac{1}{2}^-,\frac{3}{2}^-)$
4690									4679	$(\frac{3}{2}^-)$
(4715)									4709	
4790	0.016±0.003	(3)	0.036±0.006						4780	

[a] Reference 8.

[b] Reference 38.

[c] Maximum cross section measured.

[d] ^{90}Zr contaminant contribution subtracted.

[e] Possible doublet.

[f] Cross section at 25°.

[g] Values calculated supposing $j_f^\pi=\frac{3}{2}^-$.

[h] Reference 51.

[i] Values calculated supposing $j_f^\pi=\frac{7}{2}^-$.

[j] Choice based on shell model arguments.

[k] Values calculated supposing $j_f^\pi=\frac{3}{2}^+$.

by Blok *et al.*[8] were not observed in the present work.

There is overall agreement between the L values extracted in the present experiment and in the work of Blok *et al.*,[8] however, especially in the excitation region above 2.85 MeV, some more L attributions are presented. The level at 2043 keV, for which no L value is cited by Blok *et al.*,[8] is reached by an $L=2$ transition in agreement with other experiments,[32,33] although Awaya *et al.*[34] suggested $L=3$. It was not possible to obtain angular distributions associated to the two weak $L=5$ transitions located by the (p,p′) work[8] at 2189 and 2261 keV. In fact, the known ^{90}Zr(2^+) contaminant transition explains all the cross sections observed in the present experiment at 2.19 MeV. The level at 2368 keV has a tentative attribution of $j^\pi=(\frac{7}{2}^-)$, based on a Hauser-Feshbach analysis of a (α,nγ) experiment by Glenn *et al.*[42] Blok *et al.*,[8] although not presenting the corresponding fit, cite $L=(3+5)$ for this transition. In the present work $L=(4)$ was preferred, since the (α,nγ) data seem in fact to permit the assignment of a different value of j^π. The $L=2$ attribution for the level at 2931 keV is in agreement with a tentative attribution of Du Bard and Sheline.[33] The angular distribution associated to the level at 3086 keV, after the subtraction of the contamination due to the 4^+ level of ^{90}Zr, seems to be better described by an $L=3$ than by the $L=4$ transition indicated by Blok *et al.*[8] The tentative $L=3$ at-

TABLE II. Optical model parameters for deuterons of 17 MeV on ^{91}Zr.

Optical model parameters[a]	
r_c (fm)	1.25
V (MeV)	101.6
r_0 (fm)	1.1
a_0 (fm)	0.82
W_D (MeV)	15.9
r_D (fm)	1.29
a_D (fm)	0.75
V_{SO} (MeV)	5.63
r_{SO} (fm)	0.98
a_{SO} (fm)	1.00

[a] Reference 40.

tribution is, however, in disagreement with the $\frac{3}{2}^+,\frac{5}{2}^+$ spin and parity values cited by the Nuclear Data compilation, based on the analysis of (d,p) data. The level at 3238 keV is excited by an $L=(2)$ transition in both the present (d,d') and in the (p,p') (Ref. 8) experiments, and was also seen by Metzger[25] in his (γ,γ') work. A level was presented by the former Nuclear Data compilation[43] at 3235 keV, with $j^\pi=\frac{1}{2}^-,\frac{3}{2}^-$ associated to it through a distinctive $l_n=1$ transition seen in (p,d) and (d,t) experiments. Curiously no state is shown by the more recent compilation[38] near this excitation energy.

A comparison of the $\beta_L'^2$ extracted in the present experiment, by (d,d'), and by Blok *et al.*,[8] by means of inelastic scattering of 20 MeV protons, reveals that, while there is agreement between the $\beta_2'^2$, the values of $\beta_3'^2$ and $\beta_5'^2$ present a systematic discrepancy. It is interesting to note

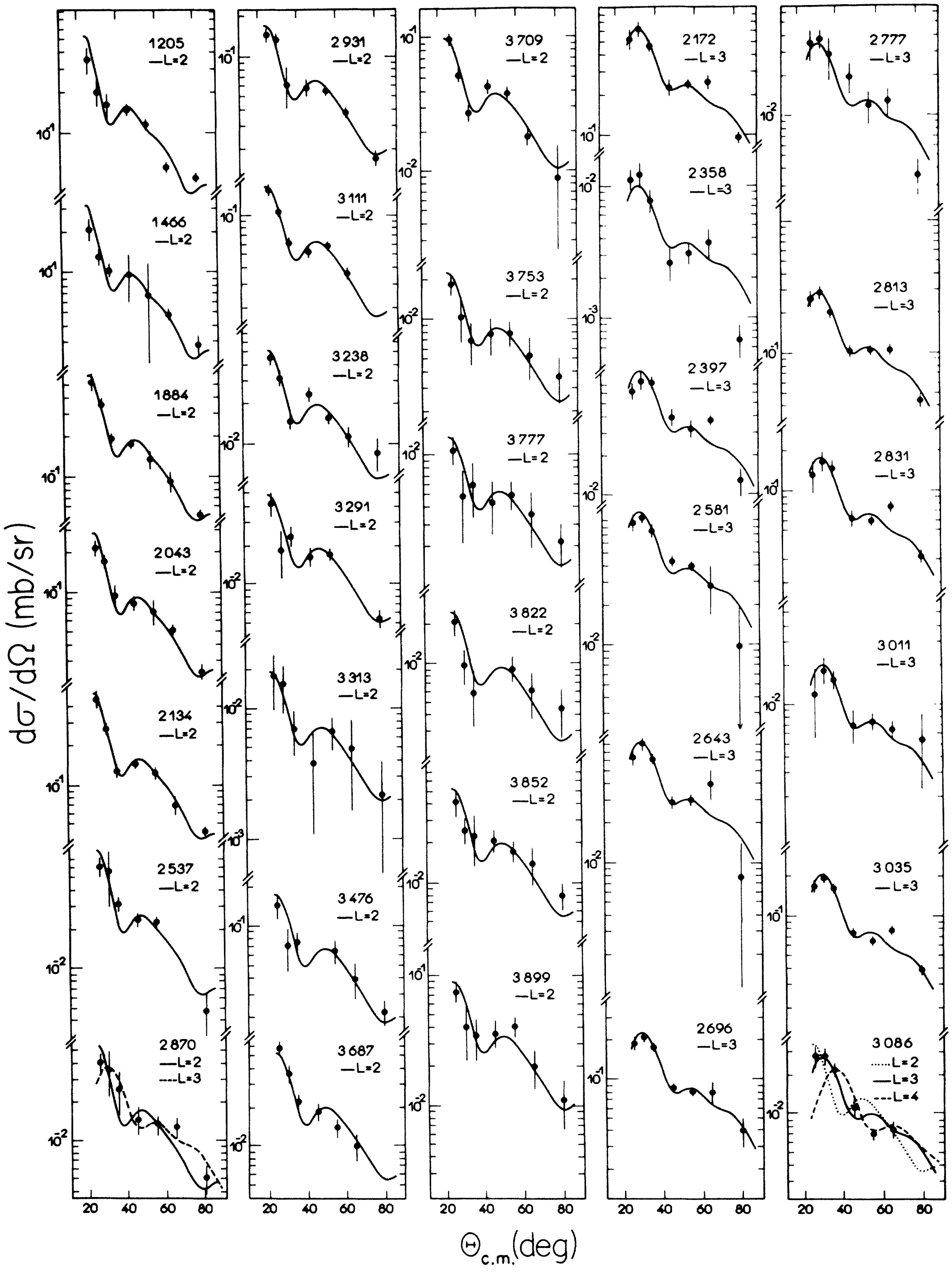

FIG. 2. Angular distributions of transitions in the ^{91}Zr(d,d')^{91}Zr* reaction. The experimental points are given with error bars corresponding to the combined effect of statistical deviations and uncertainties due to plate scanning, background subtraction, and relative normalization. The solid lines represent DWBA fits to the experimental angular distributions.

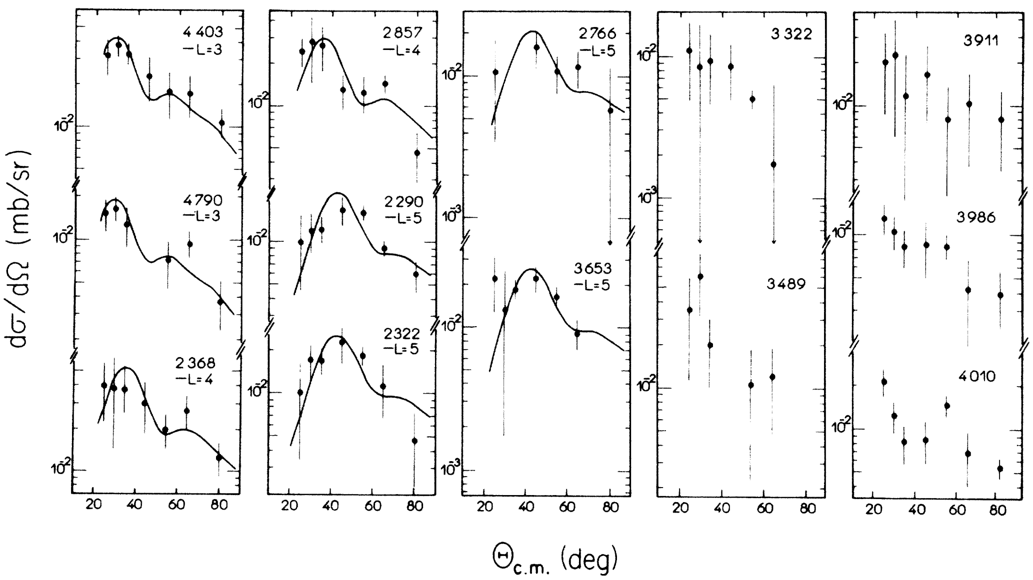

FIG. 3. See caption to Fig. 2.

that also the $\beta_2'^2$ value for the $\frac{1}{2}^+$ state at 1205 keV, is in agreement with the value which can be extracted from the analysis of the (p,p′) cross sections measured by Blok *et al.*[8] using the recommended optical parameters, although not presented by the authors. The ratios $\beta_L'^2(\mathrm{p,p'})/\beta_L'^2(\mathrm{d,d'})$ associated to $L=3$ and $L=5$ are consistently larger than 1. The mean values obtained for these ratios for $L=3(5)$, considering the 6(3) strongest transitions, are, respectively, 1.46(2.1) with spreads of less than 10%. If a prescription of equal deformation lengths had been used in data analysis of both experiments the discrepancies would have been slightly larger. A similar effect is observed if δ_L obtained by $\lesssim 20$ MeV proton inelastic scattering[15] are compared with 15 MeV deuteron[12] δ_L for the first 3^- and 5^- levels of ^{90}Zr.[44] It is felt that no reasonable change in optical model parameters could, within the reaction model adopted, reduce these discrepancies while simultaneously maintaining the accordance for $L=2$ results. In fact, less than 8% and 6% of variation was obtained for the ratios $\sigma_{3,\max}^{\mathrm{DW}}/\sigma_{2,\max}^{\mathrm{DW}}$ and $\sigma_{5,\max}^{\mathrm{DW}}/\sigma_{2,\max}^{\mathrm{DW}}$, in the analysis of 17 MeV deuteron scattering if different sets of optical model parameters were used. In the case of 20.4 MeV proton scattering, the variations of the ratios were, respectively, 11% and 7%, although the absolute values for each L transfer for protons and deuterons could be modified by up to 30%. These additional DWBA calculations were performed for deuteron scattering with three other global prescriptions[41,45,46] and with parameters[41] adjusted to reproduce elastic scattering at the same energy by odd nuclei of the same mass region and by ^{91}Zr at a lower energy.[10] One of the global potentials employed[45] for deuteron scattering used folding model ideas to confine the parameters within the range expected from nucleon scattering and allowed for a shell structure term near magic neutron numbers. For proton scattering, besides with the same parameter set used in data reduction by Blok *et al.*,[8] DWBA calculations were also done with the two global prescriptions[41] in common use in that energy region. An energy dependence of the β_L or δ_L values extracted in the usual way by low-energy inelastic proton scattering, pointed out by previous work in $A=40$, [28,47] $A=90$,[15,17,8] and $A=208$ (Ref. 48) regions, could be reflecting similar difficulties, probably due to inadequacies of the reaction model. In this sense it seems significant that Blok *et al.* normalized the sum of $\beta_L'^2$ values for every L value obtained at 14 MeV incident energy to the sum of those of their 20 MeV (p,p′) experiment.[8] On the other hand there is no support in the literature to any hypothesis linking the differences to nuclear structure effects. Even in the case of excitation of 2_1^+ states in single-closed-shell nuclei, where the effects produced by the different response of protons and neutrons to the various projectiles should be enhanced,[49,50] it amounts to at maximum ~25% on the extracted δ_L values[49,51] and in the case of single-closed-neutron-shell nuclei would produce the smallest δ_2 values for low-energy proton scattering.

V. DISCUSSION

A. Distribution of $\beta_L'^2$ and comparison with β_L of possible core states

Figure 4 shows the values of $\beta_L'^2$ extracted for all the states reached by the same L transfer, as a function of excitation energy. The $L=2$ intensity is spread among several levels up to ~4 MeV of excitation. It is interesting, however, to note that most of the intensity is concentrated in five strongly excited levels between 1.2 and 2.1 MeV, which, incidentally, have attributed spin values in agreement with the values predicted by the coupling of a $d_{5/2}$ particle with a 2^+ state of the core. On the other hand, the $L=3$ intensity, although spread among several levels, is concentrated between 2.2 and 3.1 MeV of excitation, the highest intensity being associated to the known $\frac{11}{2}^-$ state at 2172 keV. Only two states, between 2.3 and

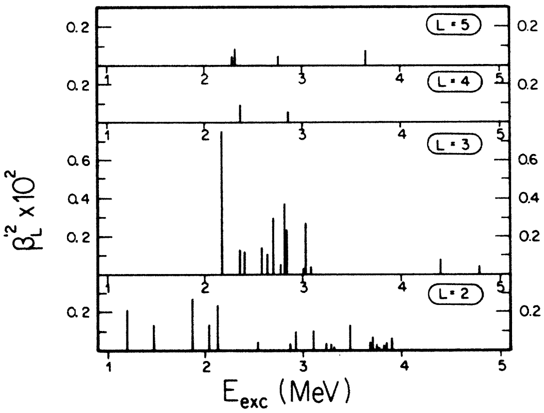

FIG. 4. Square of partial deformabilities $\beta_L'^2$ obtained for all the states reached by the same L, as a function of excitation energy. The height of each line is proportional to the value of the corresponding $\beta_L'^2$.

2.9 MeV, were tentatively associated to an $L=4$ transfer. The detected $L=5$ intensity is distributed among four states, three of them located in a range of ±0.3 MeV around 2.5 MeV of excitation.

According to rules of angular momentum and parity conservation many known levels[38] of ^{91}Zr could in principle be reached by more than one L value. It is interesting, however, to note that the experimental angular distributions associated to almost all positive parity levels are similar, irrespective of their spin values, and that at least one of these levels, the $\frac{1}{2}^+$ state at 1205 keV, can be reached only by an $L=2$ transfer. On the other hand, the shapes of the angular distributions associated to some negative parity levels reveal different dominant L values. In particular, as can be seen in Figs. 2 and 3, the known $\frac{11}{2}^-$ levels at 2172 and 2322 keV are reached by, respectively, $L=3$ and $L=5$ transfer. In general, as may be appreciated in the mentioned figures, the essential features of most experimental angular distributions are reproduced by the DWBA predictions for single L transfer in one step excitation of collective states, indicating a selectivity of the transitions.

In the case of ^{91}Zr, particle-transfer experiments indicate that the ground state is predominantly formed by a $2d_{5/2}$ particle coupled to the ^{90}Zr core in its ground state.[38,11] As long as the contribution of the valence transition can be neglected, which seems to be the case for low-multipole excitations,[17,27,28] the β_L extracted should reflect the constitution in terms of the various core states involved. The extent to which polarization phenomena are important could be evaluated by the character of the ^{91}Zr ground state and by the excitation pattern of ^{92}Zr, which has two particles outside the ^{90}Zr core.[17]

The values of β_L as deduced from the experimental $\beta_L'^2$ and j_f (Ref. 38) values are also presented in Table I. Where more than one j_f value is cited by the compilation, an option, based on arguments found in the literature, was made whenever possible. In particular, since the $(\vec{d},p)$ results by Rathmell *et al.*[52] were subjected to poor energy definition, due to their 160 keV resolution, it was assumed that the 2870 keV, 3291 keV, 3687 keV, and 3852 keV levels, also seen in the (d,p) experiment by Blok *et al.*[8] as rather strong $l_n=2$ excitations, are, respectively, the 2853 keV $(\frac{3}{2}^+)$, 3270 keV $(\frac{3}{2}^+)$, 3661 keV $(\frac{3}{2}^+)$, and 3824 keV $(\frac{5}{2}^+)$ levels reported by the polarization work. This correspondence would resolve the inconsistency noted[38] for the spin attribution of the adopted level at 2856.8 keV. In the same sense it is probable that the 3444 keV $(\frac{7}{2}^+)$ level of Rathmell *et al.*[52] is equivalent to the 3476 keV and not to the 3410 keV adopted level. On shell model arguments, the 3709 keV level observed in (p,d) experiments was supposed to have $j_f=(\frac{9}{2})^+$ and the 3822 keV and 3899 keV levels, observed in (d,p) experiments, were supposed to have $j_f=(\frac{7}{2})^+$. The 2696 keV level is cited by the Nuclear Data compilation as $(\frac{3}{2}^-)$, based on a two-point Hauser-Feshbach analysis of Glenn *et al.*[42] The same level has been observed as an $l_n=(3)$ transfer by Blok *et al.*[8] in their (d,p) work and as $L=3$ in inelastic scattering. Considering this evidence, the $(\frac{5}{2})^-$ attribution[8] was preferred.

Figure 5 is a comparison of the β_L obtained for all states to which a j_f value could be associated and which were excited by the same L transfer in the present experiment, with the deformation parameter of possible core states, as reported in the study of ^{90}Zr(d,d')^{90}Zr*, with deuterons of 15 MeV, by Todd-Baker *et al.*[12] The data are presented as a function of excitation energy and, to guide the eye, bands were drawn, each one centered at the β_L value and the experimental excitation energy of the possible parent state. These bands were extended arbitrarily by ±0.5 MeV and their widths reflect an assumed uncertainty of ±15% in the deformation parameter. The β_2 extracted for the five levels at low excitation energy reached by $L=2$ transfer are compatible or larger than the deformation parameter of the state at 2.18 MeV in ^{90}Zr.[12] In particular, the β_2 associated to the $\frac{1}{2}^+$ state at 1205 keV is larger than the other by a factor of 2. All the $L=2$ states above 2.5 MeV of excitation are weakly populated when compared with the five states at low excitation energy and the extracted β_2 are compatible with those of the other three states associated to $L=2$ in ^{90}Zr in this

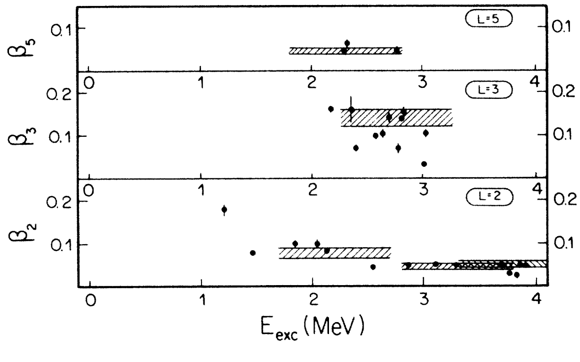

FIG. 5. Deformation parameters β_L obtained for all the states attributed to the same L transferred as a function of excitation energy and comparison with the deformation parameters of possible ^{90}Zr core states (Ref. 12). Each band is centered at the β_L value and excitation energy of the parent state.

energy range.[12] On the other hand, although ten states with known j_f were excited by $L=3$ in an energy range of about ±0.5 MeV around 2.75 MeV, for only five of them the β_3 values extracted are compatible with the deformation parameter of the 3_1^- state of ^{90}Zr.[12] For the other states the extracted β_3 values are smaller than this value. Above the mentioned energy range, the next state, tentatively associated to $L=3$, was observed at an excitation energy ~0.7 MeV lower than the 3^- state detected at 5.12 MeV (Ref. 53) in ^{90}Zr. The only β_4 value extracted in the present work, associated to the state at 2857 keV, is also compatible with the deformation parameter of the state at 3.08 MeV of ^{90}Zr.[12] Note that the β_5 obtained for the first three states excited by $L=5$ transfer in ^{91}Zr agree with the deformation parameter of the 5_1^- state at 2.32 MeV of ^{90}Zr.[12] The next state reached by $L=5$ transfer, at 3653 keV, in the present experiment, which has no attributed spin value, was detected in the same energy region as the second 5^- state of ^{90}Zr.[12]

In situations where the coupling of an odd particle to an even core is considerable, the intermingling of particle and core degrees of freedom could result in extremely complex spectra.[54] Inspection of Fig. 5 reveals that in the case of ^{91}Zr this intermingling is not sufficient to completely destroy the relation to the core states.

B. Comparison with electromagnetic information

It has been usual in the literature to intercompare deformation parameters β_L (or deformation lengths, δ_L) extracted by different inelastic scattering experiments, also with information obtained from electromagnetic transition rates. Systematic discrepancies could, in principle, give information about differences in the neutron and proton components of nuclear states. In the usual homogeneous collective model it is assumed that neutrons and protons move in phase with the same amplitude, leading to $(\beta R)_{h,h'}=(\beta R)_{\mathrm{em}}$ (where h represents generically any hadron), as long as the reaction mechanisms are adequately described. On the other hand, in the extreme shell model, single-closed-shell nuclei would exhibit much reduced oscillations of that kind of nucleons which constitute the closed shell. Core polarization effects would act in a way tending to restore the homogeneous collective model result.[49]

Also listed in Table I are the reduced transition probabilities given in Weisskopf units, $G(L)$, which naively represent a measure of the number of particles involved in the transition, as deduced from the $\beta_L'^2$ and j_f values, by use of the relation:

$$G(L)=\frac{[(L+3)Z]^2}{4\pi}\left[\frac{r_{uL}}{r_{\mathrm{em}}}\right]^{2L}\frac{(2j_i+1)}{(2j_f+1)}\beta_L'^2\,,$$

where, following the recommendation of Owen and Satchler,[55] equivalent radii r_{uL} of 1.22, 1.27, 1.31, and 1.35 fm were used for $L=2$, 3, 4, and 5, respectively, and r_{em} was taken as 1.2 fm.

The comparison of the $G(L)$ obtained in this manner with the corresponding $G(EL)$ values extracted for the previously assumed core states by Singhal *et al.*,[16] in a study of ^{90}Zr(e,e′), shows the same general agreement already pointed out by Fig. 5. In fact, the values cited by the authors[16] are, respectively, (5.50±0.48), (0.56±0.15), and (1.68±0.29) s.p.u. for the 2^+ levels at 2.18, 3.31, and 3.84 MeV, (25.2±2.9) s.p.u. for the 3^- level at 2.75 MeV, (3.32±0.90) s.p.u. for the 4^+ level at 3.08 MeV, and (8.37±0.47) s.p.u. for the 2.32 MeV 5^- level in ^{90}Zr. Every $G(L)$ of the odd nucleus is smaller or of the order of the corresponding value in ^{90}Zr, except for the $G(2)=22$ W.u. for the transition to the $\frac{1}{2}^+$ level at 1205 keV in ^{91}Zr, which is about a factor of 4 larger than that of any $L=2$ transition in ^{90}Zr.

Direct comparison of the results obtained in the present experiment with information from electromagnetic probes is hampered by the scarcity of data for odd nuclei in general and for ^{91}Zr in particular. In fact, there are in the literature just one directly determined $B(EL)$ value[56] and two sets[57,58] of lifetime measurements, which unfortunately are not accompanied by detailed information on the multipolarities of the transitions. Table III lists, for further consideration, the referred measurements and other spectroscopic information available for those ^{91}Zr states below 3 MeV excitation energy which are appreciably populated in the present experiment and are, on the other hand, observed by one-neutron transfer reactions. Where the information can be confronted the two lifetime measurements are in general agreement and smaller or of the order of the value that would be obtained taking into account the $G(L)$ results of Table I, possibly indicating admixtures of lower multipolarity. The $B(E2)$ value for excitation of the $\frac{1}{2}^+$ level at 1205 keV corresponds to (11±5) W.u. to be confronted with the $G(2)=(22\pm3)$ W.u. obtained in the present work. This transition admits no admixture of lower multipolarity and the $G(E2)=(54\pm19)$ W.u. which corresponds to the Doppler shift attenuation method (DSAM) lifetime of Gill, Gill, and Jones[57] is discrepant with both G values referred to above. However, a recent redetermination[59] of the lifetime of this level by DSAM leads to $\tau=(0.9\pm0.1)$ ps, which transforms to $G(E2)=(15\pm2)$ W.u. Although no clear-cut conclusion can be drawn from the presently available information, there is thus indication that the $G(E2)$ value is lower than the $G(2)$ value extracted by inelastic scattering for the transition to the 1205 keV level.

C. Comparison with other spectroscopic information

As can be seen in Table III, the states $\frac{1}{2}^+$ at 1205 keV, $\frac{3}{2}^+$ at 2043 keV, and $\frac{11}{2}^-$ at 2172 keV, although presenting high cross sections in (d,d′), leading to β_L values at least of the same order as those of the assumed core states, are associated to appreciable single particle behaviors. The values of S_{particle} and S_{hole} in Table III represent for each state the average of the results of three (d,p) and two (p,d) measurements,[8,52,60,61] respectively. The S values of all the other states which are strongly excited by inelastic scattering reveal small parentage with states of single particle or single hole character. On the other hand, several states with appreciable S values, such as the second $\frac{7}{2}^+$ and $\frac{1}{2}^+$ levels at 2201 keV and 2557 keV, respectively, are barely seen in any inelastic scattering experiments.

Estimates were made for the contribution which could

TABLE III. Spectroscopic factors, S_{particle} and S_{hole}, and deformation parameters β_L, for states of ^{91}Zr below 3 MeV excitation energy, detected in the present experiment and intensely populated by one-neutron transfer reactions. Also presented are the available $B(EL)$ and mean lifes τ.

E_{exc} (keV)	j_f^{π} [a]	S_{particle} [b]	S_{hole} [c]	β_L	$B(EL)$ [d] $j_i \rightarrow j_f$ ($e^2\text{fm}^{2L}$)	τ^{e} (ps)	τ^{f} (ps)
0	$\frac{5}{2}^+$	0.95	0.25				
1205	$\frac{1}{2}^+$	0.82	0.01	0.18	90±40	0.25 ±0.09	3.2 ±5.0
1466	$\frac{5}{2}^+$	0.03	0.002	0.081		0.28 ±0.16	0.51 ±0.16
1884	$\frac{7}{2}^+$	0.09		0.101			0.11 ±0.02
2043	$\frac{3}{2}^+$	0.64	0.02	0.099		<0.030	0.016 ±0.002
2134	$\frac{9}{2}^+$		0.07	0.083			0.17 ±0.02
2172	$\frac{11}{2}^-$	0.33		0.162		>8	
2322	$\frac{11}{2}^-$	0.06		0.063			
2358	$(\frac{1}{2})^-$		0.09	0.16			
2813	$(\frac{7}{2})^-$	0.06		0.139			0.023 ±0.004

[a] Reference 38.

[b] Mean values of S(d,p) from Refs. 8, 52, and 60.

[c] Mean values of $S(\text{p,d})/(2j_f+1)$ from Refs. 8 and 61.

[d] Reference 56.

[e] Reference 57.

[f] Reference 58.

be expected from the valence transitions associated to these known single-particle components in the wave functions of the lowest lying positive parity levels, along the lines of Reehal and Sorensen.[62] As already mentioned, pickup data on ^{91}Zr reveal an almost pure $^{90}\text{Zr}(0_1^+)\otimes 2d_{5/2}$ character for the ground state.[11,38] Considering the available spectroscopic information, the first $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states were supposed to consist of a superposition of only two components: a ^{90}Zr core excited to its 2_1^+ state weakly coupled to a $2d_{5/2}$ particle and a ^{90}Zr core in its ground state with the odd particle, respectively, in a $3s_{1/2}$ or $2d_{3/2}$ orbital. The amplitudes of these last components were taken as the square root of the S_{particle} presented in Table III and the single particle transition probabilities were estimated as, respectively,[62] 24 $e^2\text{fm}^4$ and 6.8 $e^2\text{fm}^4$. If the core excitation is given by the measured[16] $B(E2)_{0^+\rightarrow 2^+}=673$ $e^2\text{fm}^4$ for ^{90}Zr, a minimum polarization charge of $2.3e$ would be necessary to explain the $G(2)$ obtained for those transitions in this experiment. This value is well outside what is normally supposed to be reasonable for a neutron in this mass region, even with a restricted shell model basis.[1,3,4] If the $B(2)$ value obtained from inelastic deuteron scattering[12] on ^{90}Zr is to be used, the polarization charge would be still increased. It seems, therefore, that explicit consideration of the valence transition without *ad hoc* enhancement would not reduce the β_2 of the 1205 keV level to a value similar to that of the assumed core state.

Table IV lists for stable nuclei of $A=(90\pm 2)$, the deformation parameters, β_2 and $\beta_{2\text{em}}$, associated to the 2_1^+ levels (or, for odd A nuclei, mean values, corresponding to the low-lying levels reached by $L=2$ transfer) as seen in inelastic scattering of hadrons and by electromagnetic excitation. The inspection of Table IV reveals that, for all the stable nuclei of the region, the β_2 and $\beta_{2\text{em}}$ values differ usually by less than 25% and are at least $\sim$30% smaller than the $\beta_2 \simeq 0.18$ obtained for the transition to the $\frac{1}{2}^+$ state at 1205 keV in ^{91}Zr. In particular, the β_2 associated to the 2_1^+ state of ^{92}Zr is 0.11, which seems to indicate that polarization phenomena are not sufficient to explain the value observed for ^{91}Zr. On the other hand, there exists the possibility of two-step transfer processes

TABLE IV. Deformation parameters β_2 and $\beta_{2\text{em}}$ for the stable nuclei in the interval of $A=(90\pm 2)$, obtained, respectively, by inelastic scattering and Coulomb excitation experiments.

Nucleus	β_2 [a]	$\beta_{2\text{em}}$ [a,b]
^{88}Sr	0.12[c]	0.122[d]
^{89}Y	0.046[e]	0.068[e]
^{90}Zr	0.073[f]	0.094[f]
^{91}Zr	0.098[g]	
^{92}Zr	0.11[h]	0.105[h]
^{92}Mo	0.080[h]	0.114[h]

[a] For the odd A nuclei the average deformation parameter $(\Sigma\beta_2^2)^{1/2}$ for the low-lying states is presented.

[b] Obtained from published $B(E2)$ values.

[c] Reference 63.

[d] Reference 64.

[e] Reference 65, two states considered.

[f] Reference 44.

[g] Five states considered.

[h] Reference 66.

[e.g., ^{91}Zr(d-t-d′)^{91}Zr* and ^{91}Zr(p-d-p′)^{91}Zr* processes] that profit the high spectroscopic factors of the ground and $\frac{1}{2}^+$ states of ^{91}Zr, being responsible[67] for the apparent difficulties. Unfortunately the available CCBA codes[68] are not able, up to now, to handle the manifold possibilities opened up by the $\frac{5}{2}$ ground state spin.

VI. SUMMARY AND CONCLUSIONS

In the present study for the first time levels of ^{91}Zr have been identified, up to an excitation energy of 4.8 MeV, and L values attributed in inelastic scattering of deuterons. The only other inelastic scattering experiment of comparable quality was performed with 20 MeV protons and observed levels up to ~4.5 MeV. The overall agreement is excellent, both experiments fundamentally excite the same levels and lead to compatible values for β_2'. However, although there exists agreement of relative values, the β_3' and β_5' exhibit a systematic difference, when extracted by (d,d′) and low energy (p,p′), which cannot be explained within the usual macroscopic DWBA analysis by uncertainties in the adopted optical model parameters. Similar effects were noted in other mass regions.

Inelastic scattering experiments on ^{91}Zr reveal a clear L selectivity of the transitions, which in conjunction with the extracted β_L values points to a direct relation of the states excited in the odd nucleus with the core states observed in the same excitation energy regions. If the intermingling of core and particle degrees of freedom had been severe no such selectivity would be expected. In this sense it is felt that inelastic scattering is putting into evidence collective aspects of the wave functions of the states excited. On the other hand, although a very simple configuration has been determined for the ground state, no such simplicity persists for the excited states and certainly there is no experimental basis for straight weak coupling arguments. In particular, some of the β_2 values associated to the first positive parity levels, which furthermore are populated with high spectroscopic factors in single particle transfer, are higher than that of the corresponding core state.

The information on electromagnetic excitation of the levels of ^{91}Zr is up to now scanty and accompanied by considerable uncertainties. The lifetime studies report no reliable multipolarity determination, so that a conclusive comparison with the results of the present work is not possible. There is indication, however, that the 1205 keV level is less strongly excited by electromagnetic means than by inelastic scattering of deuterons and protons. This could point to a real difference in the response of the neutron and proton components in the excitation of this state or to some inadequacies of the reaction mechanism assumed. The necessity to include in the analysis excitation of this level by two or more steps, via transfer reactions, making use of the high single particle amplitudes of the initial and final states, is suggested.

ACKNOWLEDGMENTS

The authors are indebted to G. R. Rao for exposing the plates at the University of Pittsburgh, and to B. L. Cohen and E. W. Hamburger for their support and interest in the present project. Helpful discussions with H. Miyake and O. Civitarese are appreciated. This work was partially supported by Fundacão de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and Financiadora de Estudos e Projetos S/A (FINEP).

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