Level structure of ^{101}Ru from the ^{100}Ru(d,p) reaction

J. L. M. Duarte, L. B. Horodynski-Matsushigue, T. Borello-Lewin, and O. Dietzsch
Instituto de Física da Universidade de São Paulo, São Paulo, Brasil
(Received 2 October 1987)

Energy levels of ^{101}Ru have been studied by the ^{100}Ru(d,p)^{101}Ru reaction at an incident deuteron energy of 12 MeV. Outgoing particles were momentum analyzed by a magnetic spectrograph and detected in nuclear emulsion plates, with an energy resolution of 7.5 keV. A total of 68 levels up to 3.2 MeV excitation energy was identified, about two-thirds of them reported for the first time. Experimental angular distributions were compared to distorted-wave Born approximation predictions and reduced spectroscopic factors obtained. The total $l=2$ and 75% of $l=0$, 4, and 5 spectroscopic strengths were located. Attention is drawn to transitions to low-lying states in ^{101}Ru (below $E_{exc}=0.75$ MeV) with $l=3$ and $l=1$ character.

I. INTRODUCTION

The region of nuclei around $A=100$, in particular, the ruthenium isotopes, continues to attract attention, from both theoretical and experimental points of view, due to conflicting aspects revealed by the data when confronted with the simpler models. In fact, level energy systematics and decay properties of the lighter even ruthenium isotopes tend to follow a vibrational description, as revealed also by interacting boson approximation (IBA) calculations.[1,2] However difficulties have been found in describing the neighboring odd-A isotopes on the same footing. In particular, it was, until recently, not possible to account for the spreading in energy of levels which, according to the vibrational model, should belong to the same multiplet.[3,4]

Recently, predictions of a symmetric prolate rotor (with a variable moment of inertia) plus particle model, including Coriolis coupling, allowed the identification in ^{99}Ru of several particle-core multiplets,[5] with the correct γ-decay properties, due to the dominance of a particular value of core angular momentum R and quasiparticle parentage. In agreement with experiment, a lowering of the low spin members of the multiplets, especially those based on high-j-particle states, is predicted.

Very recently, Arias *et al.*[6] performed, for the Tc, Ru, Rh, and Pd isotopes, extensive calculations within the proton-neutron interacting boson-fermion approximation (IBFA-2) and, where comparison was made, not only level energy systematics, but also one-particle transfer spectroscopic strengths and electromagnetic properties could be satisfactorily reproduced.

From an experimental point of view, one-particle stripping reactions could help to put into evidence mainly those low spin members of the multiplets, not easily populated by (HI, $xn\gamma$) or even ($\alpha,xn\gamma$) and (^{3}He,$xn\gamma$) reactions, through admixtures of the even-core ground-state components into the wave functions of these excited states of the odd nucleus. The nucleus ^{101}Ru has been the subject of γ-ray studies with ($\alpha,3n$) (Refs. 7 and 8), (^{3}He,$2n$) (Ref. 8), and (α,n) (Ref. 9) reactions, and from the decay of ^{101}Rh^{m,g}.[4] On the other hand, a previous (d,p) work[10] covered an excitation energy range of only 1.9 MeV with an energy resolution of 25 keV. In the present experiment the ^{100}Ru(d,p)^{101}Ru reaction has been studied with better resolution to provide a detailed determination of the level spectrum and spectroscopic strengths in ^{101}Ru. A wider range of excitation energies than in the previous (d,p) study[10] has been covered, several new energy levels have been detected, and definite values of l have been assigned to a larger number of transitions.

II. EXPERIMENTAL PROCEDURE

Angular distributions and absolute cross sections for the (d,p) reaction on targets enriched to 97.2% in ^{100}Ru were measured with 12-MeV deuterons from the tandem Pelletron accelerator of the University of São Paulo. The scattered protons were detected with nuclear emulsion plates (Kodak type NTB 50 μm thick) placed in the focal surface of an Enge split-pole magnetic spectrograph. Aluminum foils, thick enough to absorb heavier reaction products, covered the emulsion. The total number of incident deuterons was determined by a current integrator, which measured the charge collected in a Faraday cup with electron suppression. Elastically scattered deuterons detected at 41.5° by a surface barrier position sensitive detector placed in the focal surface of the spectrograph provided the absolute normalization, obtained from the deuteron elastic cross section given by an optical model prediction using the potential parameters shown in Table I. The uncertainty in the absolute cross section scale is estimated to be ±15%, taking into account an uncertainty of ±10%, due to different optical model predictions for the elastic cross section and an uncertainty of ±10%, from the nonuniformity of the targets.

Targets were made by evaporation[11] of metallic ruthenium powder onto thin carbon backings. The thicknesses of the three different uniform ruthenium films used

TABLE I. Bound-state and optical model parameters used in DWBA calculations.

	Deuteron[a]	Bound neutron	Proton[b]
V (MeV)	97.32	c	$60.87-0.32E_p$
r_0 (fm)	1.15	1.17	1.17
a_0 (fm)	0.81	0.75	0.75
$V_{s.o.}$ (MeV)	7.0	$\lambda_{s.o.}=25$	6.2
$r_{s.o.}$ (fm)	0.75		1.01
$a_{s.o.}$ (fm)	0.50		0.75
W (MeV)	0		$0.22E_p-2.7$
r_W (fm)	0		1.32
a_W (fm)	0		0.60
W_D (MeV)	17.28		$13.34-0.25E_p$
r_D (fm)	1.34		1.32
a_D (fm)	0.68		0.60
r_C (fm)	1.30		1.25

[a]From Refs. 15 and 16.
[b]From Ref. 17.
[c]Adjusted to reproduce the neutron binding energy.

during this experiment were around 20 μg/cm^2.

The protons produced in the reaction were observed at seven angles, from 10° to 68°, and the exposed plates were scanned in steps of 0.2 mm along the plate. An energy resolution [full width at half maximum (FWHM)] of 7.5 keV was achieved. The spectrum obtained at a laboratory scattering angle of 52° is shown in Fig. 1 and can be regarded as typical of the spectra measured at other angles. Peaks corresponding to transitions to levels of ^{101}Ru are numbered, the ground-state group being labeled by zero. The inset in Fig. 1 shows the region of levels 2 and 3 scanned with higher magnification and in smaller steps. The identification of peaks corresponding to states in ^{101}Ru was made following the procedures described in detail elsewhere.[12]

III. RESULTS

The excitation energies shown in Table II are the average of the energies obtained from the spectra, making use of the calibration of the spectrograph.[13] Deviations of individual energy determinations and the mean were in most cases lower than 3 keV. Reported in Table II are the levels clearly detected at at least four different angles. Also shown in Table II are the results of Hollas *et al.*[10] from a study of the same reaction at 11.5 MeV with a resolution of 25 keV. The adopted levels of ^{101}Ru in the compilation of Blachot[14] are also reproduced in Table II. A comparison of the level energies obtained in the present work with the energies reported by Blachot[14] shows a good agreement. Differences with the measurements of γ-decay work[14] are typically less than 2 keV.

The experimental angular distributions, for those transitions for which at least five points were measured, are shown in Figs. 2 and 3. The error 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

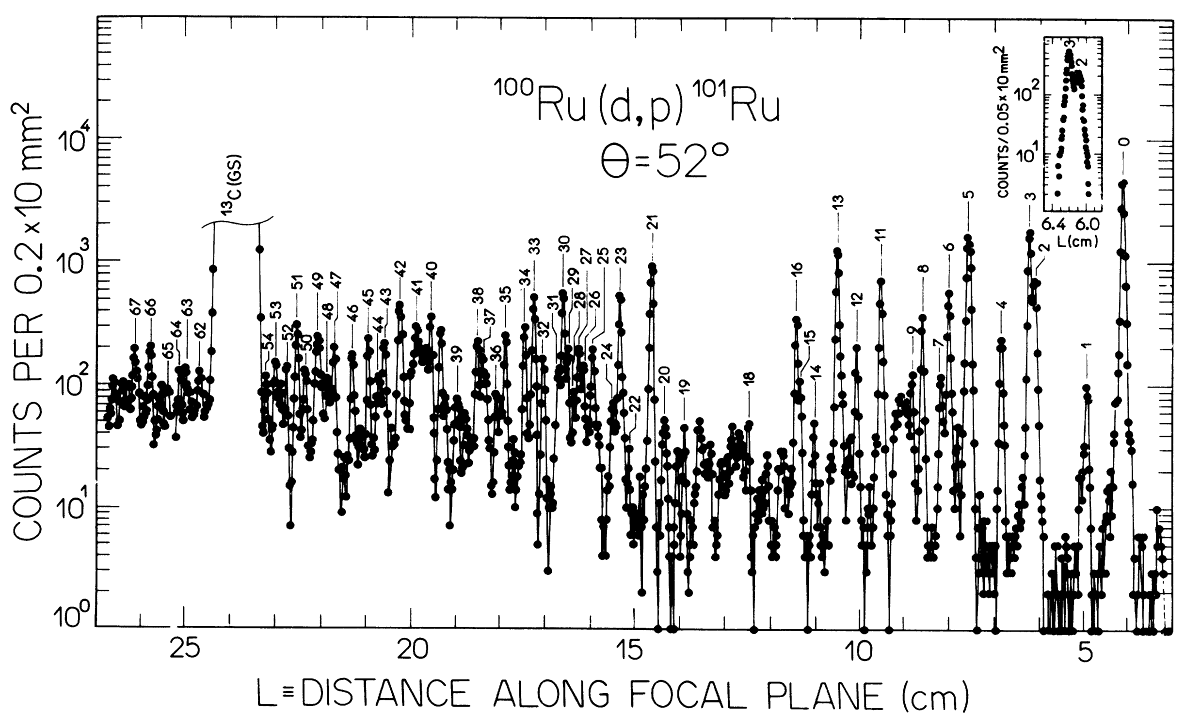

FIG. 1. Proton spectrum from the ^{100}Ru(d,p)^{101}Ru reaction at $\theta_{lab}=52°$. Peaks corresponding to transitions to ^{101}Ru levels are labeled with the numbers used in Table II. The inset shows the region of levels 2 and 3 scanned with higher magnification and smaller steps.

TABLE II. Summary of the results for ^{101}Ru from the $^{100}Ru(d,p)$ reaction and comparison with previous experiments. Assignments given in parentheses are tentative.

	Present work					Hollas *et al.*[a]				Nuclear data[b]	
Level number	E_{exc} (MeV)	$[\sigma_{exp}(\theta)]^{c}_{max}$ (mb/sr)	l	j	S'_{lj}	E_{exc} (MeV)	l	j	S'_{lj}	E_{exc} (MeV)	J^{π}
0	0.000	2.7±0.2	2	$\frac{5}{2}$	2.10	0.000	2	$\frac{5}{2}$	2.09	0.000	$\frac{5}{2}^{+}$
1	0.127	0.071±0.006	2	$\frac{3}{2}$	0.067	0.127	2	$\frac{3}{2}$	0.08	0.12723	$\frac{3}{2}^{+}$
2	0.307	0.49±0.14	4	$\frac{7}{2}$	5.3					0.30685	$\frac{7}{2}^{+}$
										0.31134	$\frac{5}{2}^{+}$, $\frac{3}{2}^{+}$
3	0.326	4.2±0.3	0	$\frac{1}{2}$	0.96	0.325	0	$\frac{1}{2}$	1.30	0.32515	$\frac{1}{2}^{+}$
										0.3441	
4	0.421	0.19±0.05	2	$\frac{3}{2}$	0.15	0.408	2	$\frac{3}{2}$	0.20	0.4221	$\frac{3}{2}^{+}$
										0.4623	
			5	$\frac{11}{2}$	5.8					0.5275	$\frac{11}{2}^{-}$
5	0.533	1.08±0.06[d]	2	$\frac{5}{2}$, $\frac{3}{2}$	0.72, 0.75	0.535	2	$\frac{5}{2}$, $\frac{3}{2}$	0.85, 1.03	0.535	($\frac{5}{2}^{+}$, $\frac{3}{2}^{+}$)
										0.54508	$\frac{7}{2}^{+}$
6	0.597	0.59±0.05	3	$\frac{7}{2}$, $\frac{5}{2}$	0.60, 0.74	0.599	4	$\frac{7}{2}$	3.62	0.5983	
										0.6163	($\frac{7}{2}^{+}$)
										0.6234	($\frac{7}{2}^{+}$)
7	0.622	0.26±0.02	0	$\frac{1}{2}$	0.063	0.625	0	$\frac{1}{2}$	0.09	0.6235	$\frac{1}{2}^{+}$
										0.6438	
8	0.685	0.25±0.02	2	$\frac{5}{2}$, $\frac{3}{2}$	0.17, 0.18	0.684	0+2	$\frac{1}{2}$, $\frac{3}{2}$	0.03, 0.15	0.684	
9	0.718	0.065±0.010	1	$\frac{3}{2}$, $\frac{1}{2}$	0.017, 0.018	0.714					
										0.7200	$\frac{9}{2}^{+}$
10	0.742	0.055±0.010									
11	0.823	0.53±0.03	2	$\frac{5}{2}$, $\frac{3}{2}$	0.40, 0.43	0.827	2	$\frac{5}{2}$, $\frac{3}{2}$	0.39, 0.46	0.827	
										0.84278	($\frac{7}{2}^{+}$)
12	0.908	0.26±0.02	1	$\frac{3}{2}$, $\frac{1}{2}$	0.057, 0.060	0.910					
										0.92872	($\frac{7}{2}^{+}$, $\frac{9}{2}^{+}$
										0.93847	($\frac{7}{2}^{+}$)
										0.9586	($\frac{15}{2}^{-}$)
13	0.972	0.88±0.06	2	$\frac{5}{2}$, $\frac{3}{2}$	0.63, 0.70	0.976	2	$\frac{5}{2}$, $\frac{3}{2}$	0.59, 0.71	0.9734	($\frac{5}{2}^{+}$,$\frac{3}{2}^{+}$)
										1.0012	$\frac{11}{2}^{+}$
14	1.051	0.026±0.005	4	$\frac{7}{2}$	0.28						
15	1.098	0.23±0.04	0	$\frac{1}{2}$	0.028						
16	1.112	0.81±0.05	0	$\frac{1}{2}$	0.17	1.110	0	$\frac{1}{2}$	0.19	1.110	$\frac{1}{2}^{+}$
										1.2068	
										1.2190	
17	1.227	0.14±0.04	0	$\frac{1}{2}$	0.016						
18	1.268	0.031±0.008	2	$\frac{5}{2}$, $\frac{3}{2}$	0.019, 0.022						
										1.3215	($\frac{11}{2}^{+}$)
										1.3899	
19	1.501	0.56±0.010								1.4993	
										1.5010	$\frac{13}{2}^{+}$
20	1.544	0.074±0.026									
21	1.584	0.75±0.04	2	$\frac{5}{2}$, $\frac{3}{2}$	0.45, 0.50	1.588	2	$\frac{5}{2}$, $\frac{3}{2}$	0.38, 0.46	1.5873	($\frac{5}{2}^{+}$)
										1.6223	($\frac{19}{2}^{-}$)
22	1.659	0.022±0.005									
23	1.689	0.26±0.03	5	$\frac{11}{2}$	3.7	1.695	5	$\frac{11}{2}$	2.14	1.695	($\frac{11}{2}^{-}$, $\frac{9}{2}^{-}$)
24	1.714	0.057±0.008	0	$\frac{1}{2}$	0.012						
										1.7618	
										1.7743	($\frac{13}{2}$ to $\frac{19}{2}$)
25	1.779	0.130±0.014	1	$\frac{3}{2}$, $\frac{1}{2}$	0.027, 0.028						
26	1.813	0.10±0.02	2	$\frac{5}{2}$, $\frac{3}{2}$	0.064, 0.068						
27	1.825	0.13±0.02	2	$\frac{5}{2}$, $\frac{3}{2}$	0.075, 0.081	1.825	2	$\frac{5}{2}$, $\frac{3}{2}$	0.13, 0.16	1.825	($\frac{5}{2}^{+}$, $\frac{3}{2}^{+}$)
28	1.842	0.08±0.02	2	$\frac{5}{2}$, $\frac{3}{2}$	0.041, 0.043					1.8434	
29	1.861	0.29±0.03	0	$\frac{1}{2}$	0.062						

TABLE II. (*Continued.*)

	Present work					Hollas *et al.*[a]				Nuclear data[b]	
Level number	E_{exc} (MeV)	$[\sigma_{exp}(\theta)]^{c}_{max}$ (mb/sr)	l	j	S'_{lj}	E_{exc} (MeV)	l	j	S'_{lj}	E_{exc} (MeV)	J^{π}
										1.8622	$\frac{15}{2}^+$
30	1.878	0.44±0.03	2	$\frac{5}{2}$, $\frac{3}{2}$	0.25, 0.27	1.875	2	$\frac{5}{2}$, $\frac{3}{2}$	0.38, 0.46	1.875	($\frac{3}{2}^+$, $\frac{5}{2}^+$)
31	1.893	0.12±0.03									
32	1.936	0.26±0.02	0	$\frac{1}{2}$	0.061						
										1.9615	
33	1.969	0.35±0.02	2	$\frac{5}{2}$, $\frac{3}{2}$	0.20, 0.21						
34	1.997	0.21±0.02	2	$\frac{5}{2}$, $\frac{3}{2}$	0.12, 0.13						
										2.0175	($\frac{13}{2}$ to $\frac{19}{2}$)
35	2.057	0.33±0.03	0	$\frac{1}{2}$	0.076						
										2.0634	
36	2.087	0.05±0.01									
37	2.133	0.14±0.02	1	$\frac{3}{2}$, $\frac{1}{2}$	0.037, 0.039						
38	2.147	0.22±0.02	(1)	($\frac{3}{2}$), ($\frac{1}{2}$)	(0.043), (0.046)						
										2.1740	$\frac{17}{2}^+$
39	2.218[e]	0.075±0.009									
										2.2229	($\frac{11}{2}$ to $\frac{19}{2}$)
40	2.299	0.16±0.06	2	$\frac{5}{2}$, $\frac{3}{2}$	0.098, 0.105						
41	2.348	0.10±0.01	(1)	($\frac{3}{2}$), ($\frac{1}{2}$)	(0.020), (0.021)					2.3459	
										2.3772	
42	2.404[f]	0.44±0.04	2	$\frac{5}{2}$, $\frac{3}{2}$	0.20, 0.23						
43	2.443	0.22±0.02	2	$\frac{5}{2}$, $\frac{3}{2}$	0.09, 0.10						
44	2.459	0.05±0.01	(3)	($\frac{7}{2}$), ($\frac{5}{2}$)	(0.042), (0.056)						
										2.4732	($\frac{32}{2}^-$)
45	2.493	0.14±0.03	2	$\frac{5}{2}$, $\frac{3}{2}$	0.063, 0.072						
46	2.544	0.12±0.03									
47	2.600	0.14±0.02	3	$\frac{7}{2}$, $\frac{5}{2}$	0.12, 0.14						
48	2.624	0.12±0.02									
49	2.654[e]	0.22±0.02									
50	2.694	0.08±0.01	2	$\frac{5}{2}$, $\frac{3}{2}$	0.038, 0.042						
										2.7979	($\frac{21}{2}^+$)
51	2.718	0.22±0.02	1	$\frac{3}{2}$, $\frac{1}{2}$	0.046, 0.049						
52	2.752	0.09±0.01									
53	2.784	0.15±0.03	3	$\frac{3}{2}$, $\frac{1}{2}$	0.026, 0.027						
54	2.815	0.08±0.02									
55	2.844	0.14±0.02	(3)	($\frac{7}{2}$), ($\frac{5}{2}$)	(0.10), (0.11)					2.8236	$\frac{19}{2}^+$
56	2.867	0.13±0.04[h]									
57	2.881										
										2.8853	
58	2.901	0.06±0.01									
59	2.918	0.15±0.04									
60	2.931	0.14±0.02									
61	2.977	0.08±0.02									
										2.9842	
62	3.019	0.15±0.02									
										3.0520	($\frac{15}{2}$ to $\frac{23}{2}$)
63	3.065	0.16±0.02									
64	3.083	0.18±0.06									
65	3.120	0.06±0.02									
66	3.173	0.13±0.02									
67	3.228	0.24±0.02	0	$\frac{1}{2}$	0.031						

[a]Reference 9.
[b]Reference 13.
[c]Maximum cross section measured.
[d]Integrated cross section ($l=5+l=2$).
[e]Possible doublet.
[f]Doublet.
[h]Integrated cross section (levels 56 and 57).

nonlocality effects, performed by means of the code DWUCK4.[15] The correction parameters employed were $R_{FR}=0.62$ 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[16] for deuteron scattering, with the addition of a spin-orbit term suggested by Lohr and Haeberli[17] and from the analysis of Becchetti and Greenlees[18] 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. The calculations were performed supposing, as usual, that the bound neutron occupies an orbital near the Fermi surface. In the case of $l=1$ and $l=3$ transfers, orbitals $3p$ and $2f$, of the next major shell, were assumed. The parameters used are presented in Table I.

Fits to the angular distributions are shown in Figs. 2 and 3 in comparison with the data, whenever an assignment of transferred angular momentum l was attempted. The reduced spectroscopic factors S'_{lj} were extracted in the fitting procedures according to the relationship

$$\sigma_{\exp}(\theta)=1.53S'_{lj}\frac{\sigma_{lj}^{\mathrm{DW}}(\theta)}{2j+1} .$$

The values of S'_{lj} are related to the spectroscopic factor by

$$S'_{lj}=\frac{2J_f+1}{2J_i+1}S_{lj}=(2j+1)S_{lj} ,$$

where J_i $(=0)$ and J_f $(=j)$ are, respectively, the spins of the target and final nuclei.

The values obtained for l and S'_{lj} are shown in Table II.

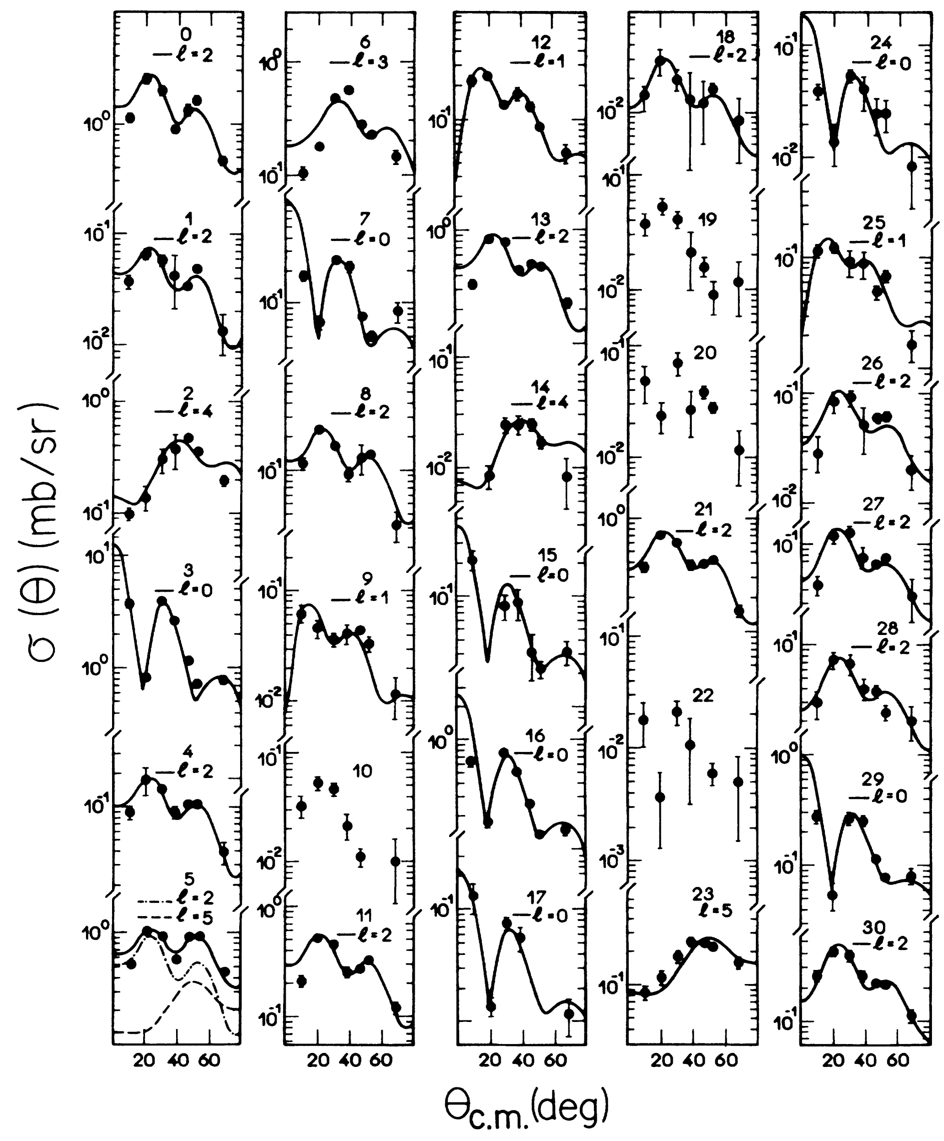

FIG. 2. Angular distributions of transitions in the ^{100}Ru$(d,p)^{101}$Ru reaction. The experimental points are given with error bars corresponding to statistics and uncertainties in plate scanning, background subtraction, and relative normalization. The solid lines are DWBA curves fitted to the experimental data.

If different global prescriptions, for the optical model parameters, are used in entrance[16,17,19] and exit[18,20] channels, a maximum variation of ±15% in the reduced spectroscopic factors occurs.

Transferred l values were extracted without ambiguities for levels below 2.0 MeV, except for levels numbered 6, 10, 19, 20, 22, and 31. The experimental angular distributions related to levels 10, 19, and 31 are similar, but their shape is not reproduced by one-step DWBA predictions, while those associated to levels 20 and 22 present no discernible structure. An $l=4$ attribution was attempted for the transition to the state at 0.597 MeV (No. 6), following Hollas *et al.*,[10] but the quality of the fit was poor when compared with other $l=4$ fits. On the other hand, this angular distribution is better reproduced by an $l=3$ transfer, especially if, as usual, emphasis is put on fitting the experimental points around the first forward-angle maximum of the cross section and its ensuing decrease. The criterium also took into account that, for the $l=2$ transfers in this excitation energy region, the data corresponding to the smallest angles lie systematically below the DWBA prediction. Figure 4 compares the quality of the $l=3$ and $l=4$ fits to both ^{100}Ru(d,p)^{101}Ru and ^{102}Ru(d,t)^{101}Ru reaction populating the state at 0.597 MeV. The pickup results, reproduced from Ref. 21, clearly characterize the transition as $l=3$. The fact that the authors of a recent (p,d) work[22] do not report a level at approximately 0.60 MeV is probably due to the poor resolution (24 keV) of these data. In their published spectrum the peak corresponding to the 0.623-MeV state presents, at the right position, a shoulder of appropriate magnitude, if compared to the (d,t) results.[21]

The transition to the state detected at 0.533 MeV (No. 5) reveals a predominant $l=2$ component, but there is a

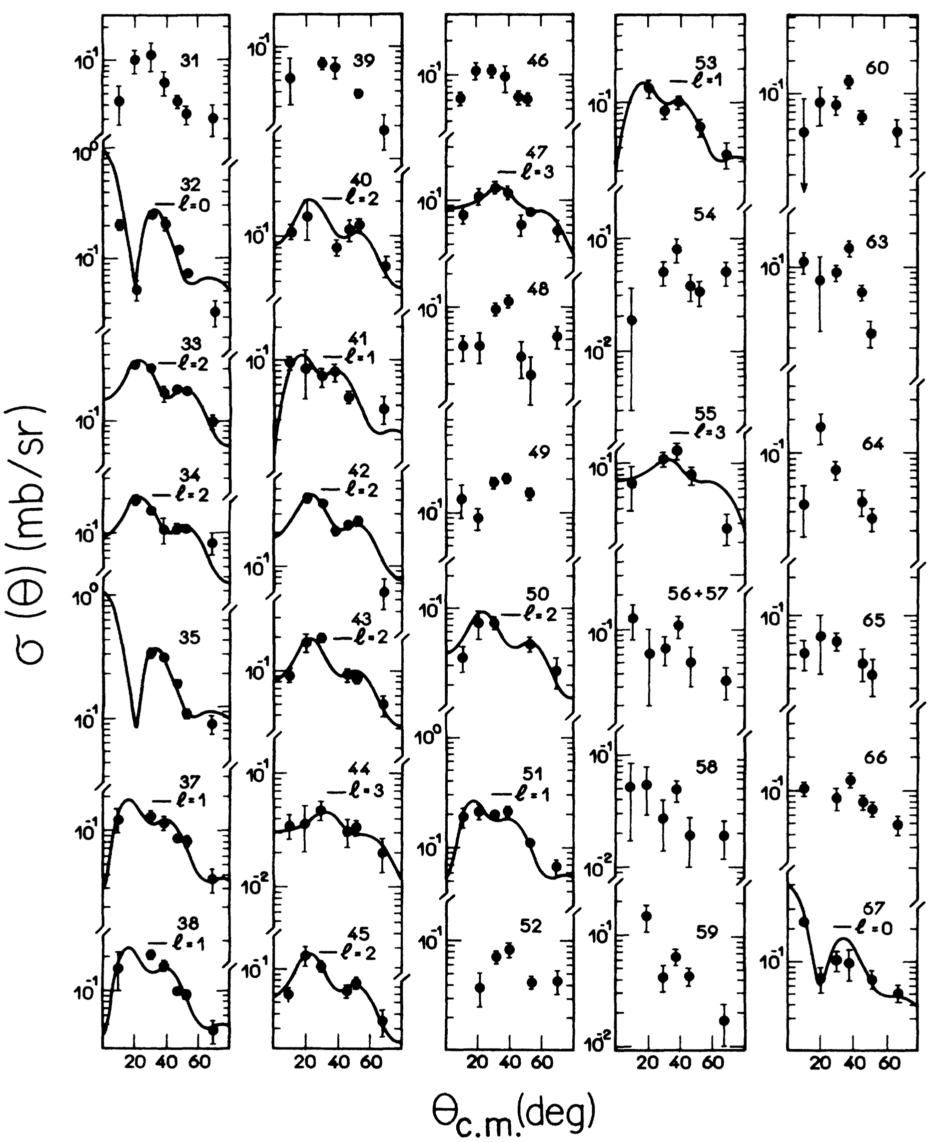

FIG. 3. ^{100}Ru(d,p)^{101}Ru angular distributions (see caption of Fig. 2).

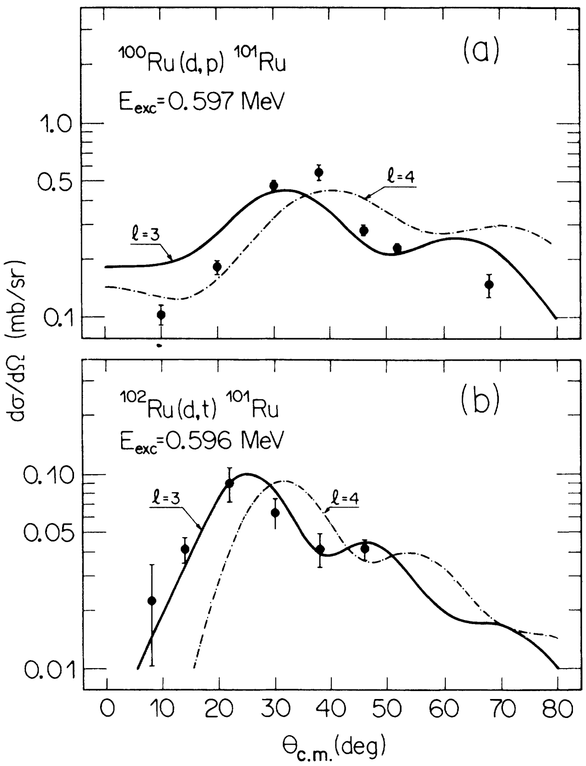

FIG. 4. (a) ^{100}Ru$(d,p)^{101}$Ru at 12 MeV, and (b) ^{102}Ru$(d,t)^{101}$Ru at 16 MeV, angular distributions corresponding both to the same 0.597-MeV final state. The curves are DWBA predictions for $l=3$ and $l=4$ transfers. (b) is reproduced from Ref. 21.

clear necessity to consider an $l=5$ contribution corresponding to the known $\frac{11}{2}^-$ level at 0.5275 MeV. The spectroscopic factors of the states involved were extracted by a least-squares fitting procedure.[23] The cross section at $\theta=10°$ for state No. 8 excludes contributions from an $l=0$ component, in disagreement with Hollas *et al.*[10]

Above 1.9 MeV most of the levels reported here have been seen for the first time. For levels 35 to 39 the carbon contamination of the spectrum at 20°, where a minimum of the cross section for an $l=0$ transfer is expected, is an impairment to the distinction between $l=0$ and $l=1$ transfers. Due to the overall fit for levels 35 and 37, $l=0$ and $l=1$ attributions, respectively, were preferred. For level 38 the $l=1$ value is tentative.

The values of the reduced spectroscopic factors are in good agreement with those published by Hollas *et al.*,[10] whenever a comparison can be made. An exception is the $l=5$ level at $E_{exc}=1.689$ MeV, where the discrepancy amounts to a factor 1.7. Due to the low excitation probability of states reached by $l=5$ transfer, this discrepancy is not incompatible with the experimental errors in the data and the uncertainties in the DWBA predictions for different optical potentials.

IV. DISCUSSION AND CONCLUSIONS

The distribution of the reduced spectroscopic factor S'_{lj} associated to a given l value is presented in Fig. 5 as a function of excitation energy. Only levels with a reliable l value attribution were included. For the detected $l=2$ spectroscopic strength there is a concentration of intensity corresponding to the known $\frac{5}{2}^+$ ground state (g.s.) and a spreading among many levels. The intensity of this strongest transition is consistent with the presence of two $2d_{5/2}$ neutron holes in the g.s. of ^{100}Ru. For the other $l=2$ transitions a $d_{3/2}$ character was arbitrarily assumed. The spectroscopic strength thus associated to the $d_{3/2}$ orbital is heavily fragmented with components extending up to 2.7 MeV of excitation. In the case of $l=0$ transitions, there is also an experimental fragmentation, but one level alone is responsible for 66% of the detected spectroscopic strength. Most of the $l=0$ and $l=2$ strengths were already located by Hollas *et al.*[10] The detected strength for $l=4$ transitions is almost totally (95%) concentrated in the state at 0.307 MeV, which was not detected by Hollas *et al.*,[10] probably due to lack of resolution in presence of the intense $l=0$ state at 0.325 MeV. Only two levels reached by $l=5$ transfers were seen. A small fragmentation for the $l=5$ strength is thus observed, since the limit of detection corresponds, in this case, approximately to $S'=0.6$.

The present experiment locates the total $l=2$ and 72% of the $l=0$ strengths, relative to the sum-rule limits. In the case of $l=4$ and $l=5$, respectively, 70% and 79% of the total spectroscopic strengths were detected, if restricted to the shell 50–82. Transitions with $l=1$ and

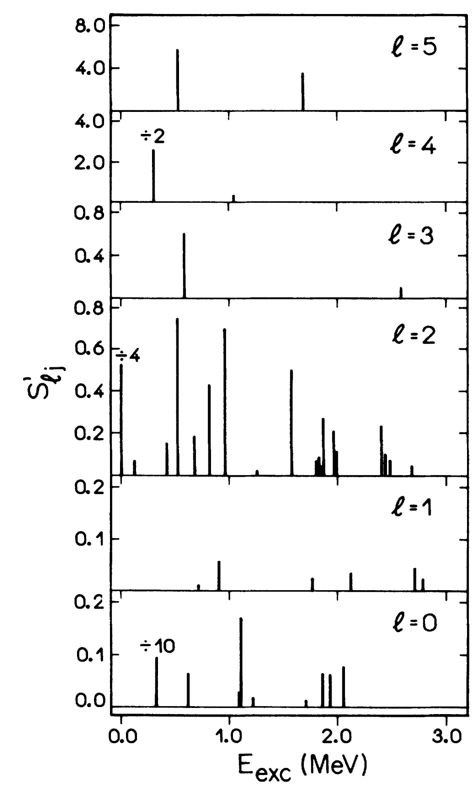

FIG. 5. Reduced spectroscopic factors obtained for all states reached by the same l transfer, as a function of excitation energy.

$l=3$ character were observed, and only lower limits of $\sum S'$ were obtained. Weak $l=1$ transitions were located below 2.8 MeV and are spread in a 2-MeV interval. For the $l=3$ transfer, on the other hand, 83% of the detected strength is carried by one state at 0.597 MeV.

Arias *et al.*[6] present a comparison of spectroscopic strengths below 1.0 MeV for $3s_{1/2}$, $1g_{7/2}$, $2d_{5/2}$, and $2d_{3/2}$ transfers in ^{100}Ru$(d,p)^{101}$Ru, as predicted by their IBFA-2 calculations, in comparison with the results of Hollas *et al.*[10] The very satisfactory agreement with experiment would perhaps be even better if the present results were taken, since the low-lying $l=4$ strength is now clearly located 0.30 MeV below the former attribution.

It is believed that the distribution of the neutron single-particle strengths among levels in ^{101}Ru, up to approximately 3.2 MeV of excitation, is now quite well established. The same experimental detail is not available for the other odd ruthenium isotopes. However, general features emerge from previous (d,p) reaction studies on ^{96}Ru (Refs. 10 and 24), ^{102}Ru (Refs. 25 and 26), and ^{104}Ru (Refs. 25 and 27). In each isotope, the strongest $l=2$ transition populates the lowest $\frac{5}{2}^+$ state and a heavy fragmentation of the remaining $l=2$ strength is observed. All the referred isotopes are found to have a strong low-lying $\frac{1}{2}^+$ state with much weaker $l=0$ strength distributed among higher excited states. A very light fragmentation is observed for the $l=4$ and $l=5$ strengths. Transitions of $l=1$ character were, up to now, reported only in the present reaction and in ^{104}Ru$(d,p)^{105}$Ru (Refs. 25 and 27), while low-lying $l=3$ strengths have been observed in ^{101}Ru and ^{103}Ru (Refs. 25 and 26), concentrated in single transitions, and in ^{105}Ru (Ref. 27), possibly split.

Negative parity states, based on the single particle orbital $h_{11/2}$, are expected in the mass region of the Ru isotopes. The simpler models, however, are not able to reproduce important experimental results. For instance, it is not evident how to bring $l=3$ and $l=1$ single-particle strengths, from the next shell down to within hundreds of keV from the ground states. Recently, Whisnant *et al.*[5] coupling the quasiparticle to a symmetric, slightly deformed prolate rotor were able to reproduce some vibrational-like features for ^{99}Ru. In particular, the calculations[5] characterized a multiplet associated to the dominant $R=2$ core excitation and $1h_{11/2}$ quasiparticle and predicted it to be spread through an 1.2-MeV interval, in good accordance with experiment. The lowest-lying member is the $\frac{7}{2}^-$ state at 1.105 MeV, in correspondence with the experimental level at 1.290 78 MeV. However, previous calculations[28,29] for the heavier ^{101,103}Ru isotopes, based on the same model, did not put a multiplet structure into evidence and present considerable differences in the predictions for ^{103}Ru. These differences may possibly be due to the consideration of an oblate core deformation for negative parity states and the neglect of part of the recoil term[29] in the calculations by Imanishi *et al.*[28] For ^{101}Ru only the results of Imanishi *et al.*[28] are available and no theoretical negative parity state, besides the $\frac{11}{2}^-$ at 0.529 MeV, is presented below 1.0 MeV.

As already pointed out, through admixtures of $R=0$ components into predominantly $R>0$ states, these could be accessible to one-particle transfer reactions. In particular, the low-lying $\frac{7}{2}^-$ levels would be seen as $l=3$ transfers in (d,p). In fact, in ^{103}Ru the experimental counterpart of the theoretical state[29] at 0.191 MeV could be the level at 0.297 MeV populated by an $(l=3)$ transition,[25,26] with a spectroscopic strength which is in agreement with the prediction.[29] Considering the lowest-lying levels populated by $l=3$, for the various isotopes, it is verified that, in going from ^{105}Ru to ^{101}Ru, their energy follows closely the increase in energy of the $\frac{11}{2}^-$ states with the strongest $l=5$ spectroscopic strengths. In ^{99}Ru, this trend would point to the level at 1.290 78 MeV, identified by Whisnant *et al.*[5] as the $\frac{7}{2}^-$ member of the $R\simeq 2$ multiplet. For ^{101}Ru the suggested accordance with the model would thus locate the $\frac{7}{2}^-$ member at 0.597 MeV. Similar considerations[30] could account for the presence of low-lying $l=1$ strength, through the contribution of $R=4$ dominant core components, resulting in the presence of $J^\pi=\frac{3}{2}^-$ states. In fact, in the recent calculation of Arias *et al.*,[6] besides the low-lying $\frac{7}{2}^-$ states, which deserved special remarks, $\frac{3}{2}^-$ states were predicted, at about 1 MeV in each isotope above the lowest $\frac{11}{2}^-$ level. In this paper[6] IBFA-2 calculations for $A\simeq 100$ nuclei were performed in a systematic way, considering the transition from SU(5) to O(6) symmetries. Arias *et al.*[6] found it necessary to include contributions of the $2f_{7/2}$ and $1h_{9/2}$ orbitals into their fermion space to match the properties of the negative parity states for which, unfortunately, no theoretical one-particle transfer strengths were published. Both approaches,[5,6] though starting from different theoretical ingredients, are thus equally able to predict important experimental evidences in the Ru isotopes. In particular, negative parity states lying relatively close in energy to the lowest $\frac{11}{2}^-$ levels seem now clearly interpreted as $\frac{7}{2}^-$, resulting essentially from the coupling of the 2_1^+ core state (which may have different descriptions) to an $1h_{11/2}$ quasiparticle.

Though the picture presented seems tempting, there are other experimental results,[9,31,32] some of them also recent, which are in possible contradiction to the mentioned $\frac{7}{2}^-$ attributions in ^{101,103,105}Ru. Kajrys and coworkers,[9,31] in $(\alpha,n\gamma)$ experiments populate the levels here interpreted as $\frac{7}{2}^-$, at 0.598 MeV in ^{101}Ru and at 0.297 MeV in ^{103}Ru, and assign to both spin and parity $\frac{3}{2}^+$. The corresponding level in ^{101}Ru was not reported by Klamra *et al.*[8] in their $(\alpha,3n\gamma)$ and $(^3\mathrm{He},2n\gamma)$ studies. In the case of ^{103}Ru, on the other hand, the result of Kajrys *et al.*[31] would supersede the $\frac{7}{2}^-$ attribution to the 0.297-MeV level made by Klamra and Rekstad,[33] based on experimental information extracted from the same reaction with more complete excitation function measurements. It is felt that, taking into account the usual difficulties[33] in spin and parity attribution through that kind of analysis, the measurements of Kajrys and coworkers[9,31] certainly do not exclude a $\frac{5}{2}^-$ attribution, although a $\frac{7}{2}^-$ may be more difficult to sustain. It is to be remembered that the $l=3$ transfer characterized by the present experiment would not be in disagreement with

$J^{\pi}=\frac{5}{2}^{-}$ for the 0.598-MeV state. Also, for ^{105}Ru, the analysis of all the available information led de Frenne *et al.*[32] to make a $(\frac{5}{2}^{-},\frac{3}{2})$ assignment for the lowest-lying level reached by $l=(3)$ in the (d,p) reaction.[27] A $\frac{7}{2}^{-}$ attribution is, in this case, improbable if a misassignment or a doublet structure are excluded, in face of the γ feeding pattern exhibited.

A theoretical counterpart for such low-energy $\frac{5}{2}^{-}$ levels would be difficult to find within the framework of the models discussed.[5,6] The connection between the odd and even Ru nuclei may, however, be considerably more complicated than supposed by these models.[5,6] In fact, in exploring the properties of the $\frac{5}{2}^{+}$ g.s. of ^{101}Ru through one neutron pickup reactions,[34,23] this state was found to be strongly related, through $l=2$ transfers, to levels of the even core at excitation energies above 2.2 MeV, not usually considered important core states in the calculations.[5,6]

ACKNOWLEDGMENTS

We are grateful to D. R. Bès and C. L. Lima for stimulating and helpful discussions. This work was partially supported by Fundação 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).

[1]J. Stachel, P. Van Isacker, and K. Heyde, Phys. Rev. C **25**, 650 (1982).

[2]P. Van Isacker and G. Puddu, Nucl. Phys. **A348**, 125 (1980).

[3]S. Bhattacharaya and S. K. Basu, Phys. Rev. C **18**, 2765 (1978).

[4]V. R. Vanin, A. Pássaro, and A. M. Pássaro, Phys. Rev. C **32**, 1349 (1985).

[5]C. S. Whisnant, K. D. Carnes, R. H. Castain, F. A. Rickey, G. S. Samudra, and P. C. Simms, Phys. Rev. C **34**, 443 (1986).

[6]J. M. Arias, C. E. Alonso, and M. Lozano, Nucl. Phys. **A466**, 295 (1987).

[7]C. M. Lederer, J. M. Jaklevic, and J. M. Hollander, Nucl. Phys. **A169**, 489 (1971).

[8]W. Klamra, K. Fransson, B. Sundström, M. Brenner, S. Engman, and R. Kvarnstrom, Nucl. Phys. **A376**, 463 (1982).

[9]G. Kajrys, R. Lecomte, S. Landsberger, and S. Monaro, Phys. Rev. C **28**, 1504 (1983).

[10]C. L. Hollas, K. A. Aniol, D. W. Gebbie, M. Borsaru, J. Nurzynski, and L. O. Barbopoulos, Nucl. Phys. **A276**, 1 (1977).

[11]K. Koide, F. C. Sampaio, E. M. Takagui, J. H. Hirata, and O. Dietzsch, Nucl. Instrum. **215**, 61 (1983).

[12]T. Borello-Lewin, C. Q. Orsini, O. Dietzsch, and E. W. Hamburger, Nucl. Phys. **A249**, 284 (1975).

[13]E. R. Cruz, M. Sc. thesis, Instituto de Física da USP, São Paulo, Brasil, 1978; this calibration was supplemented by data on ^{90}Zr(α,α') up to 5.9 MeV of excitation energy.

[14]J. Blachot, Nucl. Data Sheets **45**, 701 (1985).

[15]P. D. Kunz (unpublished).

[16]C. M. Perey and F. G. Perey, Phys. Rev. **132**, 755 (1963).

[17]J. M. Lohr and W. Haeberli, Nucl. Phys. **A232**, 381 (1974).

[18]F. D. Becchetti Jr. and G. W. Greenlees, Phys. Rev. **182**, 1190 (1969).

[19]W. W. Daehnick, J. D. Childs, and Z. Vrcelj, Phys. Rev. C **21**, 2253 (1980).

[20]F. G. Perey, Phys. Rev. **131**, 745 (1963).

[21]F. C. Sampaio, J. L. M. Duarte, L. B. Horodynski-Matsushigue, T. Borello-Lewin, and O. Dietzsch, Proceedings of the International Conference on Nuclear Structure, Amsterdam, 1982. Vol. 1, p. 54; (to be published).

[22]S. A. Dickey, J. J. Kraushaar, and M. A. Rumore, J. Phys. G **12**, 745 (1986).

[23]F. C. Sampaio, M. Sc. thesis, Instituto de Física da USP, São Paulo, Brasil, 1981.

[24]L. R. Medsker, L. H. Fry Jr., and J. L. Yntema, Phys. Rev. C **15**, 649 (1977).

[25]H. T. Fortune, G. C. Morrison, J. A. Nolen, Jr., and P. Kienle, Phys. Rev. C **3**, 337 (1971).

[26]G. P. A. Berg, M. Demarteau, A. Hardt, W. Hürlimann, S. A. Martin, J. Meissburger, W. Oelert, H. Seyfarth, B. Styczen, M. Köhler, I. Oelrich, and J. Scheerer, Nucl. Phys. **A379**, 93 (1982).

[27]P. Maier-Komor, P. Glässel, E. Huenges, H. Rösler, H. J. Scheerer, H. K. Vonach, and H. Baier, Z. Phys. **A278**, 327 (1976).

[28]N. Imanishi, I. Fujiwara, and T. Nishi, Nucl. Phys. **A205**, 531 (1973).

[29]J. Rekstad, Nucl. Phys. **A247**, 7 (1975).

[30]F. S. Stephens, Rev. Mod. Phys. **47**, 43 (1975).

[31]G. Kajrys, J. Dubuc, P. Larivière, S. Pilotte, W. del Bianco, and S. Monaro, Phys. Rev. C **34**, 1629 (1986).

[32]D. de Frenne, E. Jacobs, M. Verboven, and P. de Gelder, Nucl. Data Sheets **47**, 261 (1986).

[33]W. Klamra and J. Rekstad, Nucl. Phys. **A243**, 395 (1975).

[34]R. J. Peterson, R. A. Emigh, and R. E. Anderson, Nucl. Phys. **A348**, 8 (1980).