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THE $^{23}Na(d,p)^{24}Na$ REACTION AT DEUTERON ENERGIES 670 and 620 keV

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Angular distributions and absolute cross sections of proton groups $p_0, p_1, p_2, p_3 + p_4$ and $p_5 + p_6$ from the reaction $^{23}Na(d,p)^{24}Na$ have been measured at $E_d = 670$ and 620 keV. The experimental data are analysed in terms of Legendre polynomials and DWBA method. The DWBA calculations reproduced the angular distributions of proton groups $p_3 + p_4$ and $p_5 + p_6$.

1. Introduction

The angular distributions of different proton groups from the reaction $^{23}Na(d,p)^{24}Na$ have been studied by several authors. At higher bombarding energies the experimental results were analysed on the basis of the BUTLER [1,2,3,4] and the DWBA theories [4,5]. At lower deuteron energies, EL-BEHAY et al. measured angular distributions and excitation functions of nine proton groups in the range $E_d = 1.4 - 2.5$ MeV [6]. The angular distributions above 2 MeV generally displayed a stripping-like pattern, but in the measured excitation functions some resonance-like behaviour was observed. These results were interpreted by assuming an interference between the compound and the direct reaction mechanisms.

The aim of the present work was to extend the investigations to bombarding energies well below the Coulomb barrier in order to gain more experimental data on the reaction mechanism of different proton groups. Accordingly, the angular distributions and the absolute cross sections of the proton groups $p_0, p_1, p_2, p_3 + p_4$ and $p_5 + p_6$ from the reaction $^{23}Na(d,p)^{24}Na$ have been measured at deuteron energies 670 and 620 keV.

2. Experimental apparatus and method

Deuterons were accelerated by the cascade generator of the Institute of Nuclear Research (ATOMKI), Debrecen, Hungary. The high accelerating voltage was measured to 1% accuracy by a rotary-type voltmeter calibrated with (p, γ) resonances on ^{7}Li, ^{19}F and ^{27}Al. The ion beam, after passing through a 12° magnetic analyser and collimator system, hit the target placed in the centre of the target chamber used for angular distribution measurements [7].

A thin layer of NaCl evaporated onto a Cu foil of about 0,2 mg/cm² thickness was employed as target. The NaCl layer was evaporated from a point source, under suitable geometrical conditions, simultaneously onto Cu backings and Cu backings covered with a thin layer of CaF_2 (approx. 5 $\mu g/cm^2$). These targets were used to measure the shift of the 340 keV resonance line of the reaction $^{19}F(p,\alpha\gamma)$ due to the energy loss of protons in the NaCl layer. From the value of the shift the number of target atoms were determined by use of the reported dE/dx data [8]. The thickness of the targets was about 23 keV at $E_d = 670$ keV and about 50 keV at $E_d = 620$ keV.

The ion current was measured by a current integrator connected to a Faraday cup.

The angular distributions of the proton groups were measured with an ORTEC—SBCJ—25—300 semiconductor detector rotatable through 155°. Another semiconductor detector of the same type, mounted in the target chamber at an angle of 90° to the other, was used as a monitor. A suitable Al foil was placed in front of the detectors to absorb the scattered deuterons. After passing through charge-sensitive pre-amplifiers, main amplifiers and an electronic mixing unit, the pulses of the detectors were analysed with a NTA 512 pulse-height analyser. The application of the electronic mixing unit [9] permitted the simultaneous recording of corresponding portions of the two independent detector spectra with the 512-channel analyser. This procedure ensured precise monitoring even in the course of the lengthy measurements required by the low cross-sections.

Fig. 1 shows a typical spectrum recorded at $E_d = 670$ keV and $\Theta_{lab} = 90°$. The spectrum of the measuring detector is recorded in channels 150—512; that of the monitor detector in channels 0—130. A computer program was utilized to obtain the intensities of the poorly resolved proton groups p_1 and p_2 separately; the neighbouring proton groups p_3, p_4 and p_5, p_6 were not resolved and so were investigated together. The $p_3 + p_4$ and $p_5 + p_6$ groups of the monitor spectrum could easily be separated from the background and were thus available for monitoring purposes.

First the relative angular distributions of the various proton groups were determined at a bombarding ion current intensity of about 0,6 μA. Then the absolute differential cross sections of the proton groups were measured at an angle $\Theta_{lab} = 135°$ and the relative angular distributions were standardized to those values. During the course of the absolute measurements the bombarding ion current was reduced to 0.3 μA and the constancy of the target thickness was checked.

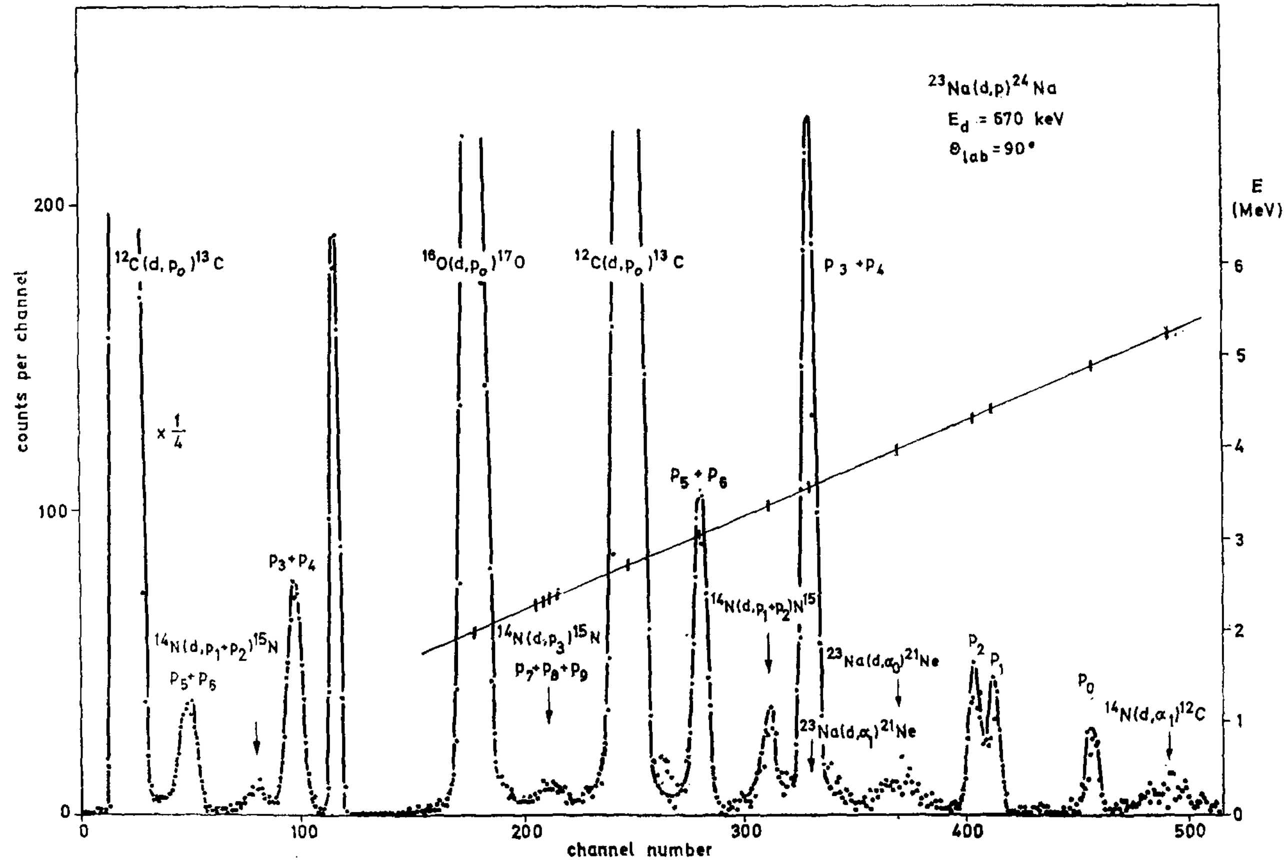

Fig. 1. A typica energy spectrum of protons from the reaction ^{23}Na(d,p)^{24}Na. The spectrum of the monitor detector is recorded in channels 0—130; that of the measuring detector in channels 150—512

3. Results and discussion

Figs. 2 and 3 show the results of angular distribution measurements in a centre-of-mass frame of reference at bombarding energies of 670 and 620 keV. The errors indicated for the experimental angular distributions refer to the reproducibility of the measurements and evaluation. The errors of the absolute cross section values deriving from the inaccuracy of the target thickness determination are estimated in general to be about 25%. The solid lines in the figures are the least squares fits of the experimental points to a series of Legendre polynomials. The angular distributions were analysed up to P_l to give an acceptable χ^2. The A_1/A_0, A_2/A_0 etc. coefficients with their errors and the calculated χ^2 values are collected in Table I.

The experimental differential cross-sections were compared with the calculations based on the DWBA model. Table II contains the optical potential parameters [10,11] adopted in the calculations.

The angular distributions of proton groups p_0, p_1 and p_2 could not be fitted with the DWBA model. It is worth noting that the angular distributions of these groups strongly change their shapes over the range $E_d = 1,4 - 2,5$ MeV [6].

Fig. 3 shows the theoretical curves for the proton groups $p_3 + p_4$ and $p_5 + p_6$ (dotted lines) fitted to the measured points by the method of least squares. The agreement between the measured and calculated angular distributions seems to be acceptable. The angular distributions of these groups at $E_d = 1,4 - 2.5$ MeV also have forms which are characteristic of a direct process [6]. For the proton groups $p_3 + p_4$ the DWBA calculations were carried out with the same potential parameters (Table II) at $E_d = 1.5$ and 2.5 MeV too. The fit of the calculated curves to the angular distributions obtained by EL-BEHAY et al. [6] is presented in Fig. 4. The theoretical calculations can be seen to reproduce the basic form of the measured differential cross sections at higher bombarding energies, too.

The quantities $[(2J_f + 1)/(2J_i + 1)]S_{l_n}$ obtained from the present DWBA analysis and from earlier work [5] are given with the χ^2 values in Table III. It is generally known that the assumptions of the DWBA model are not well satisfied for light nuclei and at low bombarding energies. In consequence of this as well as the large error in the measurement of absolute cross section, the extracted spectroscopic factors can be regarded only as order-of-magnitude estimates, even if the DWBA calculations well reproduce the shape of the angular distribution.

Summing up, it can be stated that at low bombarding energies both the compound nucleus mechanism and the direct interaction mechanism exist simultaneously in the reaction ^{23}Na(d,p)^{24}Na. The angular distributions of proton groups p_0, p_1 and p_2 are characterised by interference between the

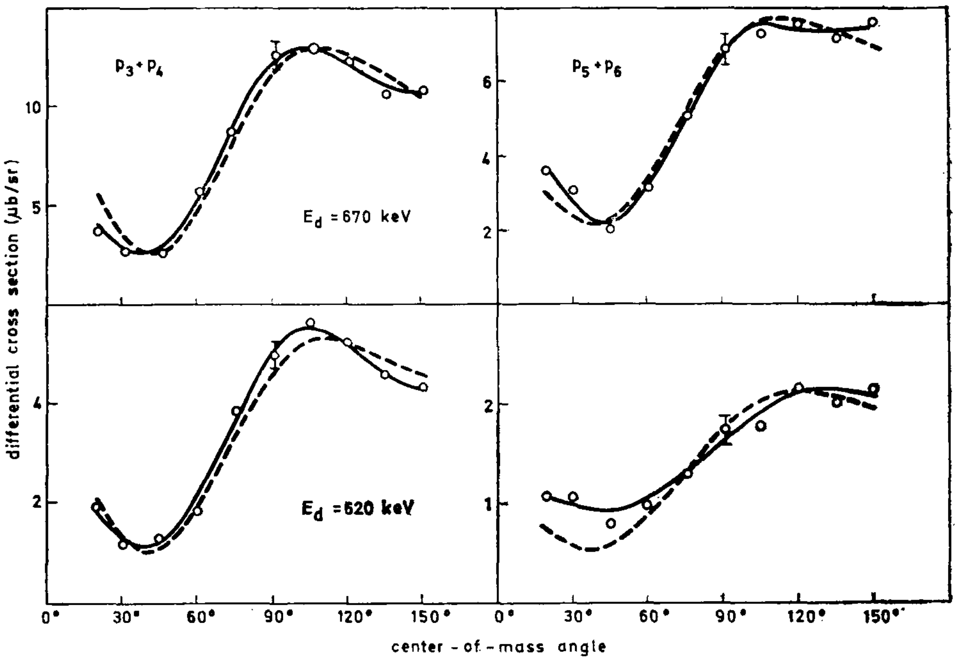

Fig. 2. Differential cross section of proton groups p_0, p_1 and p_2 from the reaction ^{23}Na(d,p)^{24}Na

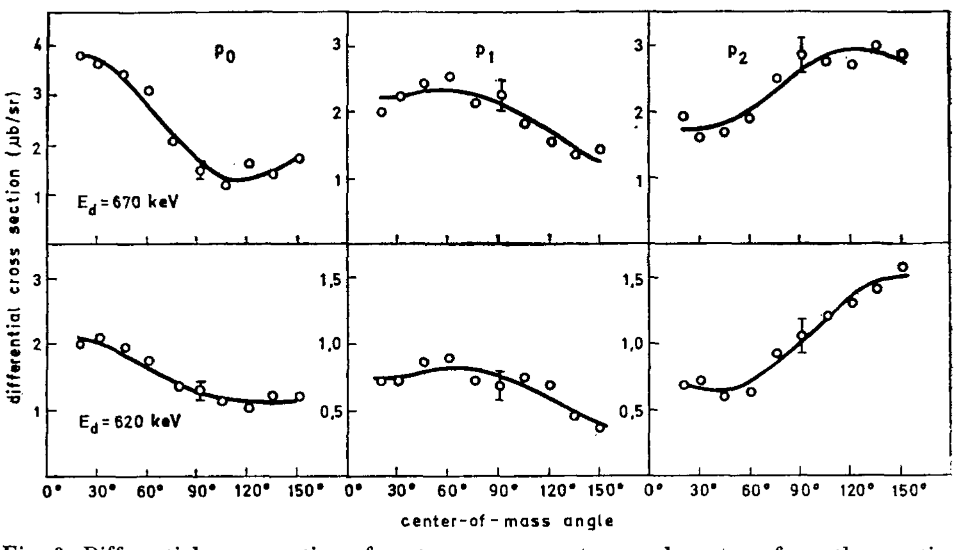

Fig. 3. Differential cross section of proton groups $p_3 + p_4$ and $p_5 + p_6$ from the reaction ^{23}Na(d,p)^{24}Na. (Dotted lines represent the DWBA fit, solid lines the Legendre polynomials fit)

direct and the compound nucleus mechanisms, whereas the reaction mechanism of proton groups $p_3 + p_4$ and $p_5 + p_6$ can be attributed mainly to direct interaction process.

Table I

Coefficients of the Legendre polynomials

$$\frac{d\sigma}{d\Omega} = \sum_{l=0}^{n} A_l P_l (\cos \Theta)$$

Index of proton groups	E_d (KeV)	A_1/A_0	A_2/A_0	A_3/A_0	A_4/A_0	χ^2
p_0	670	0.58±0.06	0.42±0.08	−0.19±0.09		2.0
	620	0.36±0.03	0.17±0.05			0.7
p_1	670	0.29±0.05	−0.18±0.07			1.2
	620	0.31±0.06	−0.26±0.09			1.1
p_2	670	−0.29±0.04	−0.13±0.06	0.11±0.08		1.3
	620	−0.52±0.04	0.08±0.05	0.12±0.06		1.0
$p_3 + p_4$	670	−0.59±0.02	−0.44±0.03	0.22±0.03	0.34±0.04	0.6
	620	−0.59±0.02	--0.41±0.03	0.34±0.03	0.34±0.04	2.8
$p_5 + p_6$	670	−0.57±0.02	0.13±0.03	0.25±0.04	0.32±0.05	1.5
	620	−0.50±0.04	0.01−0.04	0.24±0.07		1.3

Table II

Potential parameters used in the DWBA calculations [10, 11]

Potential label	Deuteron	Proton
V_0(MeV)	50	55
r_v(fm)	1.5	1.25
a_v(fm)	0,6	0.65
W_0^{vol}(MeV)	15	—
W_0^{surf}(MeV)	—	20
r_W(fm)	1.5	1.25
a_W(fm)	0.6	0.47
r_c(fm)	1.3	1.25

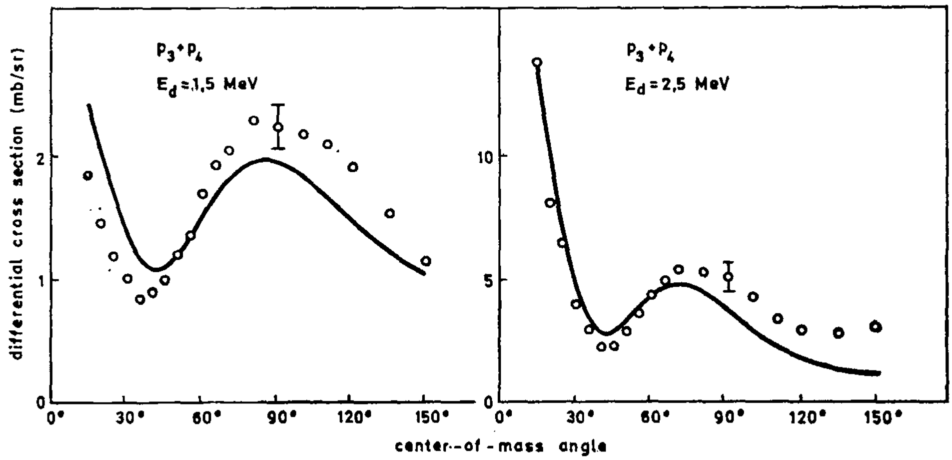

Fig. 4. Differential cross section of proton groups $p_3 + p_4$ of the reaction ^{23}Na(d,p)^{24} Nafrom [6]. (The lines represent the present DWBA calculations)

Table III

Quantities $[(2J_f + 1)/(2J_i + 1)]S_{l_n}$ obtained from present DWBA analyses and from earlier results

Index of proton groups	E_d (MeV)	$[(2J_f + 1)/(2J_i + 1)]S_{l_n}$		χ^2
		$l_n = 0$	$l_n = 2$	
$p_3 + p_4$	0.62	0.59	0.81	1.2
	0.67	0.59	0.73	2.1
	7.8[a]	0.62	(0.37)	
	1.5[b]	0.73	2.6	3.9
	2.5[b]	0.52	1.4	6.4
$p_5 + p_6$	0.62	0.13	0.41	2.9
	0.67	0.22	0.73	1.4
p_5	7.8[a]	0.20	(0.39)	
p_6	7.8[a]		0.29	

[a] [5]

[b] Calculations for experimental results from [6]

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