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ELASTIC AND INELASTIC SCATTERING OF 14 MeV NEUTRONS FROM ^{28}Si (*)

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A B S T R A C T

The scattering of 14 MeV neutrons from ^{28}Si is studied. Differential cross-sections are measured for the elastic scattering and for the inelastic scattering from the first excited level with the time of flight and associated particle method. The integrated cross-sections are also derived.

The experimental results are compared with the theoretical predictions based on different forms of the optical model.

The nuclear deformation parameter related to the first excited state is derived and compared with the values obtained with other procedures.

A fairly good agreement is obtained throughout using a distorted wave approximation with selected optical parameters.

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1. - INTRODUCTION

Recently the scattering of fast neutrons by nuclei has been used with the aim of studying the direct interaction reactions and the related processes of collective states excitation [1]. The nuclei which have been studied are not confined to a particular class but range from heavy nuclei such as Pb to nuclei like Sn and to the lighter ones like Li.

By studying the elastic and inelastic scattering of fast neutrons by nuclei, as in the case of the nuclear reactions due to charged particle (p, d, α, etc.) information can be obtained concerning the angular momentum transfer, the parity charge, the restriction in the possible values of the spin of the excited states, the nuclear deformation parameter. In order to extract such information from the experimental data it is however necessary to apply some theoretical model.

The theories which claim to interprete the fast neutron scattering data are numerous. In the low range of incident energy the compound nucleus interaction is generally taken into account; but at the higher energies there seems to be a substantial contribution of the direct interaction mechanism with excitation of collective levels. In this last case the compound nucleus interaction turns out to be almost inexistent or at last very low [2].

From the theoretical point of view there is no foundamental difference between the elastic and inelastic scattering, since both of them represent successive steps of the same process. But from the experimental point of view the data concerning the inelastic scattering are much more effective in providing a valuable check for the theories.

Among the light nuclei, ^{28}Si plays a particular role because it is placed near the upper end of the series of the so called light nuclei, it is characterized by having a filled $d_{5/2}$ shell, it has a zero spin and a quadrupole moment presumably zero.

The elastic and inelastic scattering of charged particles by ^{28}Si has been studied with protons of energy in the range of 10 - 12.3 MeV(3), and of energy of 155 MeV (4), with deuterons of energy of 8 MeV (5) and with alphas of energy of 28.5 MeV (6). The experimental results generally agree with the theoretical predictions based upon the direct interaction model making use of optical potentials and assuming collective level excitations. In the case of the (p, p') angular distribution at 155 MeV the authors find that there is a disagreement with the (n, n') angular distributions, because the diffraction patterns are missing.

The elastic and inelastic scattering of 14 MeV neutrons from ^{28}Si has been studied by Clarke and Cross (7), Martin et al.(8), Stelson et al. (9). The results of Clarke and Cross agree with those of Martin et al.; the results of Stelson et al. are slightly lower than the previous ones.

It has to be noted that the experimental methods are different: Clarke and Cross, and Martin et al. have used the time of flight method with associated particle, Stelson et al. have used the beam bunching method and the ring geometry.

In the work of Stelson et al. it is remarked that, because of the intimate nature of the scattering process, the inelastic component of the scattering can contaminate appreciably the elastic one. This is specially true in the case of nuclei with the highest quadrupole distortion since then the relative cross sections are comparable at least for some scattering angles. The variations between the two measurements are however not much pronunced and could be interpreted within the error limits if a systematic trend occurring in the whole range of angles and in both the elastic and inelastic scattering was not observed. This behaviour has not so much influence in the determination of the optical model parameters satisfying the elastic scattering as it has in the calculation of the deformation parameter relative to the lowest line of the collective state excited by the incoming neutron.

The present measurement is intended to give a contribution to the knowledge of the scattering of 14 MeV neutrons by ^{28}Si.

2. - EXPERIMENTAL PROCEDURE

The energy spectra of the scattered neutrons from a natural silicon sample (compacted powder, 92·2% of Si^{28}) were determined by a time - of-flight technique and the associated particle method. Neutrons from the $T(d,n)\ He^{4}$ reaction were produced by 200 KeV deuterons striking a thick Tritium - Zr target. After being scattered by the sample the neutrons were detected by a NE-VH2-213 liquid scintillator coupled with a 56 AVP; the associated alfa particles were detected by a very thin (0.1 mm) plastic scintillator coupled with another 56 AVP photomultiplier. The width of the neutron beam was determined by the geometry of the alpha detector: the beam had an approximately gaussian profile in the scattering plane with a maximum width of 2° degrees. From the energy of the incident deuterons and the emission angle of neutrons the energy of the beam was estimated to be 14.2 MeV, its energy spread being about 150 KeV.

The scattering sample was in the form of a rectangular slab, placed so as to subtend completely the cone of the neutron beam. It was rigidly connected with the alpha counter so that both could rotate together around the axis of the deuteron beam, while the neutron counter remained fixed. This arrangement allowed the insertion of bored iron discs between the sample and the neutrons detector to improve the shield of the detector, which was as usual formed as a lead cylinder surrounded by paraffin blocks.

The output pulses from the photomultipliers were fed to the electronics, partially transistorized, and displayed on a 200 channel analyzer, gated by the slow coincidences between the outputs of the side - channel discriminators following the two particle detectors. The time resolution of the system, due principally to the flight time of neutrons in the neutron scintillator, was about 1.50 nsec, corresponding to a resolution in energy of 0.96 MeV at 14.2 MeV.

Several measurements have been performed in order to ascertain the linearity of the electronics, the relative sensitivity of the neutron detector at different energies, the time scale of the analyzer and the background coincidence rate; all results are reported in Ref. ([10]).

The ratio of time-to-background coincidences is know to be, in the case, inversely proportional to the source intensity; therefore the neutron yield was forcely maintained low enough to obtain a good compro mise between the interference of the background and the time of the measurement.

The differential cross section at all angles was obtained with the formula:

$$\sigma(\Theta) = \frac{N}{N_0} \frac{1}{\mathcal{N} \Omega \epsilon f} \qquad (1)$$

where:

$\mathcal{N}$ is the number of scattering nuclei per cm^2 in the scattering sample;

Ω is the angle subtended by the neutron detector;

ϵ is the efficiency of the neutron detection;

f is a factor which takes into account the absorption of neutrons and their multiple diffusion in the scatterer;

N_0 is the number of α particles detected in the associated particle detector, and corresponds to the number of neutrons impinging on the scatterer; assuming unity its efficiency;

N is the number of neutrons detected after scattering.

This last number was deduced by computing the area subtended under the elastic - or inelastic peak. This determination was not always simple and precise, particularly when the elastic peak was rather high with respect to the inelastic one; in this case a double procedure was followed. The first one consisted in fitting by hand the experimental peaks with gaussian curves and estimating their relative contribution to the total area covered by them; the second one was a mathematical method which allows the damping of statistical fluctuation on the analyser channel (11). A compromise of the two was often followed.

The correlated background was measured for several scattering angles and it was found that it practically corresponded to the background detected in the energy range preceding the elastic scattering peak. So it was rather easy to evaluate it.

3. - RESULTS

The experimental values of the differential scattering cross sections for 14 MeV neutrons for the ground state and the first excited state (1.78 MeV) of ^{28}Si are reported in Table 1. In the first column are listed the angles, in the center-of-mass coordinate system, at which the measurements have been performed; in the second and third columns are reported respectively the differential elastic and inelastic cross-sections, expressed in millibarns/sr.

Table 1. - Elastic and inelastic cross-sections for 14 MeV neutrons from ^{28}Si.

$\vartheta_{c.m.}$	σ_ϑ (Q = 0) (mb/sr)	σ_ϑ (Q = -1.78) (mb/sr)
20°	$6.29 \pm 0.18 \cdot 10^{-25}$	$1.55 \pm 0.40 \cdot 10^{-26}$
30°	$1.35 \pm 0.59 \cdot 10^{-25}$	$1.00 \pm 0.14 \cdot 10^{-26}$
40°	$1.58 \pm 0.13 \cdot 10^{-26}$	$1.59 \pm 0.13 \cdot 10^{-26}$
50°	$2.88 \pm 0.21 \cdot 10^{-26}$	$2.42 \pm 0.19 \cdot 10^{-26}$
58°	$6.04 \pm 0.33 \cdot 10^{-26}$	$1.38 \pm 0.17 \cdot 10^{-26}$
65°	$7.85 \pm 0.29 \cdot 10^{-26}$	$1.43 \pm 0.12 \cdot 10^{-26}$
70°	$4.75 \pm 0.31 \cdot 10^{-26}$	$9.60 \pm 0.14 \cdot 10^{-27}$
90°	$1.23 \pm 0.16 \cdot 10^{-26}$	$8.38 \pm 0.10.10^{-27}$
110°	$8.90 \pm 0.11 \cdot 10^{-27}$	$4.17 \pm 0.81 \cdot 10^{-27}$
120°	$1.57 \pm 0.17 \cdot 10^{-26}$	$7.32 \pm 1.51 \cdot 10^{-27}$

The cross section value at 20 C.M. shown in Table 1 is the experimental one slightly corrected taking into account the correlate background contribution, which is rather high at this angle and difficult to evaluate. The correction factor has been derived from a comparison between the measured differential cross section of the ^{12}C and its mean value reported in the literature (7,12), both relative to the same angle and incident neutron energy as for the ^{28}Si. The correction was of the order of 25%.

The uncertainty of the scattering angle in the scattering plane is of the order of ±3°. The errors reported are statistical ones and are obtained from the number of events under the peak area, and considering the background contribution.

Figure 1 shows the angular distributions of the elastically and inelastically scattered neutrons. For the sake of easily inspecting the general trend of the data and comparing them with the data of other authors, curves have been traced by eye through the experimental points.

The inelastic scattering from ^{29}Si and ^{30}Si, which altogether amount to about 8% of natural Si, would not be expected to distort the angular distribution of the first excited state of ^{28}Si by more than a few percent. Although there was evidence in the experimental spectra of the existence of higher states of ^{28}Si, no attempt has been made to derive the corresponding angular distribution curves.

As can be seen from Figure 1, the present measurements agree fairly well with those of Clarke and Cross and also with those of Martin et al. The results of Stelson et al. are systematically lower.

From experimental results one can derive also the integrated elastic differential cross-section over all angles; the value obtained is 0.75 ± 0,7 b, in agreement with the value of 0,75 b reported by Clarke and Cross (7). Theoretical curve has been used to extrapolate the experimental distribution to small or high angles where no experimental points were available. The calculated integrated cross - section using the curve from optical model, as explained in the following, is 0.769 b. The total cross section for the scattering, of 14 MeV neu

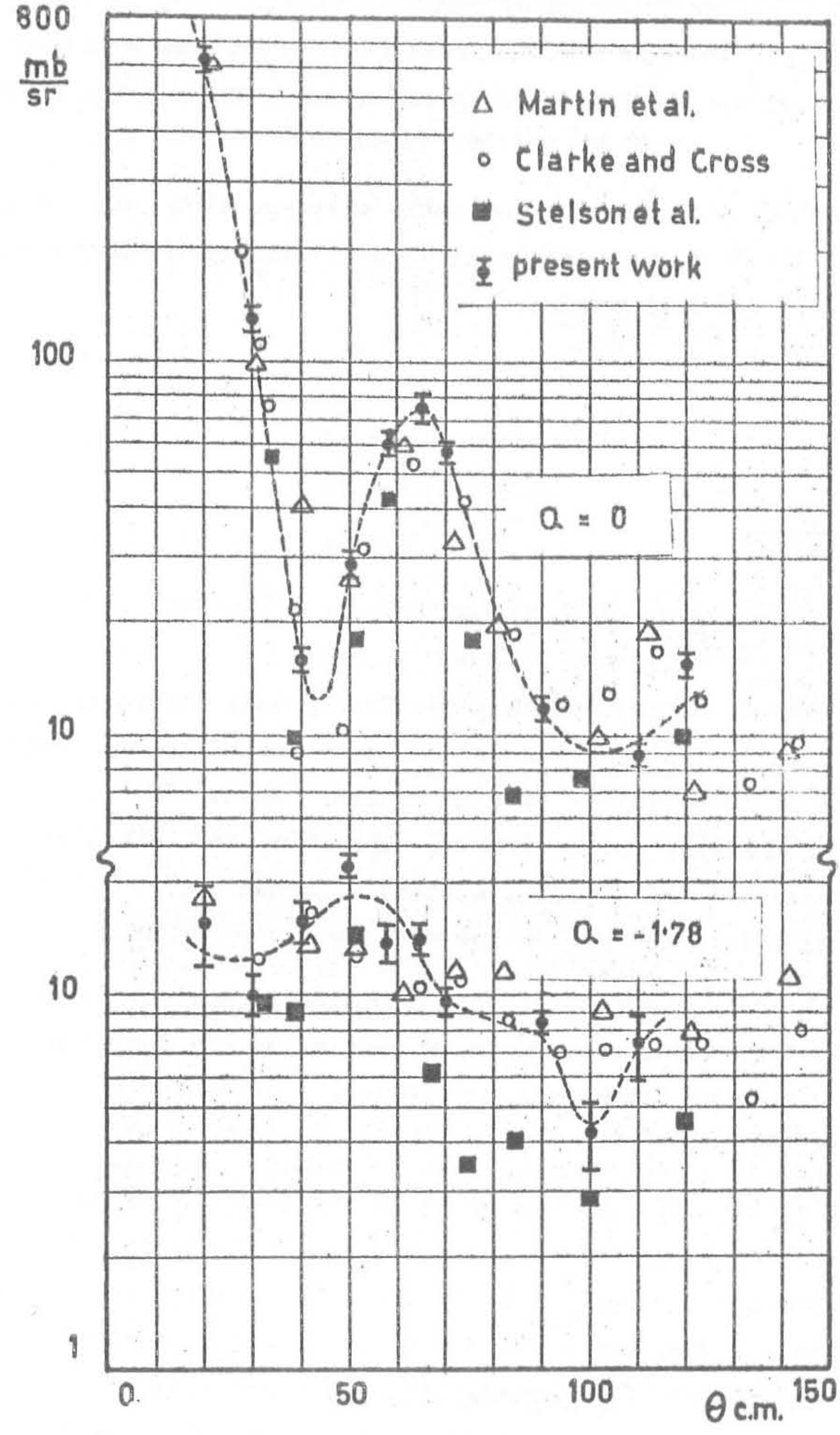

Fig. 1 - The differential cross sections for elastic (Q = 0) and inelastic (Q = -1.78) scattering of 14 MeV neutrons from silicon. The curves are explained in the test.

nucleus may suggest, as in several similar cases, the presence of a direct interaction mechanism where a surface interaction may play an important role and the interaction potential can assume different forms. A general study of the inelastic scattering with direct interaction and using the distorted waves has been carried out by Glendenning (21) particularly for the case of the inelastic scattering of 15 MeV neutrons from an hypothetical nucleus with A ~ 30.

The curve referring to the transition from the 0^+ to the 2^+ states is reported in Figure 3. It shows a general agreement with the experimental points, specially around 110°C.M. where the cross-section tends to let down.

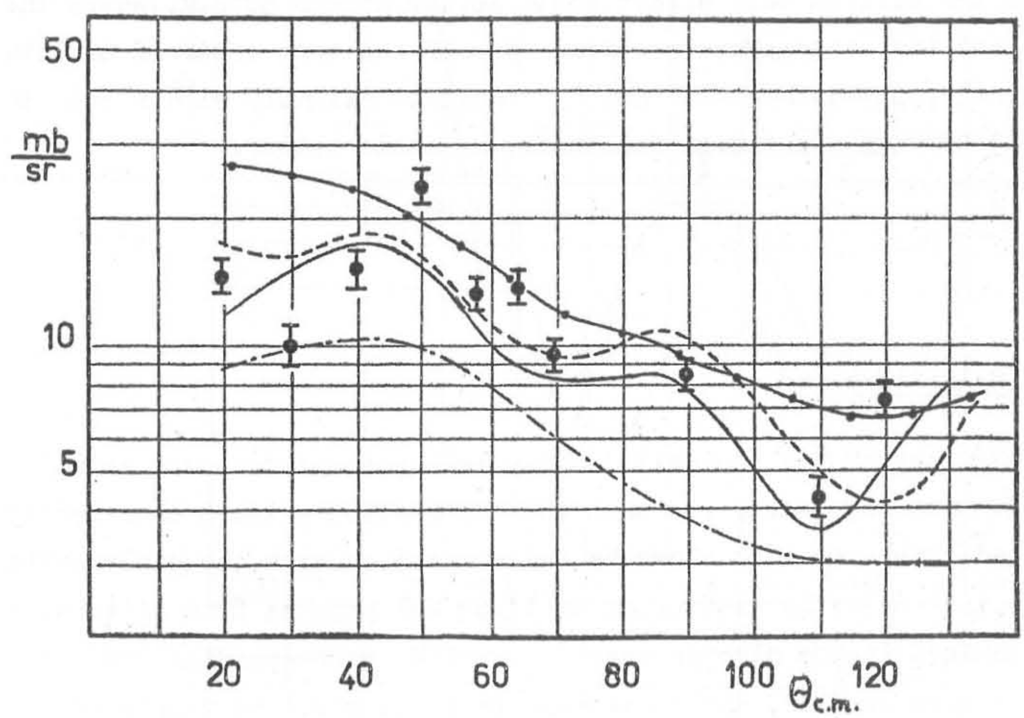

Fig. 3 - Obseved differential cross-sections for the inelastic scattering to state in ^{28}Si at 1.8 MeV, and comparison with other results:

—•—•— Inelastic scattering of 11.98 MeV protons Cohen and Cookson (3)
- - - - - Theoretical curve from Glendenning (21)
——— Theoretical curve from Clarke and Cross (7)
—·—·— Theoretical curve from Stelson et al. (9)

A better agreement is however obtained with the calculations of Clarke and Cross (7). Their calculations, based on the distorted waves Born approximation, make use of a generalized optical potential where both the real and the immaginary parts of the potential have an energy dependence of the type:

$$V = V_0 + \frac{1}{2} E, \quad W_s = W_0 - \frac{1}{2} E, \quad V_0 = 51 \text{ MeV}, \quad W_0 = 0.$$

Moreover, a volume interaction with a constant potential of -2 MeV is introduced besides the surface interaction.

The most important feature of the theory consists in the introduction of a nuclear radius dependent on the angle. This means to suppose that in the interaction comes into play a quadrupolar deformation following a collective excitation of the 2^+ state. In fact, also if the initial and final states of the nucleus have energies that can be determined on the basis of an independent particle model and a spherical potential, there is still present a collective enhancement often dominating the single particle contribution.

The theory can be then naturally developed as an extension of the optical model including non spherical potentials, whic, in the successive perturbative treatment, are assumed to induce the inelastic scattering from these vibrational or rotational collective states.

The nuclear radius appearing in the optical potential is assumed equal to

$$R(\Theta) = R_0 \left[1 + \Sigma_\mu \alpha_{\ell\mu} Y_\ell^\mu (\Theta \Phi) \right]$$

for a spherical nucleus with quadrupolar vibrations, being $\ell = 2$ for the $0^+ \rightarrow 2^+$ transition. The quantity $\langle \Sigma_\mu (\alpha_{2\mu})^2 \rangle$ is equal to the nuclear deformation parameter, β_2^2, which is also dependent on the reduced electromagnetic transition probabilities B (E2) that is,

$$\beta_2^2 = \frac{B(E2): 0 \rightarrow 2)}{\left[\left(\frac{3}{4\pi}\right) Z e R_c^2 \right]^2} \qquad (R_c = 1.2 \, A^{1/3} 10^{-13})$$

as can be derived: from the Coulomb excitation fenomena (22), from the high energy electron scattering (23), from measurements of the half life of resonance fluorescence (24).

Stelson et al. ([9]) using a generalized optical model have calculated the differential inelastic scattering for the first order, which fits better their experimental results.

This curve, as reproduced in Figure 3, appears to be lower than the other curves as much as the experimental points are lower. From their calculations Stelson et al. have also deduced for β_2 the value 0.40.

Observing that the value of β_2^2 does not affect the angular distribution of the cross-section, but only its absolute value, one can shift the Stelson's curve and normalize it to the value at 40°, for example. In this way, one obtaines for β_2 the value 0.48.

The value of the deformation parameter for silicon has been derived several times either with electromagnetic methods or from the neutron inelastic scattering. The results are summarized in Table 2.

There is a reasonable agreement among the data in spite of their being deduced with different methods. Moreover it may be observed that the same value of R_0 is assumed in all cases and principally that many sources of errors affect the calculations.

Table 2 - Summary of quadrupole deformation parameters, β_2 found from electromagnetic measurements and inelastic neutron scattering.

a	b	c
0,44[a]	0.36[c]	0.43[e]
0.40[b]	0.48[d]	0.40[f]
		0.48[g]

a - values from resonance life times; [a]Ref.([23]), [b]Ref.([25])

b - values from high energy electron scattering; [c]Ref.([26]), [d]Ref.([27])

c - values from (n, n') scattering at 14 MeV; [e]Ref.([7]), [f]Ref.([9]) and [g]Present work.

5. - CONCLUSION

The angular distributions of the neutrons scattered from silicon agree much better with the data of Martin et al. ([8]) and of Clarkeand Cross ([7]) than with those of Stelson et al. ([9]). Anyway the experimental results follow satisfactorily the theoretical predictions based upon the distorted wave approximation with different optical model parameters. Although the Si nucleus is close to the lower limit of the range of nuclei where the optical model can be thought to be applicable, the agreement between the experimental data and the theoretical predictions may be regarded as confirming that the model is effectively still valid in this case as well.

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