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ON THE MECHANISM OF THE INELASTIC SCATTERING 9.6 MeV PROTONS ON ^{27}Al

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Differential cross sections for ^{27}Al(p, p')^{27}Al have been measured at 9.6 MeV in the range 25°–150° for the inelastic proton groups corresponding to 17 excited states of Al. The energy resolution was about 70 keV.

It is shown that, similarly to the results obtained previously by other authors for 9 MeV neutrons, DWBA+Hauser-Feshbach calculation does not reproduce the experimental angular distributions nor can it explain the observed CN reduction factors.

Possible reasons for the observed discrepancies are discussed.

1. *Introduction*

The inelastic scattering of low-energy nucleons on ^{27}Al has been extensively studied in earlier works [1–8]. Although many details of its mechanism have been fairly well established, the problem is still open in the energy region about 10 MeV, where a strong competition of the direct and compound processes is expected.

The low-lying levels of ^{27}Al are interpreted as the members of the collective multiplet formed by a coupling of the hole $d_{5/2}$ and 2^+ phonon of ^{28}Si core. For these levels the excited-core model of the direct inelastic scattering are expected to be valid. For all levels a significant CN contribution is expected in (p, p'). It can be calculated using the conventional Hauser-Feshbach (HF) method.

In the simplest approach the differential cross section for the collective level is the noncoherent sum of the direct and CN contributions provided that both, the interference of the direct and CN amplitudes and the Ericson fluctuations, are negligible. For highly excited levels, the direct contribution is expected to be low so that the cross section is determined by CN contribution only.

Recently it has been reported that for the inelastic scattering of 8 and 9 MeV neutrons on ^{27}Al such approach is not valid even though it works well for the other nuclei [7].

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In the present work analogous measurements and calculations were performed for the inelastic scattering of 9.6 MeV protons. In comparison with the previously cited references, the measurements were extended to include the inelastic proton groups corresponding to the 17 excited levels of ^{27}Al up to 5.7 MeV excitation energy.

2. *Experimental procedure*

All measurements have been performed on the 9.6 MeV proton beam from the Proton Linear Accelerator in the Institute of Nuclear Research in Świerk. The beam was energy analysed in a 60° magnet and focused by the set of the quadrupole lenses in the 100 cm scattering chamber. The target of 30 keV thickness was set at 45° to the beam direction. Two silicon surface-barrier detectors were mounted in the scattering chamber. The first one, at 90° to the beam direction and the second one on the movable arm allowing the change of the scattering angle in the range from 0° to 180°.

Pulses from 90° detector were used for the monitoring of the beam. Pulses from the movable detector were analysed using TRIDAC multichannel analyser. The multichannel analyser was gated in such a way that the ADC was open only when proton beam burst was present on the target.

The peak beam current used during the experiment was about 500 nA.

In such experimental conditions the total energy resolution of the proton spectrometer was 85–100 keV, depending on the scattering angle. The estimated contribution from the energy spread of the incident beam was about 70 keV.

The spectra of the scattered protons were measured in the range of 30°–150° in steps of 5° lab.

The angular distributions were calculated from the ratios of the corresponding inelastic and elastic peak areas. The absolute values of the cross sections were calculated assuming the value of 50 mb for the elastic scattering at 60° in accordance with the results of Ref. [9] for 9.8 MeV.

In the estimation of errors, the following factors were taken into account: the statistical errors, the error in the determination of the scattering angle and the absolute cross section calibration error which, in accordance with Ref. [9], was taken to be ±5%.

3. *Experimental results*

The inelastic differential cross sections were measured for the following excited levels of ^{27}Al: 0.842, 1.013, (0.842+1.013), 2.212, 2.73, 2.98+3.0, 3.67, 3.95+4.06, 4.40+4.50, 4.81, (4.40+4.50+4.81), 5.15+5.24, 5.41+5.49+5.67 MeV. The numbers in the parentheses indicate that in the cases when peaks were badly resolved the sum of the respective cross sections were calculated.

The differential elastic cross-section obtained in the present experiment agrees with the data obtained for 9.06 and 9.37 MeV by Greenless [10] and with 9.85 MeV data reported by Hintz [9].

The experimental inelastic cross sections are plotted in Fig. 1a and 1b together with the results of the calculations which will be described later. The errors indicated are statistical ones only. The significant deviations of some of the experimental points exceeding the values which may be expected from the errors indicated are probably due to the un-

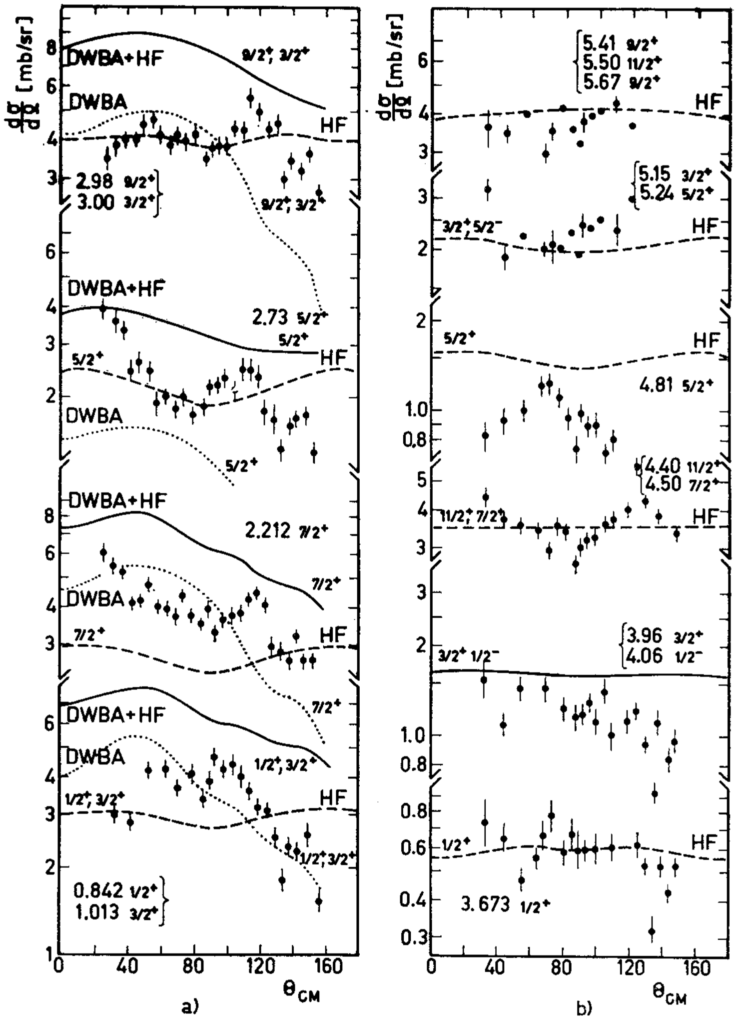

Fig. 1. Examples of the experimental differential cross sections for ^{27}Al(p, p′) at 9.6 MeV compared with the theoretical calculations: a) Proton groups corresponding to the levels of the collective $2^{+}\otimes d_{5/2}$ multiplet compared with the DWBA+HF curves; b) Proton grups corresponding to the other levels compared with the pure HF calculations

certainty in the estimation of the background level during the calculations of the inelastic peak areas.

For the inelastic groups considered, the integrated cross sections $\int_{30}^{150} \sigma(\theta) d\Omega$ have also been estimated and the numerical values are shown in Table I. No errors are indicated

TABLE I

Estimated values of the integrated cross sections for $^{27}Al(p, p')^{27}Al$ at 9.6 MeV

$-Q$ [MeV]	Spin	$\int_{30}^{150} \sigma(\theta) d\Omega$	$\sum_i \int \sigma_i$ [mb/sr]
0.842	1/2+	16.3	39.4
1.013	3/2+	23.7	
2.212	7/2+	44.3	
2.731	5/2+	24.0	
2.976	9/2+		45.3
3.000	3/2+		
3.674	1/2+	7.1	
3.959	3/2+		12.5
4.057	5/2+		
4.40	11/2+		42.3
4.50	7/2+		
4.81	5/2+	12.0	
5.15	3/2+, 5/2+		22.4
5.24	3/2−, 5/2−		
5.41	9/2+		45.0
5.49	7/2+, 9/2+, 11/2+		

because the estimation is rather crude due to the relatively large spread of the experimental points and a lack of points at backward angles for some of the levels. We expect the accuracy of this estimation to be about 20–30 per cent.

4. *Calculations*

4.1. Elastic scattering. Comparison with the optical model calculations

The optical model calculations of the elastic scattering were performed using ELSIG procedure of DWUCK distorted wave programme. The potential parameters were taken in accordance with the Perey work [11] and are listed in Table II.

The sum of the optical and CN elastic cross sections was compared with the experimental data. It was found that for CN reduction factor $R = 0.5$ deviations of the experimental points from the calculated curve are within the limits of fluctuations observed by the other authors for experimental angular distributions [9, 10]. These fluctuations are probably caused by intermediate structure resonances.

4.2. Compound inelastic scattering. Hauser-Feshbach calculations

The differential cross sections for compound inelastic scattering were calculated using the Hauser-Feshbach method modified to include the spin-orbit coupling [12] and the width fluctuation correction [13]. For this purpose the code LIANA [14] was adapted for CDC 3170.

In the calculations three particle channels have been simultaneously taken into account, namely (p, p), (p, n) and (p, α). Proton transmission coefficients were calculated using the same optical potential parameters as before. Neutron and alpha-particle potential parameters were taken to be similar to those reported in [7] and [15], respectively. They are listed in Table II. All optical potential parameters were treated as energy independent.

TABLE II

The parameters of the optical potential for protons, neutrons and alpha-particles used in the calculations

Particle	V_R	r_R	ϱ_R	W_D	r_I	a_I	V_{SO}	r_{SO}	a_{SO}
Protons 17.5 MeV	42.7	1.3	0.65	6.1	1.3	0.44	7.5	1.3	0.65
Protons 9.6 MeV	50.7	1.25	0.65	6.33	2.25	0.47	7.5	1.25	0.47
Neutrons 9.0 MeV	47,0	1.27	0.72	11.3	1.27	0.47	8.8	1.27	0.72
α	150.0	1.35	0.5	5,0	1.35	0.5	—	—	—

The differential Al(p, p′) cross sections were calculated for all levels observed in the experiment. The results of HF calculations are plotted in Fig. 1a and 1b.

To check the overall consistency of the calculations the differential cross sections were also found for n_0, n_1 and n_2 groups in ^{27}Al(p, n) reaction and α_0, α_1, α_2 and α_3 groups in ^{27}Al(p, α) and compared with the experimental results of Anderson et al. [16] for (p, n) reaction at 9.6 MeV and with Shaw et al. [17] data for (p, α) reaction at 9 MeV. It was found that the agreement is satisfactory within the limits of the experimental errors both in the angular distributions and absolute values of the cross sections.

The integrated cross sections calculated for Al (p, p′) were compared with the experimental data. Calculated values reasonably agree with the experimental data except of those for 2.212 MeV and 4.81 MeV levels.

4.3. Direct inelastic scattering in DWBA

Direct inelastic scattering has been calculated in DWBA using the programme DWUCK, a version adapted for CDC 3170. The calculations were performed for the excitation of the levels of the $2^+\otimes d_{5/2}$ multiplet and for ^{28}Si(p, p′)^{28}Si(2$^+$) scattering. The real collective inelastic formfactor was assumed for the angular momentum transfer $\Delta L = 2$, $\Delta S = 0$. The Coulomb part of the formfactor was also included. The optical potential parameters for both, the incident and outgoing, waves were taken from Perey [18]. The absolute values of the cross sections were calculated as,

$$\sigma_{Al}(J) = \frac{(2J+1)}{30} \cdot \beta^2 \cdot \sigma_{DWUCK}.$$

The dynamical deformation parameters β were taken from the experimental work [6]. These experimental values are different for each member of the collective multiplet. It is caused by the level mixing observed, for example, in ^{27}Al(d, d′) scattering for the case of $5/2^+$ levels [19]. Thus, the effect of the level mixing is automatically taken into account in our calculations.

5. Comparison with the experiment

In Figs 1a and 1b the DWBA curves are plotted. The noncoherent sum of DWBA and HF cross sections is also presented and compared with the experimental data. The main results are summarized as follows:

(*i*) The angular distributions corresponding to the levels of the $2^+ \otimes d_{5/2}$ multiplet are shown in Fig. 1a. A forward peaking characteristic for direct processes is seen for the 2.212 MeV $7/2^+$ and 2.73 Me^{2}V $5/2^+$ levels. For the same levels, the similarity of the angular distributions, required by the excited-core model, is observed. It is not fulfilled, however, for the remaining $1/2^+$, $3/2^+$ and $9/2^+$ levels.

In general, neither the pure DWBA nor DWBA+HF curves can reproduce the observed cross sections. Some of the calculated HF values are also overestimated. It is especially evident at backward angles for the curves corresponding to the $5/2^+$ level.

(*ii*) The differential cross-sections for the levels with E_x = 3.6–5.6 MeV reasonably agree with HF predictions (Fig. 1b). The only exception is the proton group corresponding to the 4.81 MeV level for which the calculated cross section exceed approximately twice the observed values.

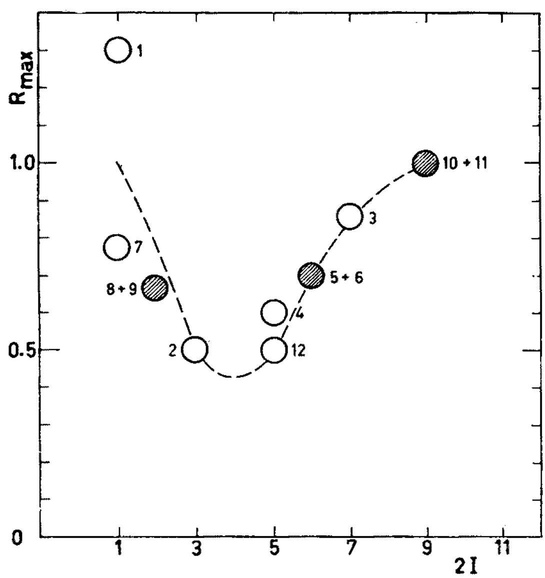

Fig. 2. R_{max} as a function of the spin of the final nucleus. Open circles: Proton groups corresponding to single levels. Full circles: Proton groups corresponding to doublets. In the case of doublets, average spin value was attributed to R_{max}. *1* — 0.842 MeV, *2* — 1.013 MeV, *3* — 2.212 MeV, *4* — 2.73 MeV, *5* — 2.98 MeV, *6* — 3.0 MeV, *7* — 3.67 MeV, *8* — 3.96 MeV, *9* — 4.06 MeV, *10* — 4.40 MeV, *11* — 4.50 MeV, *12* — 4.81 MeV

(*iii*) Neglecting the contribution of the direct scattering at extreme backward angles, the CN reduction factor R_{max} necessary to get an agreement of HF and experimental values, can be crudely estimated. The plot of R_{max} as a function of the spin of the final nucleus is shown in Fig. 2. A significant deviation of R_{max} from unity is observed for the spin values close to 5/2.

According to Ref. [21] this deviation suggests the influence of direct processes on CN cross section through the incident flux conservation. In order to estimate the contribution of the direct inelastic scattering to this effect the generalized transmission coefficients of Yoshida [22] were calculated using DWBA matrix elements. Then, HF calculations were repeated using these coefficients in the incident channel. The obtained change of the cross section is of the order of several per cent so that it cannot explain the observed values of the reduction factors.

6. Conclusions and discussion

It is evident that, similarly to the ^{27}Al(n, n′) case, the inelastic scattering of protons on ^{27}Al at 9.6 MeV cannot be described as a noncoherent sum of DWBA+HF contributions at least when an ordinary collective quadrupole formfactor is assumed in DWBA. The following reasons for these disagreements may be considered:

(*i*) The extrapolation of the excited-core model of the inelastic scattering to the incident energy $\approx$ 10 MeV is not valid and the other inelastic formfactor should be taken into the calculations. To check this, a microscopic calculations using many-particle wave functions of the excited states of ^{27}Al should be very useful.

(*ii*) The influence of the Ericson fluctuations and/or intermediate resonances which were neglected in the calculations.

The fact that the discrepancies are observed for rather large energy spread of the incident beam suggests that their origin is connected with the existence of intermediate resonances rather than with the Ericson fluctuations.

The main feature of the observed discrepancies is that the nonstatistical contribution to (p, p′) process, calculated in DWBA, is not adequate. The calculated values of the direct cross sections are in general overestimated and the shape of the angular distributions does not fit to the experimental points. The same was observed previously in [7] for the inelastic scattering of 9 MeV neutrons on ^{27}Al.

One can expect that if the intermediate resonances play an important role, a significant part of the direct contribution is damped because of the absorption of the direct inelastic wave leading to the formation of the resonances. The particles from the decay of the resonance should feed the excited states of the final nucleus in a more uniform way than it is in the case of the direct process. The existence of such absorption has been recently considered by Rao et al. [23]. According to this paper the resonances formed by a coupling of a particle and the quadrupole vibrations of the target nucleus play an important role. They should appear for the target nuclei having the vibrational excited states, for the incident proton energies equal to the sum of the partial wave resonance energies in the optical potential well and the quadrupole phonon energy.

For the optical potential used in this work for $^{27}Al+p$ the $d_{5/2}$ partial wave resonance exists at 5 MeV so that the collective intermediate resonances may appear in the energy region centered at 7–8 MeV, not very far from the energy used in the present experiment.

The intermediate resonances of this kind are characteristic for the interaction of the nucleons with the target nucleus, so that they may not appear in (d, d′) or (α, α') processes. It may be the reason why for the last two processes the excited-core model is adequate even for the relatively low energies [19, 20].

The incident proton energy $\approx$ 10 MeV corresponds to the maximum of the excitation probability of the giant dipole resonances in ^{27}Al(p, γ) ^{28}Mg reaction. Therefore, the other interesting kind of the intermediate resonances which can be involved in (p, p′) reaction are those connected with the excitation of giant resonance in the compound system.

To elucidate this point the experiment should be further extended to include simultaneous measurements of the angular distributions for many groups of the inelastically scattered protons in the relatively broad range of the incident energies, say, from 8 to 12 MeV. The excitation functions after being averaged over the Ericson fluctuations should be analysed in terms of the direct, intermediate resonance and statistical components simultaneously. To our knowledge, such experiment and analysis has not been performed yet.

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