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Author: L. Jarczyk, B. Kamys, K. Seliger, Zygmunt Wróbel, J. Lang, R. Muller i in.

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INVESTIGATION OF NUCLEON-UNBOUND STATES IN ^{29}Si AND ^{29}P BY THE REACTION ^{28}Si (d, pn)

BY L. JARCZYK, B. KAMYS, K. SELIGER, Z. WRÓBEL

Institute of Physics, Jagellonian University, Cracow*

AND J. LANG, R. MÜLLER, C. M. SCHWEIZER–TEODORESCU

Laboratorium für Kernphysik, Eidg. Techn. Hochschule, Zürich**

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Stripping reactions leading to unbound states of ^{29}Si and ^{29}P nuclei were investigated by measuring proton–neutron correlations in ^{28}Si (d, p)^{29}Si(n) ^{28}Si and ^{28}Si(d, n) ^{29}P(p) ^{28}Si reactions at $E_{\text{lab}} = 11$ MeV. Twenty three states of ^{29}Si were observed in the excitation energy range from 9.00 MeV to 13.43 MeV, and seventeen states of ^{29}P in the energy range from 5.48 MeV to 9.81 MeV. For most of them spin, parity and partial width were derived.

1. *Introduction*

The deuteron break-up reaction is a good tool to study nucleon unbound states of atomic nuclei [1, 2]. In the present paper we are studying the proton unbound states of ^{29}P and the neutron unbound states of ^{29}Si via the ^{28}Si(d, pn)^{28}Si reaction. The experimental results and an analysis limited to the most prominent peaks in the spectra of this reaction were published in an earlier work [3]. Now an extended analysis is presented, based on the "summed spectra" method [4] which enables us to identify even weak states in complicated spectra.

2. *Analysis of the experimental data*

The experimental arrangement and procedure were described in details in Ref. [3]. The following experimental triple differential cross-sections $d^3\sigma/dEd\Omega_{\text{p}}d\Omega_{\text{n}}$ were grouped in two sets for the analysis: (*i*) at the fixed angle $\theta_{\text{p}}^{\text{lab}} = \pm 30°$ for proton emission and

* Address: Instytut Fizyki UJ, Reymonta 4, 30-059 Kraków, Poland.

** Address: Laboratorium für Kernphysik, Eidg. Techn. Hochschule, 8093 Zürich, Switzerland.

for angles of outgoing neutrons changing from 30° to 165° in steps of 15°, (*ii*) at the fixed angle $\theta_n^{lab} = 25°$ for neutron emission and for angles of outgoing protons θ_p changing from 35° to 165° and −35° to −165° in steps of 10° (all in the lab. system). The angles are given with respect to the beam axis, a positive (negative) sign of θ_p indicating that the

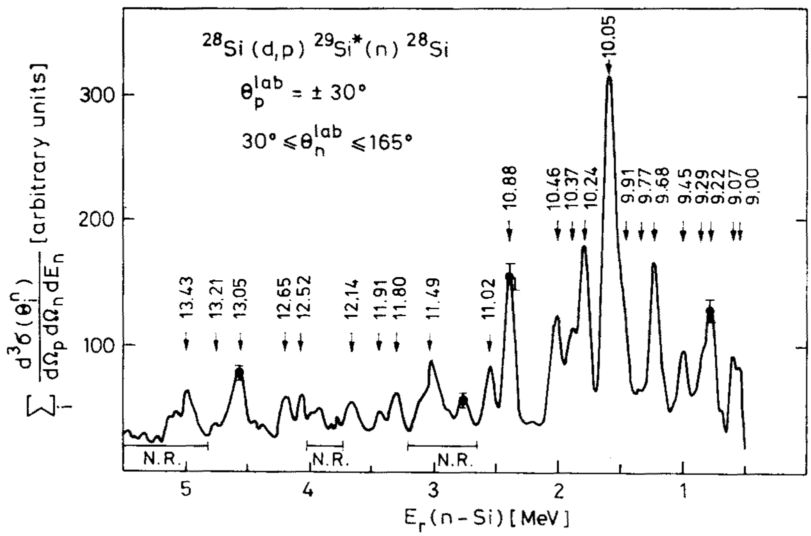

Fig. 1. A spectrum obtained by summation of excitation functions of set (*i*) (see text) in the ^{29}Si reference system. The maxima showed by arrows correspond to neutron-unbound states of ^{29}Si. These parts of spectrum in which the states could not be resolved are denoted by symbol "N.R."

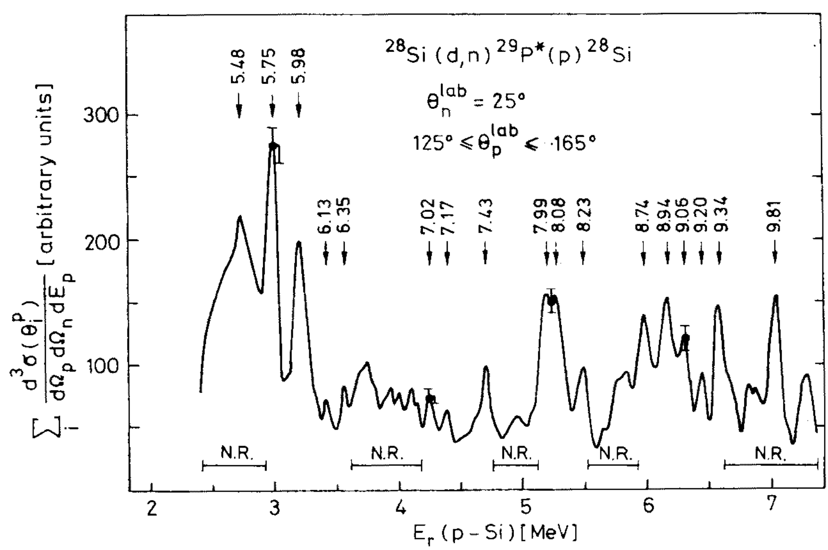

Fig. 2. The same as in Fig. 1 but for excitation curves of set (*ii*) taken in the ^{29}P reference system. Arrows indicate positions of proton-unbound states in ^{29}P

detector of the protons was situated on the same (opposite) side of the beam as the neutron detector.

To distinguish the levels connected with ^{29}Si from those corresponding to ^{29}P the procedure described in Ref. [4] was used. A spectrum obtained from summing of all spectra from set (*i*) is presented in Fig. 1 as a function of the energy in the system of the intermediate nucleus ^{29}Si. The arrows on the picture show the states of ^{29}Si taken for

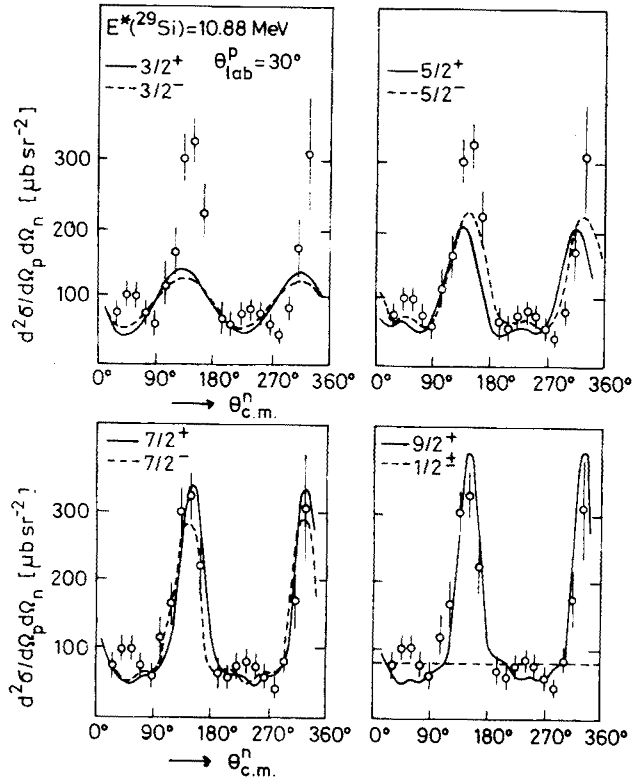

Fig. 3. An example of experimental angular distribution of double differential cross-section $d^2\sigma/d\Omega_p d\Omega_n$ (for neutron-unbound state of ^{29}Si at E_x = 10.88 MeV) together with theoretical angular distributions calculated for all assumed spin and parity values

analysis. Similarly summing of the spectra from set (*ii*) in the system of the ^{29}P nucleus gives the resulting spectrum shown in Fig. 2, where the arrows indicate positions of states of ^{29}P. The energies of states found in this way are presented in Tables I and II for ^{29}Si and ^{29}P, respectively. The decays of unbound states to the first excited state of ^{28}Si (1.78 MeV, 2+) were also observed but the low intensity of these transitions did not allow to resolve peaks even in the summed spectra.

The angular distributions of double differential cross-sections $d^2\sigma/d\Omega_p d\Omega_n$ were derived from spectra for these states using methods described in Ref. [4]. The experimental cross--sections were compared with theoretical ones, calculated by means of a modified version [5] of the DWBA code VENUS [6] in which a method proposed by Vincent and Fortune

TABLE I

Neutron-unbound states of ^{29}Si nucleus

Present work				Literature data [8]		
$E_{rel}(n\text{-}^{28}Si)$ MeV	$E_x(^{29}Si)$ MeV	J^π	$\Gamma_{G.S.}$ keV	$E_x(^{29}Si)$ MeV ± keV	J^π	Γ keV
0.53	9.00 ± 0.04	—	—	8.961 ± 6		
				8.9862 ± 1.1	(1/2, $3/2^-$)	
				8.9882 ± 0.7	($5/2^+$)	0.53
				9.0196 ± 1.2	$3/2^-$	10.4
0.60	9.07 ± 0.04	—	—	9.0403 ± 0.7	$1/2^-$	0.8
				9.0460 ± 0.7	$1/2^-$	0.4
				9.0540 ± 1.1	$3/2^+$	
0.75	9.22 ± 0.04	$3/2^-$	79.9	9.217 ± 2	$(1,2,\ 3/2)^-$	
		$3/2^+$	10.6	9.229 ± 2	$(1/2,\ 3,2)^-$	
				9.248 ± 2	$(1/2,\ 3/2)^-$	
				9.259 ± 2	$3/2^-$	27
0.82	9.29 ± 0.04	$5/2^-$	0.34	9.2885 ± 0.7		2.5
		$7/2^-$	0.26	9.3147 ± 0.7	($5/2^+$)	< 4
0.98	9.45 ± 0.04	(3/2)	—	9.418 ± 3	$3/2^-$	
		(5/2)	—	9.4545 ± 0.7		≈ 1
				9.4793 ± 0.7		1.4
1.21	9.68 ± 0.04	$5/2^+$	9.6	9.658 ± 2		< 6
		$5/2^-$	0.79	9.682 ± 2	$1/2^+$	7.0
		$7/2^-$	0.60	9.693 ± 2		6
1.30	9.77 ± 0.04	(3/2)	—	9.804 ± 4		
		(5/2)	—			
1.44	9.91 ± 0.04	($3/2^-$)	64.6	9.899 ± 3	$3/2^+$	5.5
		($3/2^+$)	11.5	9.931 ± 2		
		($5/2^-$)	0.73	9.948 ± 2	(5/2)	3.5
1.58	10.05 ± 0.04	$3/2^+$	25.2	10.0138 ± 1.1	($3/2^+$)	17
				10.045 ± 4	$3/2^-$	20
				10.0529 ± 1.1	$5/2^+$	3.5
				10.0665 ± 1.2	$5/2^+$	15
				10.092 ± 3	($3/2^+$)	≈ 2

TABLE I (continued)

Present work				Literature data [8]		
$E_{rel}(n\text{-}^{28}Si)$ MeV	$E_x(^{29}Si)$ MeV	J^{π}_{G}	$\Gamma_{G.S.}$ keV	$E_x(^{29}Si)$ MeV ± keV	J^{π}	Γ keV
1.77	10.24±0.04	3/2$^-$ 3/2$^+$	114 18.0	10.2146±1.3 10.260±4 10.267±4	(3/2$^-$) 3/2$^-$ (5/2$^+$)	2.2 45 16
1.90	10.37±0.05	5/2$^-$ 7/2$^-$	1.0 0.73	10.3333±1.4 10.3773±1.5		
1.99	10.46±0.04	5/2$^-$ 7/2$^-$ 7/2$^+$	1.7 1.2 0.18	10.470±20	$\pi = +$	
2.41	10.88±0.04	7/2$^-$ 7/2$^+$	2.0 0.49			
2.55	11.02±0.04	3/2$^-$ 3/2$^+$	99 18.3			
3.02	11.49±0.04	–	–			
3.33	11.80±0.04	5/2$^+$ 5/2$^-$ 7/2$^-$	11.6 3.0 2.4			
3.44	11.91±0.04	7/2$^+$ 9/2$^+$	0.54 0.41			
3.67	12.14±0.04	3/2$^+$ 5/2$^+$ 5/2$^-$	35 21 5.7			
4.05	12.52±0.04	3/2$^+$ 5/2$^+$ 5/2$^-$	72 43 12.2			
4.18	12.65±0.06	3/2$^+$ 5/2$^+$ 5/2$^-$	104 67 15.9			
4.58	13.05±0.04	(5/2$^+$) (5/2$^-$)	131 28			
4.74	13.21±0.04	>1/2	—			
4.96	13.43±0.06					

TABLE II

Proton-unbound states of ^{29}P nucleus

Present work				Literature data [8]		
$E_{rel}(p\text{-}^{28}Si)$ MeV	$E_x(^{29}P)$ MeV	J^π	$\Gamma_{G.S.}$ keV	$E_x(^{29}P)$ MeV ± keV	J^π	Γ keV
2.73	5.48 ± 0.04	—	—	5.527 ± 20	1/2⁻	400 ± 20
3.00	5.75 ± 0.04	5/2⁻ 7/2⁻	1.0 0.7	5.716 ± 4 5.740 ± 3	 7/2⁻	 12.5 ± 0.7
3.23	5.98 ± 0.04	3/2⁺	6.0	5.968 ± 3	3/2⁺	9.5 ± 1.5
3.38	6.13 ± 0.06	3/2⁻ 3/2⁺	9.0 1.8	6.191 ± 5	3/2⁻	95 ± 6
3.62	6.35 ± 0.04	—	—	6.328 ± 5	3/2⁺	73 ± 5
4.27	7.02 ± 0.03	3/2⁻	28	7.021 ± 5	3/2⁻	100 ± 8
4.42	7.17 ± 0.06	3/2⁻ 3/2⁺	33.5 8.5			
4.68	7.43 ± 0.04	5/2⁻	2.0	7.456 ± 5	5/2⁻	8.4 ± 0.7
5.24	7.99 ± 0.04	(7/2⁺) (7/2⁻)	3.0 4.8	7.950 ± 15 7.998 ± 30	3/2⁻ 3/2⁻	14 ± 4 125 ± 25
5.32	8.08 ± 0.04			8.104 ± 15	(3/2, 5/2)⁺	36 ± 10
5.48	8.23 ± 0.03	7/2⁻ 7/2⁺ 9/2⁺	5.8 1.8 1.4	8.220 ± 15	(3/2, 5/2)⁺	20 ± 4
5.99	8.74 ± 0.04			8.693 ± 30 8.780 ± 15	1/2⁺ 1/2⁺	120 ± 3 14 ± 3
6.19	8.94 ± 0.04			8.915 ± 15	(3/2, 5/2)⁺	33 ± 6
6.31	9.06 ± 0.04			9.079 ± 15	(1/2, 3/2)⁻	23 ± 5
6.45	9.20 ± 0.04					
6.59	9.34 ± 0.04			9.301 ± 15 9.369 ± 15 9.388 ± 15		7 ± 3 13 ± 5
7.06	9.81 ± 0.04			9.773 9.815	(3/2, 5/2)⁺ (3/2, 5/2)⁺	8 ± 3 20 ± 10

[7] was used to calculate transitions to resonant states. The program was also extended to permit the calculation of particle–particle correlation functions. Spins, parities and partial widths of the resonant states could be estimated from a comparison of experimental cross-sections with these theoretical calculations. The optical model parameters used in the calculations were the same as in Ref. [3].

The following procedure was adopted to make assignments of spin, parity and partial width: Angular distributions of double differential cross-sections were calculated assuming different values of spin and parity (J^π from $1/2^\pm$ up to $9/2^+$). The partial width was found as a normalizing factor giving the absolute value of the cross-section. The minimum of the χ^2-function was a criterion for the quality of the agreement between theory and experiment. Examples of theoretical and experimental angular distributions are shown in Fig. 3. It is clearly seen that it is rather easy to distinguish different values of spin but that the determination of the parity is not always so simple. The best fit values of spin, parity and partial width are listed together with the excitation energy of the states in Tables I and II for the ^{29}Si and ^{29}P nuclei, respectively. One set of quantum numbers is listed for these states only for which the minimum χ^2 value was at least 50% smaller than for other values of spin etc. The partial width derived from the DWBA analysis should of course be smaller than the total width of resonance observed in the experiment. This obvious fact has been used as an additional criterion for the elimination of some possible spin assignments. In some cases resonant states were not very well resolved and tails of other states could give some contribution to the observed angular distributions. A spin assignment for such states is given in parenthesis in Tables I and II.

3. Summary

In the present analysis we found 23 unbound states of the ^{29}Si nucleus in the excitation energy range from 9.00 MeV to 13.43 MeV and 17 states in the ^{29}P nucleus in the excitation energy range from 5.48 MeV to 9.81 MeV. Many of these states were investigated previously by other methods and authors. A comparison with their results, given in Tables I and II, shows a rather good agreement of spin assignments. In the case of the ^{29}Si nucleus the unbound states with excitation energies higher than 11.7 MeV were not observed previously. Values of widths obtained in the present work are in general smaller than those from the literature consistent with the fact that literature data usually show total widths obtained from nucleon scattering, while ours give partial widths for the decay to ground state of ^{28}Si. A feature of the (d, pn) reaction on ^{28}Si distinguishing it from the reaction on ^{24}Mg, is the rather small probability of a decay of the unbound states of ^{29}Si and ^{29}P nuclei to the first excited state of the residual ^{28}Si nucleus.

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