Single particle strengths in ^{103}Ru with the ^{102}Ru(d,p) reaction

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The ^{102}Ru$(d,p)^{103}$Ru reaction was studied at the Pelletron-Enge-spectrograph facility up to 3.5 MeV with the nuclear emulsion technique. In all 73 levels were populated and for 64 of them angular distributions are presented. Through the usual distorted wave Born approximation analysis, transferred l values and the corresponding spectroscopic factors could be attributed with certainty to 31 and doubtfully to ~20 more excitations, several of them new. Most of the one-particle strength is concentrated in the yrast levels, below 0.3 MeV. Only the $l=2$ strength is appreciably fragmented. Even within the extended excitation energy range and with the low detection limit of the present experiment, about half of the expected (d,p) strength remains undetected in ^{103}Ru, in contrast to ^{101}Ru. [S0556-2813(98)00711-0]

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I. INTRODUCTION

Although having been intensely investigated for at least two decades, the chain of ruthenium isotopes, as well as several other nuclei in the $A\sim100$ mass region, still presents challenges for both theoretical and experimental research. The São Paulo Nuclear Spectroscopy Group has been involved in experiments through which detailed information on the single particle and single hole neutron strength distributions for several Ru isotopes was obtained with the use of (d,p) [1,2] and (d,t) [3] reactions, taking advantage of the good energy resolution and low background allowed for by the experimental setup. The results thus obtained, which owe their quality mostly to the nuclear emulsion technique [3] and to the good characteristics of the beam, could definitely assign values of transferred orbital momentum l to several transitions in the isotopes studied and showed, in particular, a rather intense population of low-lying $7/2^-$ levels in ^{101,103}Ru [1,3]. Other features which pointed to singular nuclear structure properties of the $^{99-103}$Ru isotopes also appeared in systematic one-neutron pickup studies [3]: the lowest-lying level, detected for each characteristic l of the valence shell, always concentrates the highest spectroscopic intensity, is populated with an appreciable fraction of the total expected strength, and lies, for the heavier isotopes, mostly below 0.5 MeV. All spherical valence orbitals are thus filling, irrespective of neutron number. No filling systematic is apparent [2,3] and, for each orbital, not much fractionating is observed.

Furthermore, in the ^{104}Ru$(d,t)^{103}$Ru reaction [3] an intense $l=4$ transition, formerly unknown, was observed at 2.2 MeV of excitation, which was tentatively assigned as transferring $j=7/2$ [3]. Although previous ^{102}Ru(d,p) data existed [4,5], none of those studies covered the region above 2 MeV. Also, former work [4,5] did not exhaust the expected ^{102}Ru(d,p) strength, in contrast to what the Nuclear Spectroscopy Group found for ^{100}Ru (d,p) [1] and this could in part be due to lack of detail and/or restricted excitation energy range in the previous studies. The present work was begun mostly to confirm the characteristics of the level at 2.2 MeV, but brought, besides a much greater detail for the already investigated [4,5] range of excitation energy, several important new pieces of spectroscopic information [2], which challenge a theoretical interpretation.

II. EXPERIMENTAL PROCEDURE

The 15.0 MeV deuteron beam of the São Paulo Pelletron accelerator was focused on a uniform target of ^{102}Ru (enriched to 99.35%), after passing defining slits of 1.0 $\times3.0$ mm^2. The target was prepared by electron bombardment evaporation of metallic ruthenium powder onto a thin carbon backing [6]. The thickness of the ruthenium film was about 15 μg/cm^2. The protons produced in the reaction were momentum analyzed by an Enge split-pole spectrograph and detected in nuclear emulsion. Aluminum foils, thick enough to absorb heavier reaction products, covered the emulsion. The protons were observed at ten angles, from $\Theta_{lab}=8°$ to $\Theta_{lab}=55°$, and the exposed plates were scanned, after processing, in strips of 200 μm across the plates. An energy resolution of 11 keV was achieved. The spectrum corresponding to $\Theta_{lab}=45°$ is shown in Fig. 1 and can be regarded as typical of the spectra measured at other angles.

Relative normalization of the spectra was obtained by measuring with a current integrator the total charge collected in an aligned Faraday cup with electron suppression, while continuously monitoring the direction of the beam. Absolute normalization of the cross sections was referred to optical model predictions for elastic scattering of deuterons on the same target, measured under similar conditions. Elastic spec-

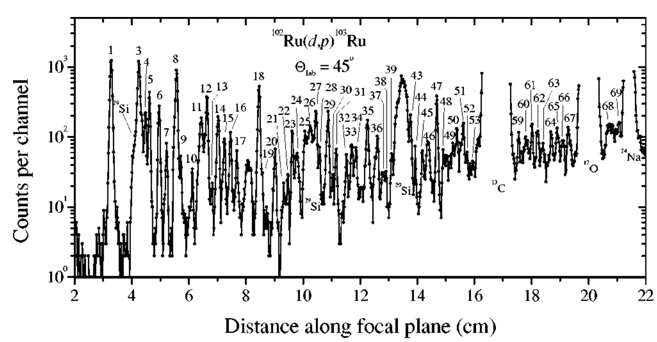

FIG. 1. Spectrum of protons at $\Theta_{lab}=45°$.

TABLE I. Optical potential for the exit and entrance channels and potential which binds the transferred neutron.

Particle	Potential	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W (MeV)	r_w (fm)	a_w (fm)	W_D (MeV)	r_D (fm)	a_D (fm)	V_{s0} (MeV)	r_{s0} (fm)	a_{s0} (fm)	r_c (fm)
Proton	BG [a]	55.17	1.17	0.75	1.48	1.32	0.61	35.19	1.32	0.61	24.80	1.01	0.75	1.25
	PP [b]	50.54	1.25	0.65				54.00	1.25	0.47	30.00	1.25	0.47	1.25
	LH [c]	111.85	1.05	0.86				39.96	1.43	0.78	14.00	0.75	0.50	1.15
Deuteron	PP [b]	96.54	1.15	0.81				72.00	1.34	0.68	14.00	0.75	0.50	1.15
	DA [d]	92.89	1.17	0.74	0.29	1.33	0.86	49.20	1.33	0.86	13.80	1.07	0.66	1.15
Bound neutron	BG [a]	fitted	1.17	0.75							$\lambda=25$			

[a]Reference [16].
[b]Reference [7].
[c]Reference [8].
[d]Reference [9].

tra were obtained at six laboratory scattering angles, from 30° to 80°. Three families of optical potentials, from the systematics of Perey and Perey (PP) [7], Lohr and Haeberli (LH) [8], and Daehnick *et al.* (DCV) [9] (see Table I), produced cross sections which differed, in the mentioned range of angles, by at most 6%. Considering furthermore the contributions of the target nonuniformity, plate scanning, and statistics in the elastic scattering data, a maximum scale uncertainty of 8% is estimated for the absolute cross section.

III. RESULTS

The excitation energies shown in Table II are the averages of the energies which resulted for each level in the several spectra, employing the calibration of the spectrograph in common use, which was obtained through the analysis [10] of the ^{90}Zr(α,α') reaction up to 5.9 MeV of excitation, covering thus a great interval of bending radii. No transitions were considered unless a peak could be discerned at the appropriate location in at least three of the spectra. For the most intense transitions, in particular those associated with levels below $E_{\mathrm{exc}}=1.0$ MeV, the totality of the ten spectra determined the excitation energy values of Table II. The dispersion of the individual values around their mean, as measured through their standard deviations, is typically 2 keV, resulting in statistical uncertainties in the excitation energies of $\leqslant 1$ keV. In addition to these uncertainties a scale uncertainty, to be discussed below, should be considered.

The previous stripping studies [4,5] were limited to a couple of MeV of excitation energy. Their results are shown in Table II in comparison with the present ones and also with the results of the (d,t) work of the São Paulo Group [3] and the adopted levels [11]. The present experiment extended the excitation energy interval analyzed by stripping reactions up to 3.5 MeV. The detection limit below ~ 1.5 MeV is less than 10 μb/sr and somewhat higher above this energy. Fortune *et al.* [4], in their (d,p) study with deuterons of 14 MeV and an energy resolution of 12 keV, declare in most cases total uncertainties of 5 keV in their excitation energies, which are thus in very good agreement with the present results. The work of Berg *et al.* [5] was performed at a high-dispersion spectrograph with deuterons of 45 MeV, a resolution between 8 and 12 keV, and has stated uncertainties of 2–3 keV in the excitation energies, but did not exceed 0.9 MeV of excitation. Berg *et al.* [5] studied both the (p,d) and (d,p) reactions leading to ^{103}Ru, unfortunately with very poor statistics. They argued that the lowest-lying $l=2$ transfer selects in the pickup reaction the known $5/2^+$ first excited state [11], in agreement with the findings of the (d,t) studies of Duarte *et al.* [3]. On the contrary, the stripping data were taken by Berg *et al.* [5] as indicating a preferential population of the $3/2^+$ ground state. If, however, the level labeled 1 in present study was forced to correspond to the excitation energy zero, an average discrepancy of (-3.3 ± 0.2) keV with respect to the excitation energies of the Nuclear Data Sheets (NDS) compilation [11] resulted, for the about 20 strong transitions (up to 2 MeV) for which a clear correspondence with levels reported in γ ray studies [12–14] could be established. This result points to an also preferential population of the first excited state at 2.81 keV [11] in the stripping, as well as in the pickup reactions, in disagreement with the indication of Berg *et al.* [5], which was adopted by the compilation [11]. Niizeki *et al.* [14] in their analysis of ^{103}Ru, following the study of the β^- decay of ^{103}Tc, had already argued in favor of this attribution.

Taking into account, furthermore, the experimental definition of the centroids of the peaks associated with level 1, in the present study an energy value of (3.3 ± 0.7) keV is finally attributed to this level. Inspection of Table II reveals excellent agreement between the level energies here obtained and those measured by γ decay [11]. It may thus be presumed that the excitation energy scale uncertainty associated with the spectrograph calibration in use is rather small. We estimate that below 2.0 MeV the scale uncertainty is $\leqslant 2$ keV and it should not exceed 5 keV below 5.0 MeV of excitation energy.

It is to be noted that with respect to the recent Nuclear Data Sheets compilation [11], in the present study many levels were seen which had not been formerly reported, in particular above 2.2 MeV of excitation. In fact, the present study detected 73 levels, which are to be compared to the 24 ones (up to 2.0 MeV) and 18 ones (up to 0.77 MeV) previously known through the deuteron stripping reactions performed, respectively, by Fortune *et al.* [4] and Berg *et al.* [5].

Figures 2–5 display the experimental angular distributions, for those transitions for which the cross section was

TABLE II. Results of the present work in comparison with former one neutron transfer results and the adopted levels.

	Present work $E_d=15$ MeV				(d,p)[a] $E_d=45$ MeV				(d,p)[b] $E_d=14$ MeV			(d,t)[c] $E_d=16$ MeV				NDS[d]	
Peak	E_{exc} (MeV)	l	j	C^2S'	E_{exc} (MeV)	l	j	C^2S'	E_{exc} (MeV)	l	C^2S'	E_{exc} (MeV)	l	j	C^2S	E_{exc} (MeV)	J^π
																0.000	$3/2^+$
1	0.003	2	5/2	1.35	0.001	2	(3/2)	1.44	0.000	2	1.40	0.002	2	5/2	1.11	0.00281	$5/2^+$
2	0.136	2	5/2	0.012					0.139	(2)	$(\leqslant 0.01)$	0.136	2	5/2	0.072	0.136079	$5/2^+$
3	0.174	0	1/2	0.75	0.176	0	1/2	1.05	0.170	0	0.85	0.174	0	1/2	0.29	0.17426	$1/2^+$
4	0.215	4	7/2	1.80	0.215	4	7/2	1.57	0.213	4	2.35	0.213	4	7/2	2.07	0.21356	$7/2^+$
5	0.240	5	11/2	3.2	0.242	5	11/2	2.35	0.237	5	3.25	0.239	5	11/2	1.47	0.2382	$11/2^-$
6	0.298	3	7/2	0.40	0.299	3	(7/2)	0.26	0.295	(1;3)	(0.17;1.5)	0.297	3	7/2;5/2	0.16;0.22	0.2971	$(7/2^-)$
																0.29748	$(3/2^+)$
7	0.347	2	3/2	0.060	0.350	2	(5/2)	0.05	0.339	(2)	$(\leqslant 0.06)$	0.346	2	5/2;3/2	0.10;0.13	0.34638	$3/2^+$
																0.40415	$7/2^+$
8	0.405	2	5/2;3/2	0.82;0.92	0.405	2	5/2;3/2	0.94;1.1	0.401	2	0.85	0.406	2	5/2;3/2	0.35;0.44	0.40608	$5/2^+;3/2^+$
9	0.433	0	1/2	0.027	0.435	0	1/2	0.08	0.429	0	0.06	0.432	0	1/2	0.070	0.43206	$1/2^+$
10	0.501	2	(5/2)	0.032	0.504	2	(5/2)	0.02	0.499	(2)	$(\leqslant 0.05)$	0.501	2	5/2;3/2	0.17;0.20	0.50115	$(5/2)^+$
					0.535	(2)	(5/2)	0.03	0.541	2	0.14	0.540				0.5354	$(5/2^+;3/2^+)$
		(1)	(3/2)	(0.018)								0.548				0.54821	$(1/2^+)$
11	0.553	0	1/2	0.046					0.551	0	0.06					0.55458	$(1/2^+)$
		2	(5/2)	0.074													
												0.556				0.5577	(9/2)
					0.562	(2)	(3/2)	0.13								0.56287	$(5/2^+;3/2^+)$
																0.56817	$(1/2^+)$
12	0.591	2	(5/2)	0.35	0.593	2	5/2	0.22	0.589	2	0.33	0.592	2	5/2;3/2	0.21;0.25	0.59197	$(5/2)^+$
13	0.624	(2)	(5/2)	(0.009)	0.626	(2)	(5/2)	0.04								0.6220	$(5/2^+)$
																0.6537	$15/2^-$
14	0.660	2	(3/2)	0.251	0.661	2	3/2	0.18	0.658	2	0.24	0.662				0.66155	$(3/2)^+$
15	0.697	4	7/2	0.71	0.697	4	(7/2)	0.37	0.696	4	1.00	0.697				0.6972	$7/2^+;9/2^+$
																0.7352	$(5/2^+)$
16	0.735	0	1/2	0.053	0.736	0	1/2	0.17	0.735	0	0.06	0.737	0	1/2	0.086	0.73689	$1/2^+$
																0.7488	$(5/2^+)$
17	0.771	4	(7/2)	0.30	0.774	(0;2)		(0.1;0.03)									
																0.7741	$(11/2^+)$
												0.775	2	5/2;3/2	0.11;0.13	0.77477	$(5/2^+;3/2)$
												0.855					
																0.87371	$(5/2^+;3/2^+)$
																0.90305	$(\leqslant 5/2^+)$

TABLE II. (*Continued.*)

	Present work E_d=15 MeV				(d,p)[a] E_d=45 MeV				(d,p)[b] E_d=14 MeV			(d,t)[c] E_d=16 MeV				NDS[d]	
Peak	E_{exc} (MeV)	l	j	C^2S'	E_{exc} (MeV)	l	j	C^2S'	E_{exc} (MeV)	l	C^2S'	E_{exc} (MeV)	l	j	C^2S	E_{exc} (MeV)	J^π
18	0.906	2	5/2;3/2	0.47;0.51	0.906	2	3/2	0.52	0.906	2	0.67	0.908	(2)	(5/2;3/2)	(0.050;0.061)	0.90536	$5/2^+;3/2^+$
																0.90764	$(\leqslant 5/2^+)$
																0.9116	$(7/2^+)$
19	0.928	0	1/2	0.008								0.928				0.92724	$(1/2^+;3/2^+)$
																0.9313	(5/2;3/2)
												0.942				0.94050	
																0.9544	(3/2)
																0.9916	
20	1.003	2	5/2;3/2	0.049;0.053					1.005	2	0.09	1.005				1.005	$5/2^+;3/2^+$
																1.0181	(5/2;7/2)
																1.0204	$(13/2^-)$
21	1.057	(4)	(7/2)	(0.17)													
												1.067				1.06514	$3/2^+;5/2^+;7/2^+$
22	1.078	(4)	(9/2;7/2)	(0.09;0.13)								1.080	(4)	(9/2;7/2)	(0.40;0.68)	1.0796	
23	1.105	0	1/2	0.066					1.105	0	0.08					1.1067	$1/2^+$
												1.109	(2)	(5/2;3/2)	(0.024;0.031)	1.1101	$(5/2^+;3/2;1/2)$
																1.1106	$(11/2^+)$
																1.1337	
24	1.138															1.1406	(5/2;3/2)
																1.1713	(1/2;3/2)
																1.17408	(3/2)
25	1.182	2	5/2;3/2	0.039;0.045													
																1.1999	$13/2^+$
26	1.215	2	5/2;3/2	0.031;0.035													
												1.238	2	5/2;3/2	0.050;0.062		
27	1.248	2	5/2;3/2	0.165;0.186					1.245	2	0.26	1.251	2	5/2;3/2	0.036;0.043	1.245	$5/2^+;3/2^+$
28	1.269	(1;2)		(0.010;0.026)												1.2698	
																1.2882	
																1.3015	$(19/2^-)$
																1.3136	$11/2^+$
29	1.322	5	11/2	1.37					1.320	(3;5)	(0.4;1.0)	1.325				1.3244	
												1.338					
30	1.346	$(\leqslant 3)$														1.34712	
31	1.370	(4;5)		(0.29;0.41)													
																1.3784	
												1.403				1.40098	

TABLE II. (*Continued.*)

	Present work $E_d=15$ MeV				(d,p)[a] $E_d=45$ MeV				(d,p)[b] $E_d=14$ MeV			(d,t)[c] $E_d=16$ MeV				NDS[d]	
Peak	E_{exc} (MeV)	l	j	C^2S'	E_{exc} (MeV)	l	j	C^2S'	E_{exc} (MeV)	l	C^2S'	E_{exc} (MeV)	l	j	C^2S	E_{exc} (MeV)	J^π
32	1.430	(2;3)		(0.039;0.047)												1.43112	
																1.4437	$(15/2^+)$
33	1.461	(2;3)		(0.052;0.058)													
																1.4738	
34	1.486											1.491					
35	1.554	(2)	(5/2;3/2)	(0.134;0.153)					1.55	(2)	(0.15)	1.559	2	5/2;3/2	0.026;0.029	1.550	$(5/2^+;3/2^+)$
36	1.604															1.60447	
37	1.642																
38	1.662	(2)	(5/2;3/2)	(0.019;0.021)													
39	1.699																
40	1.717	$(\leqslant 2)$														1.7171	
																1.7304	
41	1.751	(1;2)		(0.011;0.030)													
												1.756	1	3/2;1/2	0.05;0.06		
42	1.780	(2;3)		(0.031;0.043)													
43	1.809	0	1/2	0.081					1.805	(0)	(0.07)					1.8050	$(1/2^+)$
												1.817					
44	1.834															1.83588	
45	1.876	(2;3)		(0.045;0.063)													
																1.88054	
												1.892					
																1.90614	
46	1.910	(1)	(3/2;1/2)	(0.019;0.020)													
												1.916					
47	1.962	2	5/2;3/2	0.253;0.284					1.96	(2)	(0.35)					1.96192	$(5/2^+;3/2^+)$
48	2.004	(1;2)		(0.018;0.040)												2.0037	
												2.022					
49	2.058	(2)	(5/2;3/2)	(0.022;0.026)													
50	2.082	2	5/2;3/2	0.054;0.062													
51	2.118	(2)	(5/2;3/2)	(0.075;0.084)													
																2.1319	$19/2^+$
																2.132	$(23/2^-)$
52	2.137	(2)	(5/2;3/2)	(0.016;0.018)													
53	2.167	4	9/2	0.08								2.167	4	9/2;7/2	1.6;2.7		
54	2.207															2.20611	
												2.217					

TABLE II. (*Continued.*)

	Present work $E_d = 15$ MeV				(d,p)[a] $E_d = 45$ MeV				(d,p)[b] $E_d = 14$ MeV			(d,t)[c] $E_d = 16$ MeV				NDS[d]	
Peak	E_{exc} (MeV)	l	j	C^2S'	E_{exc} (MeV)	l	j	C^2S'	E_{exc} (MeV)	l	C^2S'	E_{exc} (MeV)	l	j	C^2S	E_{exc} (MeV)	J^{π}
55	2.224															2.2236	
												2.232					
56	2.248																
57	2.280																
												2.299	1	3/2;1/2	0.04;0.05		
												2.384	1	3/2;1/2	0.07;0.08		
58	2.405																
59	2.436																
60	2.489	(≤2)															
												2.507	1	3/2;1/2	0.013;0.018		
61	2.515	0	1/2	0.033								2.520					
62	2.548	1	3/2;1/2	0.033;0.034													
63	2.578															2.57620	
64	2.627	2	5/2;3/2	0.044;0.050													
65	2.657																
																2.680	$(23/2^+)$
66	2.694																
67	2.723																
68	2.960																
69	3.015	(0;1)		(0.037;0.025)													
70	3.062																
																3.080	$(27/2^-)$
71	3.204																
72	3.325																
73	3.512																

[a]Reference [5].
[b]Reference [4].
[c]Reference [3].
[d]Reference [11].

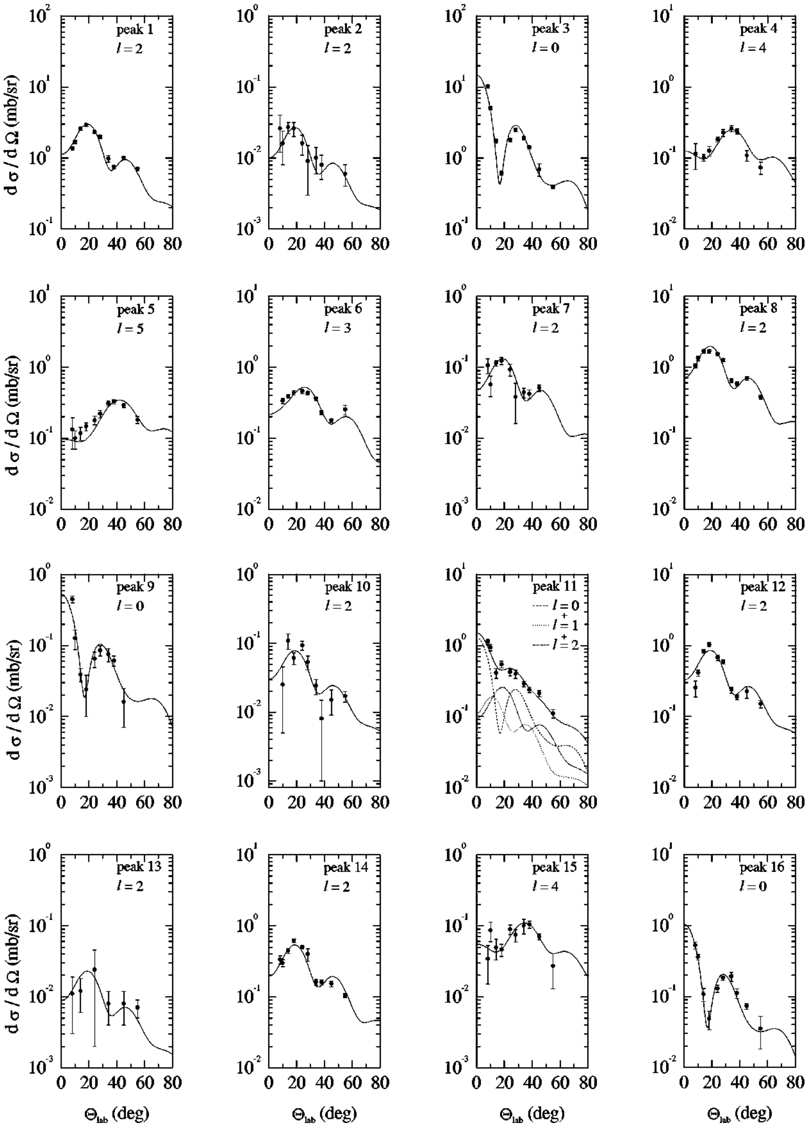

FIG. 2. Angular distributions for ^{102}Ru$(d,p)^{103}$Ru in comparison with DWBA predictions. The uncertainty bars represent contributions of statistics, plate scanning, and background (and/or contaminant) subtraction and do not include any error in the absolute cross section scale. The levels are sequentially labeled and the corresponding energies are shown in Table II.

measured at, at least, five angles. The uncertainty bars include contributions of statistical deviations and uncertainties due to plate scanning, background subtraction, and relative normalization.

The angular distributions were compared with predictions of distorted wave Born approximation (DWBA) calculations, with corrections to include finite range and nonlocality effects, performed by means of the code DWUCK4 [15]. The correction parameters for finite range and nonlocality employed were $R_{\rm FR}=0.62$ fm, $\beta_d=0.54$ fm, $\beta_p=0.85$ fm. The optical model parameters for the entrance and exit channels were taken from the analysis of Perey and Perey [7] for deuteron scattering, with the addition of a spin-orbit term suggested by Lohr and Haeberli [8], and from the analysis of Becchetti and Greenlees [16] for proton scattering. The captured neutron was assumed to be bound by a real potential well of Woods-Saxon shape plus a spin-orbit term of the usual Thomas form. The parameters used are presented in Table I, under the labels PP and BG. Except for the $1g_{9/2}$, $3p$, and $2f$ orbits, the neutron single particle orbitals taken were those of the 50–82 shell.

Least squares fits of the DWBA results to the experimental angular distributions are shown in Figs. 2–5, whenever an assignment of transferred angular momentum l was attempted. The reduced spectroscopic intensities $C^2S'_{lj}$ were extracted through the relationship

$$\sigma_{\rm expt}(\theta)=1.55\ \ C^2S'_{lj}\frac{\sigma^{\rm DW}_{lj}(\theta)}{2j+1}.$$

The values obtained for l and $C^2S'_{lj}$ are also shown in Table II. If different global prescriptions for the optical model parameters are used in the entrance [7–9] and exit [7,16] channels, a maximum variation of $\pm 15\%$ in the reduced spectroscopic factors occurs, while the shapes of the angular distributions are practically not changed.

Where comparison is possible, general agreement is found between the results of the present and former (d,p) works [4,5]. Specific comments on the experimental results are made in the following.

The region around 0.55 MeV of excitation in ^{103}Ru is recognized [11] as spectroscopically complex. In fact, the Nuclear Data compilation [11] presents six levels between 535.4 and 568.17 keV, at least two of which have inconsistent spin attributions in the different experiments. The peaks

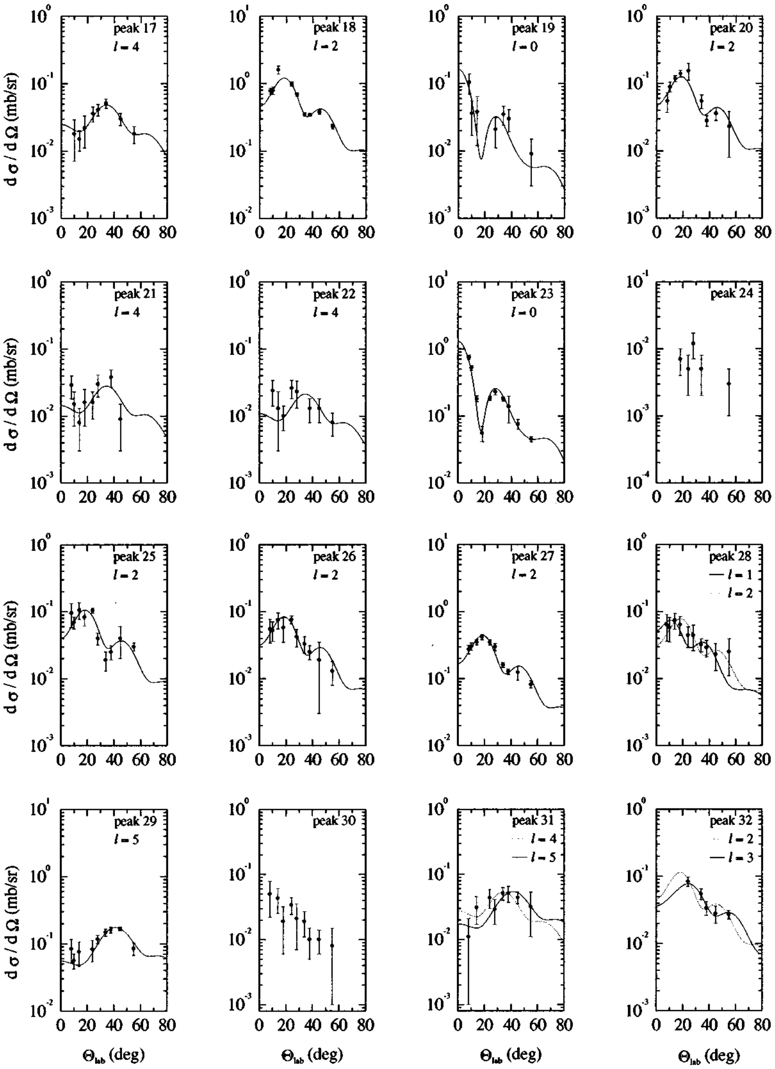

FIG. 3. Angular distributions for ^{102}Ru$(d,p)^{103}$Ru (see Fig. 2).

associated in the present experiment with level 11, in the several spectra, are at least doublets and most probably triplets. A tail is clearly seen in the higher-energy region, but the peaks are, in most spectra, also broader in the lower-energy portion. The integrated angular distribution, which is shown in Fig. 2, reveals, at the two most forward angles, a predominant $l=0$ contribution, at 552 keV of excitation energy. The spectrum at the minimum for $l=0$ ($\Theta_{\mathrm{lab}}=18°$), however, showed that admixtures of higher l are also present, but no unambiguous excitation energy attribution could be made. A good fit to the integrated angular distribution, consistent with the information contained in the spectra, was achieved through a superposition of $l=1$, $l=0$, and $l=2$ transfers (see Fig. 2). It is even possible that a fourth level contributes somewhat to the integrated cross section. In the former (d,t) work [3] three peaks were seen, the lower one at 540 keV being much weaker than the other two. Reanalysis of the published integrated angular distribution (see Fig. 6) showed these higher-lying two peaks to possibly correspond to $l=1$ and $l=4$ components, predominating in that reaction, with a smaller contribution of $l=0$ or perhaps $l=2$. The $l=0$ would correspond to the 554.58 keV $(1/2^+)$ level, integrated into these other two. If $l=2$ should be considered instead, its contribution exceeds what could correspond to the intensity at 540 keV. The information available in the literature for this region is conflicting. To begin with, the weakly excited level at 535 keV was reported only by the (d,p) study of Berg *et al.* [5], was not identified in their published spectra, and is incompatible with the present findings. The 541 keV level was separated by Fortune *et al.* [4] from their predominant $l=0$ excitation at 551 keV through a peak-shape fitting procedure. The present study rules an $l=2$ excitation with the spectroscopic intensity proposed by Fortune *et al.* [4] at as low an energy as 541 keV completely out. Of the three levels identified in this region as $(1/2^+)$ by the compilation [11], the lowest one, at 548.21 keV, has had formerly an attributed spin and parity of $(5/2)^-$ in the (n,γ) study [17] and in the older $(\alpha,n\gamma)$ one [13]. The (n,γ) work [17] based its attribution on the $E2+M1$ character determined for the γ transition to the 297.3 keV state, which in turn, as stated by the authors, decays by an $(E1+M2)$ transition to the $5/2_1^+$ level. The $J^\pi=(5/2)^-$ value would be consistent with the $7/2^-$ character for the intermediate state, but $J^\pi=3/2^-$ could possibly also accomodate the experimental information, and would then correspond to the $l=1$ excitation seen in (d,p) and (d,t). The 548.21 keV level is not seen in β^- decay. On the other hand, the adopted level at 554.58 keV, seen in β^- decay [14] and (n,γ) [17] which has by both attributed $(1/2^+)$, is most probably to be associated

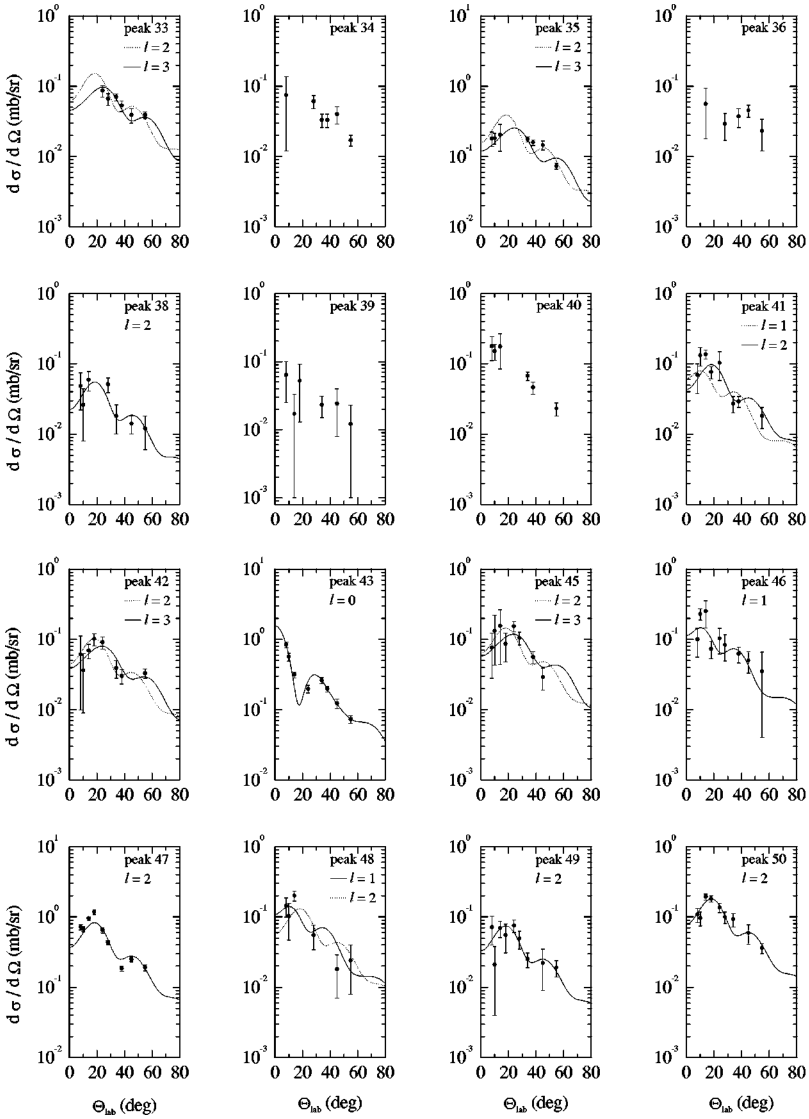

FIG. 4. Angular distributions for ^{102}Ru$(d,p)^{103}$Ru (see Fig. 2).

with the predominant $l=0$ component located by the present work at 552 keV and at 551 keV by Fortune *et al.* [4]. The $(\alpha,n\gamma)$ works [13,18] defined a (9/2) level at 557.7 keV, not seen in the other γ ray studies, and this probably corresponds to the $l=4$ component seen in (d,t). Finally, all γ works locate a level at $\sim$563 keV with possibly $(3/2^+,5/2^+)$ characteristics, but present differing decay modes for it. This level, if excited, should appear as integrated into the peak labeled 11, being seen as a tail. This tail could also contain a contribution to the 568.17 keV level seen in (n,γ) and $(\alpha,n\gamma)$. This last level is now assumed to have $J^\pi=(1/2^+)$ [11], but had, in the older γ works, $(3/2,5/2,7/2)^-$ attributed to it [13]. The $l=(2)$ level located by Berg *et al.* [5] at 562 keV, and for which no angular distribution was shown, cannot correspond to the present result, in view of its high spectroscopic strength.

Peak 17 was detected at eight angles, the corresponding excitation energy of 770.9 keV presents a standard deviation of only 1.6 keV, and the angular distribution displays a clear $l=4$ transfer pattern. On the other hand, the ^{104}Ru(d,t) reaction had previously populated [3] an $l=2$ excitation at 775 keV, which was associated with the adopted [11] 774.77 keV $(5/2^+,3/2)$ excitation formerly seen in the (n,γ) [17]. Considering also the energy difference of 4 keV, the complementary transfer reactions are almost certainly exciting different states in this energy region. The angular distribution at 774 keV associated by Berg *et al.* [5] with a superposition of $l=0+2$ could, in fact, be interpreted as due to $l=4$.

Peaks 21, 25, and 26 are new results of this work and lie below the detection limit stated by Fortune *et al.* [4]. Peak 35, contaminated at intermediate angles, shows an angular distribution which is consistent with the former $l=2$ attributions [3,4] and will be considered as sure in the computation of the total strength. It is worth noting that the corresponding level energy of 1550(10) keV, adopted by Ref. [11], is based only on the former (d,p) work by Fortune *et al.* [4], being thus in accordance with the other transfer results. New $l=2$ and $l=0$ excitations were also seen above 2.0 MeV (levels 50, 64, and 61).

Table II shows that the values of the reduced spectroscopic factors are in good agreement with those published by Fortune *et al.* [4], in general even better than if those were affected by the estimated uncertainty of 50%, declared by the authors. An exception is the level number 6, where the discrepancy, considering their tentative $l=3$ attribution, amounts to a factor of 4. However, even in this case, the spectroscopic strengths extracted in both studies turned out compatible in reanalyzing the data of Fortune *et al.* [4] under

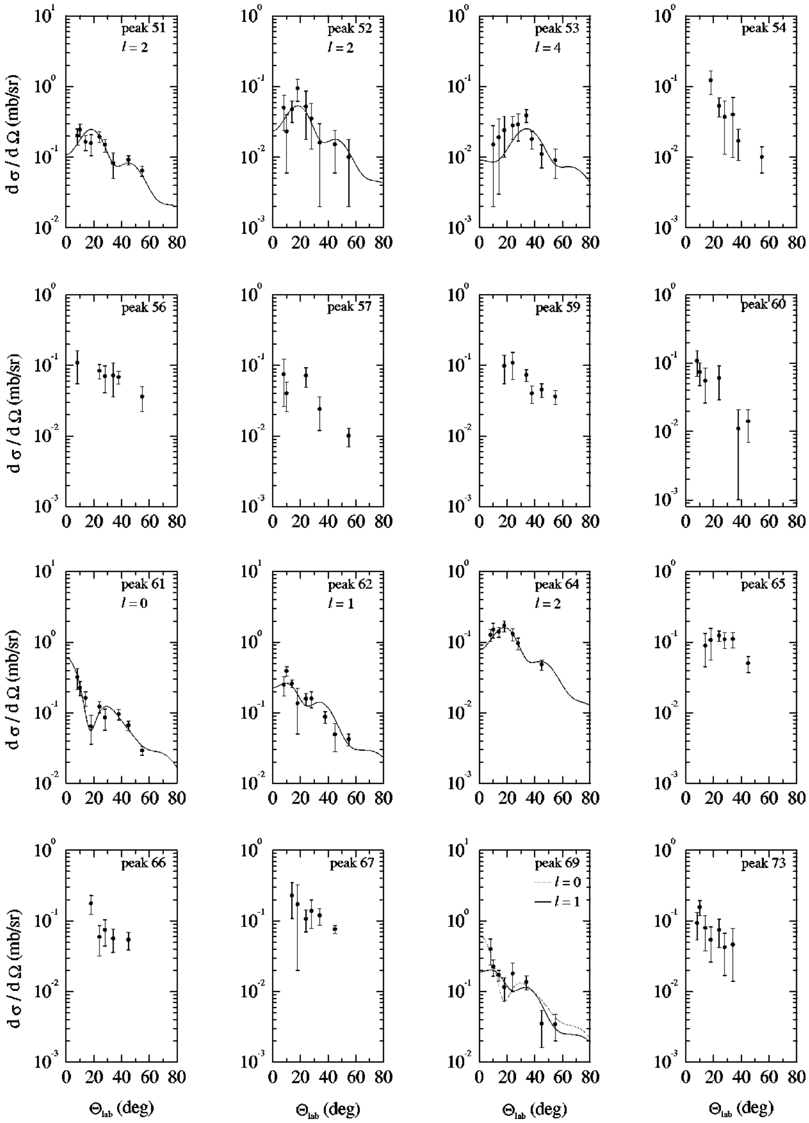

FIG. 5. Angular distribution for ^{102}Ru$(d,p)^{103}$Ru (see Fig. 2).

the assumption, which is here preferred, which considers this transition associated with the $2f_{7/2}$ orbital, of the next shell and not with the $1f_{7/2}$ one. The spectroscopic factors of Berg *et al.* [5] are, considering their declared uncertainty of 30%, in agreement with the present ones, with an exception made to the $l=0$ excitations, mainly those at 435 and 736 keV. The inspection of the corresponding experimental angular distributions reveals a poor fit by the DWBA predictions, particularly in the region of the first valley, indicating possible problems of background or contaminant subtractions in their analysis.

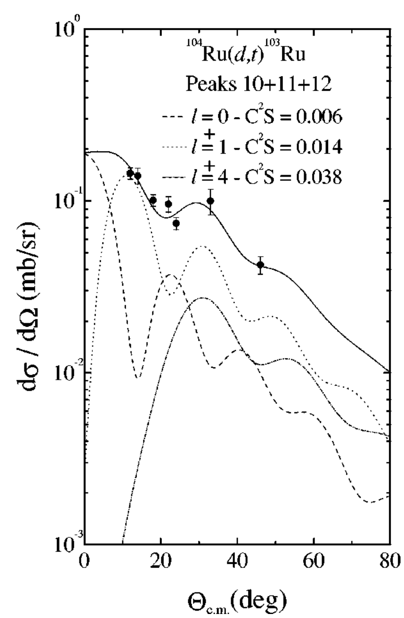

FIG. 6. Integrated angular distribution corresponding to peaks 10+11+12 of Ref. [3], detected in ^{104}Ru(d,t), respectively, at 540, 548, and 556 keV. The extracted spectroscopic intensity for each component is presented.

IV. DISCUSSION

A. Comparison with results from gamma ray studies

Besides having been extensively studied by one-neutron transfer reactions, ^{103}Ru has formerly been observed in a series of other reactions through the detection of γ rays. These results form the basis for most of the adopted levels [11] shown in Table II; therefore, the information is briefly discussed.

Of the 19 levels seen, below 1.1 MeV, in the β^- decay of the $5/2^+$ ground state of ^{103}Tc [14] to ^{103}Ru, only the 404.4

keV level and the 562.9 keV one, besides the ground state, could not be discerned in the present study or in the previous (d,t) one [3]. The neutron capture reaction on ^{102}Ru [17] reports 47 levels below 2.6 MeV in ^{103}Ru. With exceptions made to the ground state, the difficult region around 0.55 MeV and the triplet of levels at $\sim$0.91 MeV (seen as one in the present work), only three further levels [at 991.6, 1174.08, and 1730.4 keV, all adopted [11] exclusively with basis on the ^{102}Ru (n,γ) results] were not detected in transfer. The γ decay following the neutron capture populates preferentially the $3/2^+$ ^{103}Ru ground state.

In contrast to the former γ ray studies, and in part due to the possibility of a higher angular momentum transfer in this reaction, ^{100}Mo$(\alpha,n\gamma)$ [13,18] populates several levels in ^{103}Ru, below its detection limit at 2.1 MeV, which are not observed in one-neutron transfer. Thus, of the 45 levels attributed to this reaction by the Nuclear Data compilation in their summary [11], even excluding the complex region around 0.55 MeV, 22 levels are not populated in any of the transfer reactions. Several of these have tentative spin attributions which make them, in principle, accessible to one-neutron transfer. In particular, in the excitation energy region above 0.91 MeV there are about ten levels, which have only been seen in the most recent [18] of the two ^{100}Mo$(\alpha,n\gamma)$ studies. Some of them, as the 911.6 and 931.3 keV levels, could be smaller components integrated into neighboring excitations, but several of them would be isolated states and are, if existent, weakly excited in transfer.

Therefore, in contrast to what was determined under similar experimental conditions for ^{99,101}Ru [3], several adopted levels [11] in the low-excitation-energy region were not seen either in (d,p) or (d,t). The most intriguing situation refers to levels which might be associated with $(3/2^+,5/2^+)$: altogether 24 such levels are reported below 1.11 MeV by Ref. [11], but only about half are observed in transfer, in spite of the low detection limit of the present study. The situation is different for the two lighter Ru isotopes investigated. All eight states which in this energy region have attributed spin parity $(3/2^+,5/2^+)$ in ^{99}Ru were detected in (d,t) [3], and of the 11 levels of this type existent in ^{101}Ru below 1.11 MeV, only one was not seen in transfer [3]. These findings can mean either that ^{103}Ru really presents a considerably more complex structure than ^{99,101}Ru or that the γ ray studies were able to reveal more detail for this nucleus.

B. One-neutron particle strength distributions

To complement the information already presented in a previous Brief Report [2], Fig. 7 displays additional results obtained in ^{102}Ru(d,p), for $l=1$ and $l=3$ transfers, which lie outside the $N=50$–82 valence space and were not formerly shown. Logarithmic scales are employed for the spectroscopic strengths, $G_{\rm strip}=C^2S'$, and the $l=0$, $l=2$, $l=4$, and $l=5$ data are again displayed, this time showing only those states where the l attribution is certain.

When the level spin J is not known, the valence orbital j was taken in computing the strength. For $l=2$, if the level had not been attributed $3/2^+$, $j=5/2$ was arbitrarily assumed, giving for those levels, where this assumption should prove incorrect, a somewhat subestimated strength. For $l=1$ and $l=3$ transfers, in computing $G_{\rm strip}$, respectively, the $3p_{3/2}$ and the $2f_{7/2}$ orbitals were supposed.

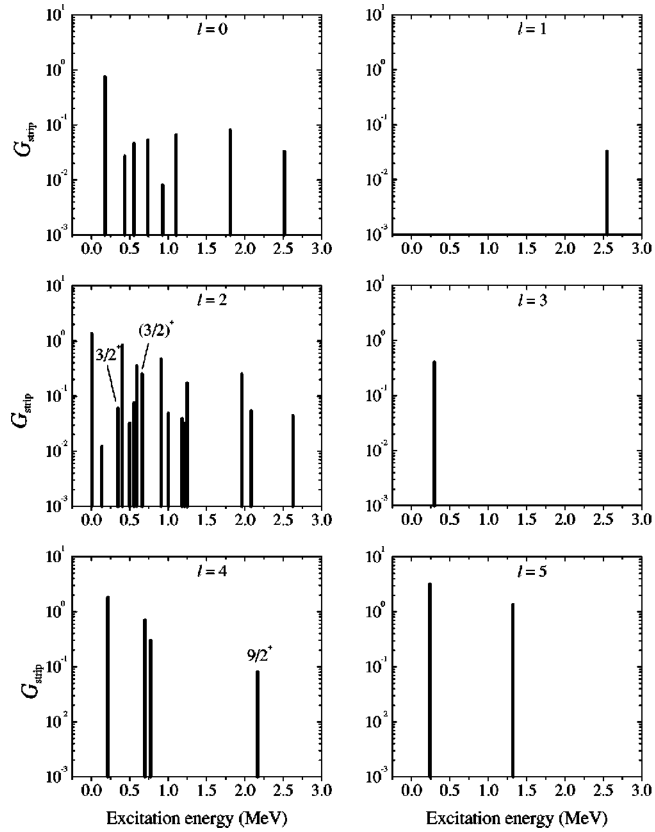

FIG. 7. One-neutron particle strength distributions for ^{103}Ru.

Most of the levels strongly excited in stripping are also excited in pickup [3], as may be seen with the help of Table II. In particular, both reactions populate, contrary to previous assumptions [5], preferentially the first excited $5/2^+$ state in ^{103}Ru and not the ground state. The state at 2.167 MeV, reached by an $l=4$ transfer, which in part motivated the present study, was, on the other hand, shown to be very little excited through (d,p), displaying therefore a strong hole characteristic and pointing on simple lines to a parentage to the $1g_{9/2}$ orbital. The high value of $C^2S=1.6$ thus determined for this state through the ^{104}Ru(d,t) results is remarkable, since this orbital belongs to the ''closed'' $N=50$ core. In comparing ^{103}Ru with ^{101}Ru, no such state is seen in the lighter isotope.

In contrast to what is verified for the majority of the other levels, most of the states associated with $l=1$ transitions, being thus states outside the valence shell, which were detected in ^{104}Ru(d,t) were not seen in the present study (see Table II). These weakly populated states are spread over a wide excitation energy range and the associated hole strength, given by the (d,t) results [3], is larger than the particle one, seen in this work, considering only the sure attributions. This fact is taken as indicative that most of the $l=1$ hole spectroscopic strengths formerly detected may be possibly associated with core excitations of the $2p$ orbitals and should perhaps have their strengths revised, while the states reached by $l=1$ in the present work could be the particle ones, pertaining to the $3p$ orbitals of the next shell. Only the lower-lying state of the two reached by $l=5$ in the (d,p) reaction was also characterized in (d,t), as seen

TABLE III. Strength distribution for ^{100,102}Ru.

Isotope	Orbital	$\Sigma G_{\rm strip}$	$\Sigma G_{\rm pick}$	$\Sigma G_{\rm strip}+\Sigma G_{\rm pick}$	$2j+1$
^{100}Ru	$3s_{1/2}$	1.48	0.29	1.77	2
	$2d_{5/2}+2d_{3/2}$	5.95	2.30	8.25	10
	$1g_{7/2}$	5.6	1.8	7.4	8
	$1h_{11/2}$	9.5	0.6	10.1	12
	Total	22.5	5.0	27.5	32
^{102}Ru	$3s_{1/2}$	1.06	0.49	1.55	2
	$2d_{5/2}+2d_{3/2}$	4.19	3.36	7.55	10
	$1g_{7/2}$	2.8	2.3	5.1	8
	$1h_{11/2}$	4.6	1.2	5.8	12
	Total	12.6	7.4	20.0	32

through Table II, but it has to be remembered that the detection limit for $l=5$ is higher than for the lower l values, in both reactions.

Figure 7 demonstrates that, for both $l=0$ and $l=2$ transfers, the values for the spectroscopic factors determined in the present experiment vary over two orders of magnitude. Only the $l=2$ strength is appreciably fractionated. If uncertain $l=(2)$ attributions were considered, somewhat more strength could be added. However, besides the levels at 1554 keV, already commented on, and the one at 2118 keV, each of the other ones would correspond to values of C^2S' ≤ 0.05. Several levels were excited through $l=0$, but with about an order of magnitude smaller spectroscopic factors than the yrast one. The doubtful $l=(0)$ strength is very small. In addition to the very-low-lying $l=3$ excitation, there could be some more $l=(3)$ strength in the energy range around 1.5 MeV, but corresponding each to an order of magnitude smaller value of C^2S' than that relatively strong transition. Three certain $l=4$ excitations, which are probably associated with the $1g_{7/2}$ orbital, are seen below 1 MeV of excitation. Only three other of the states detected could be $l=(4)$, all weaker than the certain ones. The detection limit for $l=4$ transfer in the present study is estimated to lie below $C^2S'=0.1$ and to be about $C^2S'=0.2$, for $l=5$. Only one more state, at 1370 keV, could doubtfully be $l=(5)$, it then being weaker by almost an order of magnitude than the strongest excitation.

C. Total spectroscopic strengths

Another way of employing the data for spectroscopic purposes is to extract information on shell model vacancy in the ground state of the even Ru nucleus from which the reaction starts. Table III shows the summed spectroscopic strengths which could be associated, without doubt, with each l transferred in reactions which start from the ground states of the nuclei ^{100,102}Ru. As discussed in Sec. IV B, adding the strength corresponding to transitions with doubtful l attribution would not alter significantly the picture. Occupancy data ($\Sigma G_{\rm pick}=\Sigma C^2S$) extracted from the analysis of ^{100,102}Ru$(d,t)^{99,101}$Ru reactions by Duarte *et al.* [3] and vacancy information ($\Sigma G_{\rm strip}=\Sigma C^2S'$) from ^{100}Ru$(d,p)^{101}$Ru [1] are employed to complement the results of the present work. According to the previous discussion, the contribution of the $l=4$ transition to the state at 2.167 MeV for ^{102}Ru(d,p) was not considered in the vacancy value computed for $1g_{7/2}$ and, similarly in the occupancy, the strength to the known ^{101}Ru $9/2^+$ level at 0.719 MeV [3] was not included. Vacancy plus occupancy for each orbital is shown in column 4, and should be compared with the limit $(2j+1)$ or, for $l=2$, to the sum of the limits for $2d_{5/2}$ and $2d_{3/2}$. Therefore, in ^{102}Ru, experimentaly only 78%, 76%, 64%, and 48% of the expected total strength associated with the 50–82 shell was detected, respectively, for $l=0$, $l=2$, $l=4$, and $l=5$. Lines 6 and 12 of Table III inform the summed strength detected in (d,p) and (d,t) and the total experimental strength associated with the shell model orbitals of the $N=50$–82 shell. For this shell an upper limit of 32 for the total strength is expected, while $\Sigma G_{\rm pick}$ should, for ^{100,102}Ru, correspond, respectively, to 6.0 and 8.0 at maximum, under the assumption of a $N=50$ closed core. It may be appreciated that both (d,t) reactions located at least 83% of the expected neutron particles in the ^{100,102}Ru ground states, although spread among all available orbitals and with no apparent systematics in the filling pattern. Since the ^{100}Ru$(d,t)^{99}$Ru reaction was only able to study the region below $E_{\rm exc}=1.2$ MeV, due to its relatively low Q value and the consequent contamination with inelastic scattering [3], a loss of $\sim 17\%$ in strength is of no concern. In contrast, even with this possible loss, in ^{100}Ru, the total sum $\Sigma(G_{\rm pick}+G_{\rm strip})_{\rm valence}$ exhausts 86% of the expectation, while, in ^{102}Ru, only 62% of the total expected strength was seen. This is due to the very low value of $\Sigma G_{\rm strip}$ for ^{102}Ru, corresponding to a little more than half of the expectation. The already commented characteristics of our experimental method rule out the possibility of an appreciable part of (d,p) strengths being simply lost below 3.5 MeV. It is to be stressed that the ^{104}Ru(d,t) reaction [3] which also leads to ^{103}Ru, previously studied, leaves 37% of the valence strength outside the first 2.5 MeV of excitation (considering the $l=4$ excitation at 2.2 MeV associated with the $1g_{9/2}$ orbital, as seems now probable). This lack of intensity is taken as evidence that it is difficult to form the odd neutron ^{103}Ru nucleus starting from the ground states of the neighboring even-even isotopes.

D. Systematics of the spectroscopic information

As already put forward in previous publications of the Nuclear Spectroscopy Group [2,3], one-neutron transfer reactions which lead to the odd Ru isotopes show several peculiar characteristics: the strength is, for each of the valence shell orbitals, heavily concentrated in the lowest state, exception being made to the $2d_{3/2}$; the strength is widely spread among all valence orbitals; and for ^{103,105}Ru the $3/2^+$ ground states have small overlap with the ground states of their neighboring even-even isotopes [2]. Besides, similar $3/2^+$ levels exist in other Ru nuclei and in their isotones [2]. In spite of several available theoretical interpretations which at first sight seem conclusive, the chain of Ru isotopes has for a long time defied a consistent description. In fact, on closer inspection, it is verified that Whisnant *et al.* [19] had to take the collectivity of the even ^{98}Ru core as almost half of what is experimentally verified, besides employing the variable moment of inertia (VMI) approach in their apparently very

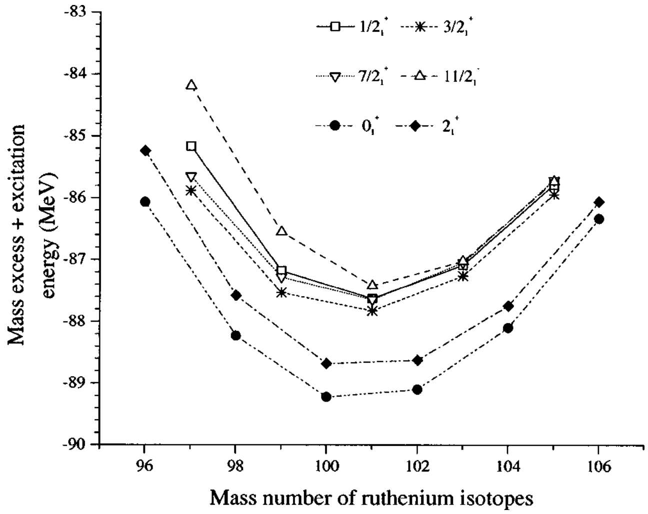

FIG. 8. Yrast levels of Ru isotopes on an absolute scale. The information was always taken from the most recent Nuclear Data Sheets compilation, except for the $1/2_1^+$ level of ^{99}Ru where the (d,t) result [3] was preferred.

complete interpretation of ^{99}Ru within a particle-symmetric-rotor model with Coriolis coupling. Within a similar model, Imanishi *et al.* [20] for ^{101,103}Ru and Rekstad [21] for ^{103}Ru had also to resort to such decreased collectivity of the cores, producing furthermore for the isotope here studied considerably discrepant results. A further difficulty verified in the cited model predictions is that they are unable to put negative and positive parity states on the same absolute energy scale. Interacting boson-fermion model (IBMF) calculations that consider neutron and proton degrees separately seem to do better [22,23], but a definite evaluation of their success must wait for more systematic interpretations.

From an experimental point of view, it is interesting to compare levels with similar characteristics in this mass region. Such systematics has been presented in a previous Brief Report [2]. Here, Fig. 8 completes the analysis showing some of the there highlighted levels of the odd Ru isotopes on the same absolute energy scale as the ground states and the lowest quadrupolar excitations of their even-even cores, taking into account the experimental mass excesses.

The mass ''parabola'' shows ^{101}Ru to be the tightest bound odd isotope and, in general, displays the regularity of the evolution. In particular, the $11/2_1^-$ level (and the $7/2_1^-$ accompanying [2] one) grossly follows the average values of the neighboring cores, but clearly comes down in energy, even on an absolute scale. In contrast, the $3/2^+$ and $7/2^+$ yrast levels follow in detail the behavior of the mean energies of the ground states of the neighboring even isotopes. On this absolute energy scale the yrast $5/2^+$ levels lie very close to the $3/2^+$ ones: at most 0.19 MeV below (^{97}Ru) and at most 0.03 MeV above (^{105}Ru).

The $3/2_1^+$ state merited special attention in the previous publication [2]. It has a small overlap with the ground states of its even-even neighbors and is either the proper ground state or lies very low in energy in the odd neutron nuclei in this mass region [2]. The addition of neutron pairs little affects the $3/2_1^+$ state, as Fig. 8 indicates. The same is true for proton pairs [2] unless very close to the ^{96}Zr or Sn cores, which have been since long detached for their semimagic character. On the other hand, the evolutionary behaviors of the excitation energies of the $1/2_1^+$ and $11/2_1^-$ levels in the isotones [2] clearly demonstrate that structure changes occur as protons are added beyond $Z=38$, even if the neutron number is maintained the same.

A survey of the Nuclear Data compilations shows that for odd neutron nuclei in the $A\sim 80$ region a low-lying $7/2^+$ level (which is the ground state of some nuclei, in particular ^{81}Kr, ^{79}Se, and possibly ^{83}Sr) is observed, it also being weakly populated in one-neutron transfer reactions. This state, sometimes called an anomalous coupling state, was by some authors taken as resulting from a $(1g_{9/2})^3$ configuration. In analogy, a $(2d_{5/2})^3$ coupling to $3/2^+$ could be invoked for the yrast state of this spin and parity in the $A\sim 100$ mass region and explain its small population in one-neutron transfer. The puzzling ingredient in such assumptions is that most $(j)^n$ states may not be quantitatively explained by the usually taken pairing interaction energy. An important long-range interaction must be added to an empirical effective interaction [24] and, in fact for $j\geqslant 5/2$, the state with a resulting spin of $J=j-1$ is sufficiently lowered. As stated by Bohr and Mottelson [25], an alternative interpretation could be given in terms of a coupling to quadrupole deformations, either dynamical or statical. For this interpretation drawbacks also exist, as far as the $3/2_1^+$ levels follow the trend of the 0_1^+ states and not of the 2_1^+ ones and the γ decay pattern in the odd nuclei is not typical of collective excitations. The $3/2_1^+$ level is, in particular in ^{103}Ru, linked mostly to other $(3/2^+,5/2^+)$ states which are also weakly excited in transfer, such as the $5/2_2^+$ level at 136.079 keV, the $3/2_2^+$ one at 346.38 keV, and the 562.87 keV $(5/2^+,3/2^+)$ one [11]. Those levels are, incidentally, the most populated ones, besides the ground state, in the β^- decay to ^{103}Ru [14], starting from the $5/2^+$ ground state of ^{103}Tc (which, for $Z=43$, is not a valence shell single proton state). In general, two sets of levels, intraconnected by preferential γ decay, may be discerned in ^{103}Ru, the first one being related to the $3/2_1^+$ and the $5/2_2^+$ levels, while the second one connects with the $5/2^+$ first excited state. Most levels also strongly populated in the one-neutron transfer reactions, as the $7/2_1^+$ at 213.56 keV, the $(7/2_1^-)$ at 297.1 keV, and the 406.08 keV $(5/2^+,3/2^+)$ belong to the second set, while the $1/2_1^+$ state at 174.26 keV, although strongly excited in (d,p), is clearly more akin to the first set, whose levels are, in general, weakly seen in the transfer studies. It is significant that the $5/2_2^+$ and $3/2_2^+$ states which pertain to the here so-called first set of levels could not be explained by the particle-rotor interpretation of ^{103}Ru [21].

V. CONCLUSIONS

This section summarizes the principal conclusions which were drawn in this study and also refers to several results from previous works of the Nuclear Spectroscopy Group on $^{99-103}$Ru. It was shown that in ^{102}Ru(d,p), the ^{103}Ru ground state is weakly or not populated and, therefore, has a small similarity with ^{102}Ru in its ground state coupled to a single neutron. The complementary ^{104}Ru(d,t) reaction had already shown that, in an analogous manner, little overlap exists between the ground state of this odd isotope and that of

^{104}Ru and a neutron hole. If data collected through gamma ray studies are also taken into account, it seems that in ^{103}Ru two sets of levels may be distinguished: one with states akin to the 3/2$^+$ ground state and populated in β^- decay from the 5/2$^+$ ground state of ^{103}Tc; and the other akin to the first excited 5/2$^+$ level and populated in one-neutron transfer. The $1/2_1^+$ level is an exception to this statement. In all, 73 levels were populated below 3.5 MeV in ^{102}Ru(d,p) and for 64 of them an angular distribution was presented. For 31 states a transferred l value could be attributed with certainty and, for some 20 others, either a doubtful value or limits were imposed. Several l identifications are new in the literature, it being remarkable that at least five of them are sure attributions above 2 MeV. The $l=4$ excitation at 2167 keV was associated with the $1g_{9/2}$ orbital. It was shown that most of the strength is concentrated in few states, only the $l=2$ strength being appreciably fragmented. At this level of experimental detail, it is possible to argue that, up to the experimental limit in excitation energy, a considerable fraction of spectroscopic strength is lacking, in a similar but even more impressive way than was determined for ^{104}Ru(d,t). All these observations may point to coexistence phenomena at low excitation in ^{103}Ru, so that one set of levels is not built on the ground states of the even neighbors. On the other hand, for each transferred l value, it is always the state detected at lowest energy which concentrates the largest fraction of the spectroscopic strength, in a manner which also characterizes the lighter odd Ru isotopes. The behavior of these yrast levels can be followed along the isotopic chain and presents several systematic features. The now well-documented strong and low-lying $l=3$ excitation fits into the overall picture established through the study of the other odd Ru nuclei. Finally, it may be said that ^{101,103}Ru are now experimentally well known.

From a theoretical point of view, on the other hand, there seem to be still some ingredients lacking in the available theoretical interpretations of the $A\sim100$ region. In particular, it is clear that only a part of the spectrum of the odd nuclei will be explained, if calculations which start from the neighboring even nuclei adding one single quasiparticle are performed. The greatest difficulties are probably to be expected for ^{103,105}Ru.

ACKNOWLEDGMENTS

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