CHAPTER VI

APPLICATION OF PLASTIC TRACK DETECTOR FOR THE STUDY OF
$^{27}\text{Al} \ (d,\alpha) \ ^{25}\text{Mg}$ NUCLEAR REACTION IN THE ENERGY RANGE

$E_d = 650 - 540$ keV

6.1 Introduction

The measurements of the angular distributions and
the excitation functions of the $\alpha$-groups emitted in the
$^{27}\text{Al} (d,\alpha) \ ^{25}\text{Mg}$ nuclear reaction below 5 MeV, more
specifically at bombarding energies $1.2 - 2.0$ MeV, $^{168}$
$1.4 - 2.3$ MeV, $^{169}$ $1.5 - 2.3$ MeV, $^{170}$ $1.5 - 2.6$ MeV, $^{171}$
$2.0 - 5.0$ MeV, $^{172}$ and $2.4 - 2.6$ MeV $^{173}$ give results
characteristic of the statistical compound reaction
mechanism. For individual $\alpha$-groups the excitation
functions show resonance-like maxima and the shape of the
angular distributions varies strongly with the bombarding
energy. Generally these results have been analyzed on
the basis of the statistical compound reaction theory.

Below 1.2 MeV bombarding deuteron energy no data is
available for the $^{27}\text{Al} (d,\alpha) \ ^{25}\text{Mg}$ nuclear reaction. Due to
low bombarding energy as compared to the Coulomb barrier,
the cross-sections in this region become so low that the
measurement of angular distributions by using single
semiconductor detector becomes practically impossible due to
large backgrounds and the errors caused due to the fluctuations in the beam current during long accelerator time needed to collect a worthwhile statistics for various angular settings of the conventional detectors.

Due to their insensitivity to γ-rays, x-rays, protons, β-particles etc. and suitable energy resolution the Cellit-T cellulose acetate plastic detectors could be used for angular distribution measurements of various α-groups from $^{27}$Al (d,α) $^{25}$Mg nuclear reaction even in the bombarding energy range $E_d = 650 - 540$ keV. The discussions of our results and the measuring technique including the problems encountered in the present measurements and the methods used to overcome them will be presented in relevant detail in this chapter.

6.2 Possibility of α-particle Angular Distribution Measurements with Plastic Track Detectors

Our observation of the fact that α-particles of different energy entering normally into a plastic track detector give tracks of different diameters at a given etching time (see Fig. 48 and 33) offers itself as a possibility to select different α-groups emitted in a nuclear
reaction and to measure their angular distributions.
To elaborate this, let us consider the problem in a little more detail by referring to Fig. 49.

**Fig. 49.** Measured track diameter growing curves for $\alpha$-particles of different energies entering normally into the cellulose acetate (Cellit-T) plastic etched in solution B (see Chap. III) at 50°C. The parameter is the etching time in hours. The filled circles represent black tracks which can be counted very well while the open circles denote 'pale' tracks. Note the increasing tendency of the slope with energy which indicates better energy resolution at higher energies. The useful part is shown between two dotted lines.
It has already been mentioned in chapter II that out of a range $R(E)$ of an $\alpha$-particle of energy $E$, only a length $l_0$ measured from the end of the particle trajectory has a preferential etching and as a consequence of this, if the detector is etched only from the side of the irradiated surface (front surface), the tracks of $\alpha$-particles of energy $E$ will appear on the etched surface of the detector only after an

\[ l_0 = R(E_c) \]

\[ l_0 < R(E_c) \]

\[ R(E') \]

\[ R(E) \]

\[ h \]

**Fig. 49.** Showing maximum etchable lengths in the trajectories of $\alpha$-particles of different energies ($E' < E$) entering normally into the plastic track detector. The shadowed parts show the parts of particle trajectories having preferential etch rate.
eating up of \([R(E) - l_0]\) thickness of the material or after an etching time \([R(E) - l_0]/r_B\) where \(r_B\) is the bulk etch rate. In this case the maximum etchable length \(l_0\) is equal to the range \(R(E_C)\) of \(\alpha\)-particle of energy equal to a critical energy \(E_C\) in the material corresponding to the critical P.I. or RSL (see Chap. II). If particles of energy equal to or less than \(E_C\) strike the surface normally, the preferential etching along the track starts just from the surface of the detector and \(l_0\) will correspondingly be equal to or less than the range \(R(E_C)\) of particle having the critical energy \(E_C\).

Usually the plastic detector is etched by simply suspending the whole film into an etchant and so the etching proceeds from both the sides of the detector. Under these conditions, tracks of \(\alpha\)-particles of energy \(E\) incident normally on the detector will first appear on the irradiated surface of the plastic after an etching time

\[
t(E) = \frac{[R(E) - l_0]}{r_B} \quad \text{if} \quad [R(E) - l_0] < [h - R(E)]
\]

or on the back etched surface of the plastic after an etching time

\[
t'(E) = \frac{[h - R(E)]}{r_B} \quad \text{if} \quad [R(E) - l_0] > [h - R(E)]
\]

If \(\alpha\)-particles of two different energies \(E\) and \(E'\) \((E > E' > E_C)\) enter the detector surface normally, the preferential etching along these tracks begins at different etching times and this time difference (which will be the same in the case of tracks etching from either surface) will be given by
\[ \Delta t = \Delta t' = \frac{[R(E) - R(E')]}{r_B} \]

Obviously, the low energy \( \alpha \)-group will appear first and the higher energy one afterwards as observed from the side of the irradiated surface. Reverse is true for track appearance on the back surface. It is because of this reason that at a given etching time, the group which appears first has bigger diameter than that which appears later. On etching from the irradiation side, low energy \( \alpha \)-group has bigger diameter than the high energy ones at a given etching time but reverse is true for etching from the back side (see Fig.50). If the \( \alpha \)-particles of energy equal to or less than the critical energy \( E_c \) enter the detector surface normally, the preferential track etching starts just from the irradiated surface of the detector but even then, at a given etching time there remains a substantial difference in the diameters of etched tracks of different energy \( \alpha \)-particles due to the fact that the track etch rate \( r_T \) is different at different points of the trajectory (Cf., Eq. (A-1.7) in Appendix I).

![Fig.50. Optical micrograph and histogram of the etched tracks of \( \alpha \)-particles of two different energies, \( E_{\alpha} = 5.6 \text{ MeV} \) (smaller tracks) and \( E_{\alpha} = 4.74 \text{ MeV} \) (bigger tracks) in Cellit-T plastic at 5.5 hour etching time in solution B (see Chap.III) at 60°C.](image-url)
Thus we find that in every case, the \( \alpha \)-particles of different energies entering the plastic detector normally give different track diameters on the etched surface of the detector at a given etching time and it is possible to select the different \( \alpha \)-groups emitted in a nuclear reaction according to their track diameter distribution.

Some of our arbitrary experiments showed that Cellit-T plastic could be used to discriminate clearly the tracks of normally entering \( \alpha \)-particles differing in energy by about 150 keV above 3 MeV. This suitable energy resolution of Cellit-T plastic enabled us to measure the angular distributions of \( \alpha_0 \) and \( \alpha_1 \)-groups emitted in the \( ^{27}\text{Al}(d,\alpha)^{25}\text{Mg} \) nuclear reaction at very low bombarding energies \( E_d = 650, 585 \) and 540 keV.

The irradiation chamber used in our case is shown in Fig. 51. In this chamber the flexible property of the plastic has been utilized to irradiate the detector surface by emitted \( \alpha \)-particles at different lab-angles simultaneously, thus avoiding any error caused due to possible fluctuations of the beam current in the accelerator during long exposures needed for the low cross-section nuclear reaction. In actual practice, the
chamber essentially consisted of a flat brass cylinder, 90 mm in diameter, which could be fitted in the vacuum chamber of the 800 keV cascade generator of ATOMKI. The thin aluminium target was mounted at the centre of the cylinder making an angle of $45^\circ$ with the collimated ion beam that entered the chamber after passing a 12 degree magnetic analyzer. Two bent cellulose acetate (Cellit-T)

![Diagram of the irradiation chamber](image)

**Fig. 5.** The irradiation chamber used for the angular distribution measurements of $\alpha$-groups emitted in the $^{27}$Al($d,\alpha$)$^{25}$Mg nuclear reaction using plastic track detectors.

plastic sheets used as detectors were mounted along the curved circular wall of the irradiation chamber, one for receiving the $\alpha$-particles at the forward angles
(20, 30, 45, 60, 75 and 90 degrees) and the other at backward angles (90, 105, 120, 135, 150 and 165 degrees w.r.t. the ion beam) through circular openings 4 mm in diameter in appropriate positions. Under such geometrical arrangement the emitted α-particles entered the detector surface almost at right angles and a single long exposure could record data at every lab-angle simultaneously. Moreover two sets of data were available for $\theta_{\text{lab}} = 90^\circ$.

6.3 Preliminary Requirements

Our experience showed that for a proper discrimination based on the diameter distribution of the α-tracks in Cellit-T plastic the following two conditions must be satisfied: (i) the energy of the α-particles to be discriminated must not be less than 1.0 MeV otherwise the etch pits on the surface are 'pale' and it becomes difficult to discriminate them from the surface imperfections, and (ii) the energy difference between the two α-groups to be discriminated must not be less than 150 keV otherwise reliable discrimination is not possible due to very little difference in the diameters of the tracks belonging to different energy α-particles. In the case of $^{27}\text{Al} (d,\alpha) ^{25}\text{Mg}$ nuclear reaction the first five α-groups had such energies that they satisfied both of these
conditions \( Q_0 = 6.706 \text{ MeV}, Q_1 = 6.122 \text{ MeV}, Q_2 = 5.730 \text{ MeV}, Q_3 = 5.095 \text{ MeV} \) and \( Q_4 = 4.744 \text{ MeV} \) and could be discriminated on the basis of diameter distribution with Cellit-T detector.

Before actually performing the irradiations for real measurements some preliminary irradiations and etchings had to be done to find various interfering effects and real possibilities. The various preliminary requirements will now be described in sequence.

(a) **Knowledge of the Range-Energy curve of the emitted particle \( \alpha \)-particles in the detector material.**

The range-energy curve for the emitted \( \alpha \)-particles in the detector material must be known in order to be able to select different \( \alpha \)-groups with the help of plastic detector. In our case Cellit-T plastic sheets were used as detectors because they gave better energy resolution than cellulose nitrate and besides being free from background tracks they were in the form of very clean, transparent sheets having a uniform thickness of about 97 microns. The ranges of \( \alpha \)-particles of different energies were calculated in this material at the ODRA-1013 computer of ATOMKI for \( C_{10}H_{14}O_7 \) chemical composition using the following formula:

\[ \text{rate of energy loss in the compound material} \]

\[ \text{for the derivation of this formula see Appendix II.} \]
where \( N_i \) and \( A_i \) are respectively the relative numbers of atoms of each element in the compound and the atomic weight of the elements, and \( n \) is the total number of elements forming the compound. The value of stopping power \( \frac{dE}{d(x)} \) in MeV/gm cm\(^2\) for various elements of the compound material was obtained from the data compiled by Williamson et al.\(^{(174)}\). The ranges finally obtained by integrating the inverse of the above equation (because range \( = \int_0^R \frac{dE}{d(x)} \left( \frac{dE}{d(x)} \right)^{-1} \approx \frac{dE}{d(x)} \) gm/cm\(^2\)). For this purpose numerical integration was done making use of Simpson approximation.

The range-energy curve for \( \alpha \)-particles obtained for Cellit-T plastic is shown in Fig.30 and has been tested by actually locating the end points of the different known energy \( \alpha \)-particle tracks in this material.

(b) **Calculation of degrader thickness to be used**

As the energy of a given group of \( \alpha \)-particles emitted in a nuclear reaction varies with lab-angle the \( \alpha \)-particle tracks belonging to the same group do not have equal diameters at different angles on the etched surface of the detector at a given etching time and as such it becomes very difficult to select with certainty the tracks belonging to a given group according to their diameters. To avoid this impasse
use was made of different thickness of aluminium foils to degrade the $\alpha$-particles of a given group to such an extent that all of them had same energy while entering the detector surface at every lab-angle. Thus $\alpha$-particles belonging to a given group showed nearly equal diameters at every lab-angle at a given etching time and the different groups appeared at different instants on the etched surface of the detector.

For calculating the suitable thickness of degrader foils, first the energy variation of $\alpha$-particles of a given group with lab-angle had to be calculated at every bombarding deuteron energy. For this purpose use was made of the well known formula

$$\sqrt{E_b} = v + \sqrt{v^2 + w}$$

where

$$v = \frac{\sqrt{M_a M_b E_a}}{M_b + M_Y} \cos \theta_{\text{lab}}$$

and

$$w = \frac{M_Y Q + E_a (M_Y - M_a)}{M_b + M_Y}$$

corresponding to the nuclear reaction

$$X + a \rightarrow Y + b + Q$$
In our case the reaction equation can be written as

\[ ^{27}\text{Al} + ^{2}\text{d} \rightarrow ^{25}\text{Mg} + ^{4}\text{He} + 
\]

For \( E_d = 650 \text{ keV} \) the calculated results are shown in Fig. 52 for the first four \( \alpha \)-group \( \alpha_0, \alpha_1, \alpha_2 \) and \( \alpha_3 \) from the \( ^{27}\text{Al}(d, \alpha) ^{25}\text{Mg} \) reaction. Similar calculations

![Graph showing variation of energy of \( \alpha \)-particle groups emitted in the \( ^{27}\text{Al}(d, \alpha) ^{25}\text{Mg} \) nuclear reaction with lab-angle at \( E_d = 650 \text{ keV} \).]
were also made (not shown in the Fig.) for all the three
bombarding energies (650 keV, 585 keV and 540 keV). From
Fig. 52 it is seen that the $\alpha$-particles belonging to $\alpha_0$-group
received in the direction $\theta_{lab} = 165^\circ$ have a minimum energy
of about 5.92 MeV while those received in the direction
$\theta_{lab} = 20^\circ$ have an energy of about 6.7 MeV and particles
at intermediate angles have intermediate energies. Because
of this reason the $\alpha$-particle tracks belonging to same
$\alpha_0$-group will not appear simultaneously on the etched surface
of the detector at every lab-angle. To make them appear
simultaneously on the etched surface and to get nearly the
same diameters for them at every lab-angle at a given
etching time, the $\alpha$-particles belonging to $\alpha_0$-group have to
be retarded to the extent that all of them have the same
energy 5.92 MeV while entering the detector; in other words
the solid curve (Fig. 52) belonging to $\alpha_0$ has to be brought
to the desired dotted curve ($\alpha_0)^d$. Similarly the solid curve
belonging to $\alpha_1$ group has to be brought to the position of
the desired dotted curve ($\alpha_1)^d$ and so on. This was done by
suitably retarding the $\alpha$-particles with Al- foils making
use of the range- energy curve of $\alpha$-particles in Al shown
in Fig. 30. It is obvious that in different regions of $\theta_{lab}$
different thicknesses of degrader foils have to be used.
Fortunately in our case, the desired thickness of degrader
foil for different $\alpha$-groups at a given $\theta_{\text{lab}}$ was not very much different. A compromise had to be made with the Al-foils available in the laboratory at the time of measurements and the desired thicknesses. At $E_d=650$ MeV, we used five different thicknesses of Al-foils: 4.45 mg/cm$^2$ at $\theta_{\text{lab}}=20^\circ$, 30$^\circ$, 45$^\circ$; 4.25 mg/cm$^2$ at $\theta_{\text{lab}}=60^\circ$, 75$^\circ$; 4.07 mg/cm$^2$ at $\theta_{\text{lab}}=90^\circ$, 105$^\circ$; 3.90 mg/cm$^2$ at $\theta_{\text{lab}}=120^\circ$, 135$^\circ$; and 3.00 mg/cm$^2$ at $\theta_{\text{lab}}=150^\circ$. Using these thicknesses we could retard the various $\alpha$-groups to the level of the desired dotted lines (Fig. 52). To be more precise, after passing the used Al-foils at various lab-angles the $\alpha_0$-group particles had an energy of $E_{\alpha_0}=5.9$ MeV, the $\alpha_1$-group had $E_{\alpha_1}=5.4$ MeV, and $\alpha_2$-group had $E_{\alpha_2}=5.0$ MeV within an accuracy of $\pm 0.1$ MeV as shown in Fig. 53. The corresponding ranges of these $\alpha$-groups from our calculated range-energy curve (Fig. 30) are found to be $R_{\alpha_0}=36.5\mu$, $R_{\alpha_1}=31\mu$ and $R_{\alpha_2}=27.5\mu$ within $\pm 1\mu$. It is seen from Fig. 53 that the curves belonging to various $\alpha$-groups from the $^{27}$Al ($d,\alpha$) $^{25}$Mg reaction are parallel to the $\theta_{\text{lab}}$-axis, meaning thereby that the energies of $\alpha$-particles belonging to a given $\alpha$-group will be the same at every lab-angle after passing the degrader foils and therefore the $\alpha$-particles belonging to one group will simultaneously appear on the
etched surface of the detector at every lab-angle and will have very nearly equal diameters at a given etching time. Different $\alpha$-groups will appear at different times and if at any time two $\alpha$-groups will be present, they will have different diameters as explained in Sec. 6.2.

![Graph](image)

**Fig. 53.** Lines passing through the filled circles show the energies of $\alpha$-particles of various groups emitted in the $^{27}\text{Al}(d,\alpha)^{25}\text{Mg}$ reaction, after passing the degrader foils used at $E_q=650$ keV, as a function of lab-angle. The lines passing through the open circles show the remaining energy variation of $\alpha$-groups emitted in the interfering $^{14}\text{N}(d,\alpha)$ reaction with lab-angle.
It should be noted that at different bombarding energies a little different thickness of degrading foils had to be used.

(c) Consideration of disturbing effects caused by charged particles produced in other probable reactions

1) From $^{14}\text{N}(d,\alpha)$ reaction - Preliminary experiments with semiconductor detector revealed the production of $\alpha$-particles from the $^{14}\text{N}(d,\alpha)$ reaction due to the nitrogen contamination of the target in the irradiation chamber of the cascade generator. These $\alpha$-particles also gave etchable tracks in the plastic detectors and made it difficult to count with certainty the tracks belonging to the $\alpha$-particles from the $^{27}\text{Al}(d,\alpha)$ reaction. Great care had to be taken to avoid these undesired $\alpha$-tracks. In our case the energy variation with lab-angle of the $\alpha_0$, $\alpha_1$ and $\alpha_2$-groups emitted in the $^{14}\text{N}(d,\alpha)$ reaction after passing the used degrader foils is shown in Fig.53 at $E_d = 650$ keV. It is seen that $\alpha_3$-group produced in the $^{27}\text{Al}(d,\alpha)$ reaction energetically mixed with $\alpha_2$-group produced in the $^{14}\text{N}(d,\alpha)$ reaction and therefore the $\alpha_3$-group from the $^{27}\text{Al}(d,\alpha)$ reaction could not be discriminated easily. The other three groups namely the $\alpha_0$, $\alpha_1$ and $\alpha_2$ from the $^{27}\text{Al}(d,\alpha)$ reaction energetically lay
in between the $\alpha_1$ and $\alpha_2$ groups from the $^{14}\text{N}(d,\alpha)$ reaction. The $\alpha_0$ and $\alpha_1$ groups from the $^{14}\text{N}(d,\alpha)$ reaction lay quite distant from the $\alpha_0$-groups of the $^{27}\text{Al}(d,\alpha)$ reaction and could be easily avoided by using such a thickness of the plastic detector that the etchable parts of the trajectories of these particles passed through the thickness of the detector and consequently their tracks could not be seen on etching. For this purpose a proper thickness of the detector had to be chosen. This was done as described in Sec. 63 (d).

11) From the d+d reaction taking place at the self-made deuterium target - Another disturbing effect that was present in our experiments on the $^{27}\text{Al}(d,\alpha)$ reaction was, however, used with advantage. The deuterons ions coming from the accelerator tube on striking the Al-target got embedded into it due to continuous bombardment and produced the so-called deuterium self-target which resulted into the production of $^3\text{He}$ particles from the following reaction.

$$^2\text{d}_1 + ^2\text{d}_1 \rightarrow ^3\text{He} + ^1\text{H}_0$$

These $^3\text{He}$ particles could form disturbing tracks in the plastic. The yield of this reaction is about three orders of
magnitude higher than that of the $\alpha$-particles produced in the $^{27}\text{Al}(d,\alpha)$ reaction but as the range of these $^3\text{He}$ in Cellit-T plastic after passing through the used degraders, was very small (only a few microns) - much smaller than the ranges of $\alpha$-particles from the $^{27}\text{Al}(d,\alpha)$ reaction to be studied, their tracks appeared on the etched surface of the detector after relatively a shorter etching time and produced translucent circular spots visible to naked eye, marking the boundaries of the detector surface open for irradiation at different lab-angles. To avoid their disturbing effect, the tracks of the desired $\alpha$-particle groups were etched from the back side of the detector surface. The irradiated detector, in fact was first etched from both the sides and when a very dense $^3\text{He}$ tracks appeared on the irradiated surface marking the boundary of the irradiated parts of the plastics, the etching was continued only from the backside to reach the desired $\alpha$-groups. The translucent circular areas demarkated by the $^3\text{He}$ tracks at every lab-angle open for irradiation were used with advantage for counting the desired $\alpha$-tracks from the $^{27}\text{Al}(d,\alpha)$ reaction lying in these areas.
(d) **Preparation of plastic (detector) sheets of proper thickness before irradiation**

As explained in Sec. 6.3 (c) thin plastic detectors had to be used to get rid of the $\alpha_0$ and $\alpha_1$-groups coming from the $^{14}\text{N}(d,\alpha)$ reaction. The Cellit-T plastic available in our laboratory had a uniform thickness of about 97 microns. Before mounting for irradiation it had to be thinned to about $(38 \pm 1)$ microns because the range of disturbing $\alpha_1$-group in Cellit-T from the $^{14}\text{N}(d,\alpha)$ reaction after passing the used degrader foils lay between 42-52.5 microns corresponding to their energies of 6.45 - 7.55 MeV at two extreme angles (see Fig. 53).

The thinning was done in two steps. First the Cellit-T film was etched in a solution containing 30 gm. $\text{K}_2\text{Cr}_2\text{O}_7$ + 95 ml. conc. $\text{H}_2\text{SO}_4$ + 120 ml $\text{H}_2\text{O}$ at 60°C. (We discovered this solution as a result of many empirical experiments and found it to give quite a fast and homogeneous bulk etch rate of about 10.5 $\mu$/hour. It is important to note that this solution++ does not etch the $\alpha$-particle tracks in Cellit-T).

After about 2.5 hour of etching when the thickness of the Cellit-T film remained only $\sim 45\mu$, it was washed in flowing water and then etched for a little more than 1 hour in the

++ This solution was, however, found to be good for etching the fission fragment tracks in Cellit-T.
track etching solution B (as mentioned in Chap. III) containing 20 gm. NaOH + 16 gm. KOH + 4.5 gm. KMnO$_4$ + 90 ml H$_2$O at 60°C in which the bulk etch rate was about 5 μ/hour. After this, the plastic was dipped in 20% dil. HCl solution to remove the sticking layer of MnO$_2$. Finally it was washed in flowing water and dried. The final sheets so obtained had a thickness of $(38 \pm 1)$ μ at different places and were quite clean.

According to our experience the thinning up of the plastic by the dichromate solution must be stopped about 5 μ before reaching the desired thickness and this remaining layer of 5 μ should be removed by using the track etching solution. This procedure is essentially needed because the potassium dichromate solution is found to diffuse into the surface layer of the plastic and alter its bulk etch rate resulting into a change of the track revealing features of the surface layer as compared to the bulk material.

6.4 Target Preparation and its Thickness Measurement

Very thin $^{27}$Al-targets were made by evaporating spectroscopically pure $^{27}$Al in a vacuum evaporator. A thin copper backing was necessary to hold the very thin Al-targets. To measure the target thickness the 345 keV $^{19}$F($p,x$)$^7$F resonance reaction was utilized and therefore some $^{19}$F had also to be
deposited on the copper backing. The whole procedure will be described in the following steps.

(a) Making of thin copper backings

For making copper backings, 70 mg of spectroscopically pure copper was placed in the molybdinum boat connected to two terminals having about 30 volt potential difference and a current of about 30 to 100 amp. inside a vacuum evaporator (pressure $\sim 4 \times 10^{-5}$ mm of Hg). The evaporated copper was deposited on two microscope slides placed at about 16 cm from the centre of the boat. Fixed with the slides and facing the boat were brass plates having circular openings of 1 cm diameter which allowed circular films to be deposited on the microscope slides. After complete evaporation the whole equipment was allowed to cool for about 5 minutes and then the microscope slides having circular copper films on them were placed slantingly in a shallow trough in which water level gradually rose upwards due to water coming into the trough from a beaker with the help of a cotton-wool's capillary action connecting the two vessels. As the rising water level in the shallow trough touched the copper foils and passed under them, these foils slid down one by one and started floating on the water surface.
The floating copper foils were carefully lifted up concentrically on an alcohol-cleaned rectangular thin (0.3 mm) but strong copper frame having circular openings of ~7 mm diameter. Great care had to be taken during this step so as not to puncture the thin copper films. The thin foils so mounted on the frames were carefully dried by thin filter paper and tested for any little holes by holding them against an electric lamp. The punctured foils were thus rejected and good ones kept for use. The retained backings had a thickness of about 0.5 mg/cm²

(b) Evaporation of CaF₂ for the deposition of $\text{^{19}F}$ on the copper backing foils.

Seven such frames having thin intact copper backing foils made as described above were, then, fixed on a hemispherical surface of 16 cm radius placed concentric with the molybdenum boat now containing 12 mg of CaF₂ which was then evaporated for the deposition of $\text{^{19}F}$ on the thin copper foils needed for the thickness measurements of the aluminium targets to be used in the experiments for the study of $^{27}\text{Al}(d,\alpha)$ reaction. CaF₂ had to be slowly and carefully evaporated in order to avoid its jumping out of the boat.
Evaporation of Al-target on the copper backing foils

Now three mounts having (Cu + CaF$_2$) films and four having only Cu films were mounted on the hemispherical surface described above and placed inside the evaporator. Some milligrams of spectroscopically pure $^{27}$Al was evaporated in the usual manner but using a tantalum evaporating boat. Thus after cooling etc. four films were obtained having (Cu + Al) and three having (Cu + CaF$_2$ + Al) layers. At least twice the number of (Cu + Al) targets actually needed were made because 50% of them got destroyed during long irradiation time and had to be replaced.

The thickness of the target was measured in the following manner.

or

d) Target thickness measurement/determination of the number of target atoms per cm$^2$ using $^{19}$F$(p, \alpha \gamma)$ resonance reaction

$^{19}$F gives a well known $(p, \alpha \gamma)$ resonance at proton bombarding energy of 345.4 keV. This resonance reaction has been used to measure the thickness of the Al-targets by measuring the shift $\Delta E$ of this resonance peak. The shift was measured for at least three different targets produced
in the same lot. For this purpose three targets having (Cu + CaF₂) layers and three having (Cu + CaF₂ + Al) layers made as described above were used.

First a target having (Cu + CaF₂) was mounted in the vacuum irradiation chamber of the cascade generator and the protons with energy about 330 keV (actually 63 divisions in the rotation type voltmeter reading—this rotation type voltmeter had a calibration curve showing the voltmeter divisions as a function of proton energy, 1 div = 5.125 keV) were bombarded normally on it. The γ-rays (6 MeV) emitted by it were counted by means of a NaI(Tl) crystal in the usual manner (see Fig.54). The value of proton energy (actually the voltmeter divisions) was increased in small steps until about 350 keV. For every setting of the proton

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Fig.54. Block diagram showing the equipments used to measure the peak shift ΔE of the ²⁹⁸F(p,αγ) resonance reaction for measuring the target thickness.
energy the number of $\gamma$-ray impulses was counted for
50 integrated counts in the Faraday cup. It was found
that about 345.4 keV there was a peak of the $^{19}$F(p, $\alpha \gamma$)
resonance reaction. The proton energy corresponding to
this peak was noted.

Next a target having (Cu + CaF$_2$ + Al) was mounted in
the vacuum irradiation chamber and similarly, as above,
the number of $\gamma$-ray impulses for different value of proton
beam energy was noted every time for 50 integrated counts
in the Faraday cup. It was found that the peak position
got shifted to a different proton energy. This peak
shift $\Delta E$ was thus determined and is related to the target
thickness as shown below. (As we used the target at 45°
to the deuteron beam in actual experiments, the effective
target thickness at 45° was calculated from the formula
$\Delta E(45°) = \Delta E(90°)/\cos 45°$.

According to Bethe-Bloch formula, the rate of energy
loss of a particle of velocity $v$ and charge $ze$ in a material
of atomic number $Z$ is given by

$$\frac{dE}{dx} = \frac{4\pi e^4 Z}{mv^2} \left[ z \left\{ \ln \frac{2mv^2}{I} - \ln (1 - \beta^2) - \beta^2 \right\} - c_k \right] \ldots (VI-1)$$

where $m$ is the mass of the electron, $I$ the average excitation
potential of the atoms of the absorbing material, $N$ the number
of atoms of the absorbing material per cubic centimeter, 
\( \beta = v/c \) and \( C_k \) is a correction constant.

If we consider particles only with a given mass \( m \) and charge \( z \) the equation (VI-1) may be transformed to the following form (175)

\[
- \frac{d\Delta E}{dx} = b_{(m,z)}(E,z) \frac{L}{M} \rho \text{ erg/cm} \quad \ldots \ldots \quad (VI-2)
\]

where \( (L/M) \rho = N \), the number of atoms in a cubic centimeter, \( \rho \) is the density, \( M \) the molecular weight, \( L = 6.0247 \times 10^{23} \) the Loschmidt number per gm mole and \( b_{(m,z)}(E,z) \) the specific stopping power of the given material for given type of charged particles which is a function of only the energy \( E \) of the particles and the atomic number \( Z \) of the stopping material.

If we express the value of the quantity \( b_{(m,z)}(E,z) \) in \( \text{BeV/(gm. atom/cm}^2 \text{)} \), the equation (VI-2) gets the following form

\[
\Delta E = b \rho' \times 10^3 \quad \ldots \ldots \quad (VI-3)
\]

where \( \rho' \) is the surface density in unit of gm/cm\(^2\) and \( \Delta E \) is the energy loss of the particles in MeV.

Equation (VI-3) may finally be written in the form

\[
p' \text{ (gm/cm}^2\text{)} = \frac{\Delta E \text{ (MeV)}}{\text{stopping power (MeV.cm}^2/\text{gm}}} \quad \ldots \quad (VI-4)
\]

if the stopping power is expressed in \( \text{(MeV.cm}^2/\text{gm)} \) as given by Williamson et al (174).
Thus, by measuring \( \Delta E \) in MeV from the resonance peak shift and seeing the stopping power of Al for protons of energy 0.350 MeV (or more exactly 0.3455 MeV); the surface density could be calculated.

To give an example, in one case we found the peak shift of 20 keV \((-20 \times 10^{-3}\) MeV\)) and the value of stopping power of Al for protons of energy 0.350 MeV as seen from Ref. 174 is \(2.965 \times 10^2 \text{ (MeV/cm}^2\text{ gm}^{-1}\)) and so the surface density of the target

\[
\rho' = \frac{20 \times 10^{-3} \text{ MeV}}{2.965 \times 10^2 \text{ MeV/cm}^2 \text{ gm}^{-1}} = 6.765899 \times 10^{-5} \text{ gm/cm}^2
\]

Thus, knowing the value of surface density \(\rho'\) of the target, the number of target atoms/cm\(^2\) could be determined by the following equation

\[
N_t = k n_c = k \rho' m \quad \ldots \quad (VI-5)
\]

where \(N_t\) is the number of target atoms/cm\(^2\), \(n_c\) is the number of molecules in the target compound per cm\(^2\), \(k\) is the number of atoms in the molecule of the target compound (for us \(k=1\)) and \(m = L/M = 6.0247 \times 10^{23}/M\) i.e., the number of molecules in one gramme.
For the example given above, the number of target atoms per cm\(^2\) in one of our cases was
\[N_t = 1 \times 6.765899 \times 10^{-5} \times 6.0247 \times 10^{23}/27\]
\[= 1.509722 \times 10^{18} \text{ atoms/cm}^2\]
as \(N\) for Al = 27.

6.5 Counting of \(\alpha\)-tracks Belonging to \(\alpha_0\) and \(\alpha_1\)-groups from the \(^{27}\text{Al}(d,\alpha)^{25}\text{Mg}\) Reaction

After irradiations the 38 \(\mu\) thick Cellit-T detector sheets were etched in the solution B (20 gm. NaOH + 16 gm. KOH + 4.5 gm. \(\text{K}_2\text{MnO}_4\) + 90 ml. \(\text{H}_2\text{O}\)) at 60°C in gradual steps from both the sides and constant observation of \(\alpha\)-tracks on the back side of the sheets was made. With this thickness, the end point of the \(\alpha_0\)-groups could be reached after removing a 1.5 \(\mu\) layer of plastic from the back surface of the detector by etching. However, for track counting under microscope the most suitable diameter (\(>5 \mu\)) could be reached after 4 \(\mu\) removed layer from the end point of the track. As the plastic was etched from both the sides up to this stage, the remaining thickness of the plastic at the stage of counting of \(\alpha_0\)-group was \([38 - 2 (1.5 + 4)] = 27 \mu\).

The \(^3\text{He}\) tracks from the \(d-d\) reaction due to the self-target of deuterium, made a clear-cut boundary of the irradiated
areas on the front surface of the detector and helped in correctly knowing the areas in which the $\alpha$-particles from the $^{27}$Al$(d,\alpha)$ reaction had to be counted. The counting of the desired $\alpha$-tracks was done from the backside of the detector using a square ocular graticule at 750 X magnification. As the detector sheet was very thin it had to be adhered to the microscope slide with a thin film of water run around its periphery by means of a glass rod dipped in water.

When the diameter of the $\alpha$-$\alpha$-group tracks from the $^{27}$Al$(d,\alpha)$ reaction grew to about 5 $\mu$, counting was easily done under the microscope because the tracks were quite black and at this stage tracks due to the $\alpha$-$\alpha$-group had either not appeared or were seen as very small dots. It should be noted that while counting the $\alpha$-$\alpha$-tracks from the $^{27}$Al$(d,\alpha)$ reaction, no $\alpha$-$\alpha$-tracks from the $^{14}$N$(d,\alpha)$ reaction were seen in the forward angular positions; in the backward angular positions over etched very 'pale' $\alpha$-$\alpha$-tracks from this reaction could also be seen but they could be easily distinguished from the tracks of $\alpha$-$\alpha$-group of the $^{27}$Al$(d,\alpha)$ reaction. Counting of $\alpha$-$\alpha$-group was performed at two different stages of etching and the results agreed quite closely to each other.
To reach good countable size for $\alpha_1$ and $\alpha_2$-groups from the $^{27}\text{Al}(d,\alpha)$ reaction, if the plastics were etched after the counting of the $\alpha_0$-group (at 27 $\mu$ thickness) from both the sides, the remaining thickness of the plastics after etching would have been 16 and 9 $\mu$ respectively. Handling of such thin plastic films is practically very difficult. To get rid of this difficulty the etching of the plastics was continued only from the back surface to reach the $\alpha_1$-group, by mounting the detector films into plexiglass frames provided with rectangular rubber rings to avoid the reaching of the etching solution to the irradiated surface of the detectors and allowing only their back surface to come in contact with the etching solution - thus avoiding the growth of the $^3\text{He}$ tracks on the front surface of the detectors as well as too much thinning up of the plastics which might have resulted into their tearing off. In one case the position, when the $\alpha_1$-group from the $^{27}\text{Al}(d,\alpha)$ reaction was counted, has been photographed and is shown in Fig.55. Here the small black dots belong to $\alpha_1$-group and the larger dots to $\alpha_0$-group. The background translucency is due to the dense $^3\text{He}$ tracks on the other surface of the detector and could be photographed because of very small thickness of the plastic sheet at this stage.
It was felt that $\alpha_2$ and $\alpha_3$-groups from the $^{27}\text{Al}(d,\alpha)$ reaction could not be counted because the films became very thin ($\approx 12 \mu$) and were difficult to handle.

The results of countings of the $\alpha_0$ and $\alpha_1$-groups from the $^{27}\text{Al}(d,\alpha)$ reaction at $E_d = 650$ keV, 585 keV and 540 keV and presented in Table VI.

6.6 Calculation of Differential Cross-Sections

The differential cross-sections for a certain $\alpha$-group from the $^{27}\text{Al}(d,\alpha)$ reaction could be calculated from the well known formula

$$
\sigma^\alpha(\theta) = \frac{N^\alpha(\theta)}{\Omega N_d N_t}
$$

where, $N^\alpha(\theta)$ = No. of $\alpha$-particles of a certain group
emitted in the $\theta_{\text{lab}}$ direction in a certain time,

$$\Omega = \text{solid angle subtended by the detector on the target,}$$

$$N_d = \text{No. of incident deuterons on the target in the same time for which the } \alpha\text{-particles were counted, and}$$

$$N_t = \text{No. of target nuclei per cm}^2$$

If many targets are used in one long exposure (as was necessary in our case due to destruction of targets during very long irradiations needed to collect worthwhile statistics), the differential cross-sections, obviously, have to be calculated by the formula

$$\sigma'(\theta) = \frac{\sum_i N_{\alpha_i}(\theta)}{\Omega \sum_i N_d \cdot N_{t_i}}$$

Thus, to calculate the differential cross-sections, the only quantities that were needed to be known were

(a) $\sum_i N_{\alpha_i}(\theta)$

(b) $\Omega$

(c) $\sum_i N_d \cdot N_{t_i}$

Of these, $\sum_i N_{\alpha_i}(\theta)$ was found by counting the tracks in the Collit-T plastic detectors after etching as described
in Sec. 6.5. The determination of $\Omega$ and $\frac{N_d}{N_t}$ will now be described below.

**Determination of $\Omega$**  
As the deuteron beam during the reaction did not strike the target into a point but in a small area, the following well known formula was used to calculate the solid angle $\Omega$ subtended by the detector on the target.

$$\Omega = 2 \pi \left[ 1 - \cos \theta \left( 1 + \frac{3}{32} \cdot \frac{r^2}{d^2} \cdot \sin^2 2\theta \right) \right]$$

where, $r$ = radius of the spot on which the ion beam strikes the target.

d = distance between the detector and the target, and, $\theta = \arctan \frac{R}{d}$

where $R$ = radius of the detector surface open for receiving the $\alpha$-particles.

In our case,

$r = 1.2\, \text{mm}$ (as seen by the spot made on the target visible to naked eye, due to heating up of the target)

d = 45\, \text{mm}

and $R = 2.25\, \text{mm}$,

and so the value of solid angle subtended by the detector on the target was

$$\Omega = 7.83472 \times 10^{-3}\, \text{sr} - \text{radian}.$$
Determination of $N_{di} = N_{di1}$: The determination of $N_{di}$, i.e., the number of target nuclei per cm$^2$ has already been described in Sec. 6.4 (d).

To determine $N_{di}$, i.e., the number of incident deuterons in a certain time, a current integrator connected to the Faraday cup was used but a prior calibration of the integrator counts was needed. To calibrate the integrator a circuit shown in Fig. 56 was used.

![Circuit Diagram](image)

**Fig. 56.** Showing the circuit used for the calibration of the current integrator needed to determine the number of incident deuterons on the target in a certain time.

The capacitor C whose value was very accurately known was charged to 250 volt by a D.C. variable powersupply and then connected to the integrator. The counts
recorded in the integrator were noted till the voltmeter reading fell to 150 volt. Thus knowing the integrator counts corresponding to a certain charge which had flown through the integrator due to the discharge of the condenser C from 250 to 150 volt, the conversion factor of the integrator could be calculated as explained below.

In our case,

\[ \Delta V = 100 \text{ Volts} \]

\[ C = 0.5763 \mu F \pm 0.1\% \]

Average number of impulses recorded in the recorder,

\[ N = 127.4 \text{ impulses} \]

The charge flown through the integrator

\[ Q = C \cdot \Delta V \]
\[ = 0.5763 \times 10^{-6} \times 100 \]
\[ = 0.5763 \times 10^{-4} \text{ coulomb} \]

The conversion factor of the integrator

\[ k = \frac{Q}{N} = \frac{0.5763 \times 10^{-4}}{127.4} \]
\[ = 0.4524 \mu \text{ coulomb/impulse} \]

Thus one integrator count corresponded to 0.4524 micro coulomb of charge and so 10,000 integrator counts corresponded to \( 0.4524 \times 10^{-6} \times 10^4 = 4.524 \times 10^{-3} \) coulomb of charge.
As one deuteron carries a charge equal to charge of an electron i.e., \(1.5921 \times 10^{-19}\) coulomb, 10,000 integrator counts which corresponded to \(4.524 \times 10^{-3}\) coulomb of charge were obviously equivalent to \(4.524 \times 10^{-3}/1.5921 \times 10^{-19} = 2.84153 \times 10^{16}\) deuterons.

\[
10,000 \text{ integrator counts} = 2.84153 \times 10^{16} \text{ deuterons}
\]

Thus by noting the integrator counts during the irradiation periods and using the above conversion factor, the number of incident deuterons \(N_d\) could be determined for every irradiation of the target.

Knowing all the required quantities, the differential cross-sections were calculated by using the already mentioned formula. The calculated values are given in Table VI.
As one deuteron carries a charge equal to charge of an electron i.e., $1.5921 \times 10^{-19}$ coulomb, 10,000 integrator counts which corresponded to $4.524 \times 10^{-3}$ coulomb of charge were obviously equivalent to $4.524 \times 10^{-3}/1.5921 \times 10^{-19} = 2.84153 \times 10^{16}$ deuterons.

10,000 integrator counts $= 2.84153 \times 10^{16}$ deuterons

Thus by noting the integrator counts during the irradiation periods and using the above conversion factor, the number of incident deuterons $N_{d_1}$ could be determined for every irradiation of the target.

Knowing all the required quantities, the differential cross-sections were calculated by using the already mentioned formula. The calculated values are given in Table VI.
### Table VI

OBSERVED RESULTS OF THE ANGULAR DISTRIBUTION MEASUREMENTS OF \( \alpha_0 \) AND \( \alpha_1 \) - GROUPS FROM THE \(^{27}\text{Al}(d,\alpha)^{25}\text{Mg} \) NUCLEAR REACTION USING PLASTIC TRACK DETECTORS

**Table VI(A), \( E_d = 650 \) keV, \( \sum_{i} N_{d_i} \cdot N_{t_i} = 13.841 \times 10^{33} \)**

<table>
<thead>
<tr>
<th>Group</th>
<th>( \theta_{\text{lab}} )</th>
<th>( \mathcal{N}_{\alpha_1}(\theta) )</th>
<th>( \frac{\Delta \mathcal{N}<em>{\alpha_1}(\theta)}{\sqrt{\mathcal{N}</em>{\alpha_1}(\theta)}} )</th>
<th>( \sigma(\theta) \text{ nb} )</th>
<th>( \Delta \sigma(\theta) \text{ nb} )</th>
<th>( \Delta \sigma(\theta) \text{ in } % )</th>
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<td></td>
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| 20°   | 689            | 26.25           | 49.779          | 1.896          | 3.81           |
| 30°   | 661            | 25.71           | 47.757          | 1.8575         | 3.89           |
| 45°   | 723            | 26.89           | 52.236          | 1.9428         | 3.72           |
| 60°   | 669            | 26.25           | 49.786          | 1.8965         | 3.81           |
| 75°   | 681            | 26.10           | 49.202          | 1.8857         | 3.83           |
| 90°   | 639            | 25.28           | 46.167          | 1.8265         | 3.96           |
| 105°  | 633            | 25.16           | 45.734          | 1.8178         | 3.97           |
| 120°  | 662            | 25.73           | 47.829          | 1.8890         | 3.89           |
| 135°  | 619            | 24.88           | 44.722          | 1.7916         | 4.019          |
| 150°  | 662            | 25.73           | 47.829          | 1.8890         | 3.89           |
| 165°  | 631            | 25.12           | 45.589          | 1.8149         | 3.98           |
Table VI (B), $E_d = 585$ keV; $\sum_{i=1}^{N_d} \cdot N_{t_i} = 0.0904 \times 10^{33}$

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<th>Group</th>
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<th>$\sigma_1(\theta)$ nb</th>
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<tr>
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<table>
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<th>$\lambda_1 \alpha_\lambda$</th>
<th>$\sigma(\theta)_{\text{nb}}$</th>
<th>$\Delta \sigma(\theta)_{\text{nb}}$</th>
<th>$\Delta \sigma(\theta)_{\text{st. rad.}}$</th>
<th>$\Delta \sigma(\theta)_{\text{st. rad.}}$</th>
<th>in %</th>
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<td>0.7825</td>
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<td>0.8481</td>
<td>7.71</td>
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<td>0.7880</td>
<td>8.30</td>
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<td></td>
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</tr>
<tr>
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</tr>
<tr>
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<td>145</td>
<td>12.042</td>
<td>9.488</td>
<td>0.7880</td>
<td>8.30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.7 Results and Discussion

The measured absolute differential cross-sections of the $\alpha_0$ and $\alpha_1$-groups from the $^{27}\text{Al}(d,\alpha)^{25}\text{Mg}$ reaction in the centre-of-mass system at $E_d = 650, 585$ and $540$ keV bombarding energies are shown in Fig.57. The bars in the

![Diagram showing angular distributions of $\alpha_0$ and $\alpha_1$-groups](image)

**Fig.57.** Angular distributions of $\alpha_0$ and $\alpha_1$-groups emitted in the $^{27}\text{Al}(d,\alpha)^{25}\text{Mg}$ nuclear reaction at bombarding deuteron energies $E_d = 650, 585$ and $540$ keV as measured by using plastic track detectors.
figure represent the error of the relative angular distribution. According to the uncertainty in the target thickness determination, the errors in the absolute cross-sections are estimated to be 35% in general. The curves in the figure are the least square fits of the experimental points to series of Legendre polynomials.

Table VII contains the \( A_0, A_1 \ldots \) etc. Legendre coefficients with their errors and calculated \( \chi^2 \) values. The experimental angular distributions were analyzed up to \( p_1 \) needed for the best fit in accordance with the experimental errors. The Table therefore contains only those coefficients for which the normalized \( \chi^2 \) values are nearly equal to unity.

**Table VII**

**Coefficients of the Legendre Polynomials**

\[
\frac{d\sigma}{d\Omega} = \sum_{l=0}^{n} A_l \cdot P_l (\cos \theta)
\]

<table>
<thead>
<tr>
<th>Group</th>
<th>( E_d (\text{keV}) )</th>
<th>( A_0 )</th>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>650</td>
<td>199.6 \pm 2</td>
<td>-9.7 \pm 2.9</td>
<td>-13.2 \pm 3.9</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>585</td>
<td>60.1 \pm 1.1</td>
<td>4.8 \pm 1.7</td>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>540</td>
<td>24.9 \pm 0.5</td>
<td></td>
<td></td>
<td>0.70</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>650</td>
<td>49.7 \pm 0.5</td>
<td></td>
<td></td>
<td>0.54</td>
</tr>
<tr>
<td>( \beta )</td>
<td>585</td>
<td>20.6 \pm 0.5</td>
<td></td>
<td></td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>540</td>
<td>10.0 \pm 0.2</td>
<td></td>
<td></td>
<td>0.60</td>
</tr>
</tbody>
</table>
From the results it can be seen that the angular distributions are nearly isotropic as expected at such low bombarding energies. At $E_d = 650$ and $585$ keV, however, a small anisotropy can be seen in the case of $\alpha_0$-group, but the angular distribution of this group averaged over the examined energy range also becomes isotropic.

These results are in accordance with the previous works at higher energies ($E_d < 5$ MeV) and suggest the presumption of the statistical compound reaction mechanism for the $^{27}$Al($d,\alpha$)$^{25}$Mg nuclear reaction. It is therefore worthwhile to examine if the intensities of the observed $\alpha$-groups correspond to the $(2I + 1)$ rule characterizing the statistical compound reaction mechanism. The $(2I + 1)$ rule can not be directly applied in our case because the conditions of its applicability as given by Mac Donald$^{(176)}$ are, obviously, not satisfied. However, with simplifying condition introduced in our experimental circumstances it is possible to follow in detail the formation of the statistical weight factors for the two measured alpha transitions.

At these low bombarding energies in the incoming deuteron channel $I=0$ is most probable. Therefore, in the $^{29}$Si$^*$ compound nucleus only those states can be excited which have the spins equal to the possible channel spin values $3/2$, $5/2$ and $7/2$ and have positive parities. The transition
from a certain excited level of the $^{29}$Si$^+$ compound nucleus to the $5/2$ and $1/2$ states of the residual nucleus can take place with different $l'$ values, where $l'$ is the orbital angular momentum carried out by the emitted $\alpha$-particle (for example, the $7/2 \rightarrow 5/2$ transition can take place with $l' = 1, 2, \ldots, 6$ in total $(2 \times 5/2) + 1 = 6$, and the $7/2 \rightarrow 1/2$ transition with $l' = 3, 4$ in total $(2 \times 1/2) + 1 = 2$ possible orbital angular momentum values). According to the parity conservation rule $l'$ must be even and this further limits the possible values of $l'$. The possible $l'$ values corresponding to the different transitions are given in Table VIII.

\textbf{T A B L E - V I I I}

\textbf{THE POSSIBLE $l'$ VALUES IN THE TRANSITIONS FROM THE $7/2^+$, $5/2^+$ AND $3/2^+$ LEVELS OF THE $^{29}$Si$^+$ COMPOUND NUCLEUS TO THE $5/2^+$ GROUND STATE AND $1/2^+$ FIRST EXCITED STATE OF $^{25}$Mg.}

<table>
<thead>
<tr>
<th>$J \rightarrow$</th>
<th>$7/2^+$</th>
<th>$5/2^+$</th>
<th>$3/2^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/2^+$</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$5/2^+$</td>
<td>2, 4, 6</td>
<td>0, 2, 4</td>
<td>2, 4</td>
</tr>
</tbody>
</table>
It can be seen from this Table that with these values of $l'$ the transition from the excited state of the compound nucleus to the $5/2^+$ ground state and $1/2^+$ first excited state of the residual nucleus can take place in eight and three different ways respectively. If the penetration factors in the outgoing channels are neglected then—because of the assumed statistical character of the process—the transitions with each possible $l'$ values have equal probabilities. Further, if the spin dependence of the level density is also neglected then the intensity ratio of the $\alpha_0$ and $\alpha_1$ transitions can be expected to be $8/3$. However, taking into account the penetration factors of the outgoing $\alpha$-particles this ratio will change. The penetration factors for the emitted alpha energies were determined by interpolation for $l' = 0, 2, 4$ using the Table given by J.R. Huizenga and G.J. Igo (177) (the penetration factor for $l' = 6$ was taken to be zero). A more correct calculation of the ratio of $\alpha$-group intensities was made by summing up the weighted relative frequency of occurrence of the possible $l'$ values by their respective penetration factors leading to the ground state and the first excited state of the residual nucleus. As a result of this a value of 3.04 was derived for the intensity ratio of the two $\alpha$-groups.
If the spin dependence of the level density in the usual form \( F_L = (2J+1) \exp \left[ - \frac{(J+1/2)^2}{\sigma^2} \right] \) was also taken into account then only less than 4% change of the above mentioned intensity ratio was obtained.

In the latter calculation a value of the spin cut-off parameter \( \sigma^2 = 6 \) was used which reproduced satisfactorily the results of \(^{27}\text{Al}(d,\alpha)^{25}\text{Mg}\) nuclear reaction at higher bombarding energies. (176)

### TABLE IX

**THE MEASURED AND CALCULATED RELATIVE INTENSITIES OF THE \( \alpha_0 \) AND \( \alpha_1 \)-GROUPS**

<table>
<thead>
<tr>
<th>( E_d ) (keV)</th>
<th>( \alpha_0 ) ( 5/2^+ )</th>
<th>( \alpha_1 ) ( 1/2^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>1</td>
<td>0.24</td>
</tr>
<tr>
<td>585</td>
<td>1</td>
<td>0.34</td>
</tr>
<tr>
<td>540</td>
<td>1</td>
<td>0.40</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>1</strong></td>
<td><strong>0.327</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Relative intensities calculated without penetration factor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0.375</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Relative intensities calculated with penetration factor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0.328</td>
</tr>
</tbody>
</table>
The relative intensities of the measured \( \alpha \)-groups integrated over the \( 0^\circ - 180^\circ \) angular region and their mean values are displayed in Table IX. This Table also contains the relative intensities calculated first by neglecting and then by taking into account the effect of penetration factors. For a ready comparison the intensity of the \( \alpha_0 \)-group is normalized to unity.

Although the experimental relative intensities change with the bombarding energy their mean values are found to be in agreement with those calculated when the effect of penetration is included. This agreement between the experimental result and the former simple calculation for the statistical weight factors supports the validity of the statistical compound reaction mechanism assumptions for the \( ^{27}\text{Al}(d,\alpha)\ ^{25}\text{Mg} \) reaction in the examined energy region.

6.8 Conclusions

From the above description it is clear that the use of plastic track detectors has been quite successful in giving new data on the angular distributions of the \( \alpha_0 \) and \( \alpha_1 \)-groups emitted in the \( ^{27}\text{Al}(d,\alpha)\ ^{25}\text{Mg} \) nuclear
reaction at very low bombarding deuteron energies
($E_d = 650, 585$ and $540$ keV). It is believed that the Cellit-T plastic will be very useful for studying very low cross-section nuclear reactions of the $(p,\alpha)$, $(d,\alpha)$, $(t,\alpha)$ and $(\gamma,\alpha)$ type. At low neutron energies, the study of $(n,\alpha)$ type reactions also appears to be feasible but at high neutron energies (above $4$ MeV) the $\alpha$-tracks from the $^{12}$C$(n,n\alpha)$ $3\alpha$ reactions due to the carbon content of the plastic cause comparable disturbing backgrounds.

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