

ON THE RANGE OF 30 MeV ALPHA PARTICLES IN PURE AND IMPURITY DOPED KCl CRYSTALS

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Pure and Mg doped KCl crystals are irradiated with 30 MeV alpha particles. *F* centers are produced in the crystal and the efficiency of *F* center formation is estimated. The efficiency is found to be independent of impurity and crystal orientation. The range of alpha particles is shorter in impurity doped crystal than in pure one. The results are interpreted according to current observations.

1. Introduction

The energy loss of charged particles when moving through matter has attracted wide attention from scientific point of view. Bohr¹⁾, Bethe²⁾ and Bloch³⁾ studied the energy loss of charged particles in amorphous medium. Energy loss of alpha particles in crystalline medium was studied by several authors⁴⁻⁷⁾, and excellent review works are available on the subject^{8,9)}.

When high energy alpha particles travel through a solid medium, the predominant mode of energy loss is by inducing electronic excitation with atomic electrons along their path. The theoretical investigation on the ionization loss (dE/dx), of heavy particles by Bohr¹⁾, Bethe²⁾ and Bloch³⁾ has led to the following expression:

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{mv^2} NZ \ln \frac{2mv^2}{I}$$

where, e is the electronic charge, N the number of atoms per unit volume of the material, Z and z are the nuclear charge of the material and the incident particle,

respectively, I the mean excitation potential of the material, m the electronic mass, and v the velocity of the incident particle. The range of alpha particles in homogeneous amorphous medium can be estimated from the Bragg curve¹⁰⁾ as the distance, where the specific ionization becomes zero. Large departures are expected when alpha particles move through a crystalline medium. In an amorphous medium, the scattering centers are randomly distributed. But in a crystal, the regular arrangement of scattering centers may introduce a strong correlation between successive events, leading to a significant decrease in the rate of energy loss. So a reduction in energy loss is observed when the particles travel along certain low index directions of the crystal. The crystal orientation dependence of the energy loss and hence the range of alpha particles may be explained in terms of channeling phenomenon.

The present work has been undertaken to study the range of alpha particles in pure and impurity doped KCl crystals. The range of the alpha particles have been determined by measuring¹¹⁾ the number of F centers produced by alpha particles at various depths below the surface of the crystals. An estimation of the efficiency of F center formation shows that it is independent of the crystal orientation and impurity incorporation in the medium.

2. Experimental

Thin flakes (9 mm \times 6 mm \times 2 mm) of pure KCl $\langle 100 \rangle$ and KCl $\langle 110 \rangle$ were cleaved from single crystals of KCl and polished for necessary optical measurements. Samples of KCl $\langle 100 \rangle$ and KCl $\langle 110 \rangle$ crystals doped with magnesium (0.01 atomic %) were also prepared.

The specimens were mounted on an aluminium holder and then inserted into an evacuated scattering chamber (attached to cyclotron channel). The holder can be moved from outside, so that each sample could be irradiated with a well-collimated beam of alpha particles at room temperature. The energy and dose of the particles were maintained at 30 MeV and 0.12 μC , respectively, in each case of irradiation. The alpha particles were made incident normally ($\pm 0.01^\circ$) on the surface of the specimen and F centers were produced in the specimen. The critical angle ψ_c for stable channeling of 30 MeV alpha particles in KCl crystal was calculated¹²⁾. The value of the angle, ψ_c , is 0.19° .

The samples were taken out from the scattering chamber after irradiation, in a light-tight box. A uniform circular area got coloured on the surface of the crystal and the diameter of the coloured region was measured with a travelling microscope. Divergence of the beam was calculated by comparing the observed diameter with that of the collimator slit, to be of the order of 0.03° .

The optical density of the irradiated specimen was measured with a Carl-Zeiss (SPM-2) spectrophotometer and F -absorption curves were plotted. The optical absorption curves (not shown) are found to have the position of maximum absorption at the wavelength position 560 nm for all the samples at room temperature. The number of F centers produced per cm^2 (N_F) was calculated using Smakula's equation¹³⁾, and the efficiency (η) of F center formation was determined from the relation¹⁴⁾ $\eta = N_\alpha E_\alpha / N_F$, where N_α is the number of incident alpha particles per cm^2 and E_α is their energy.

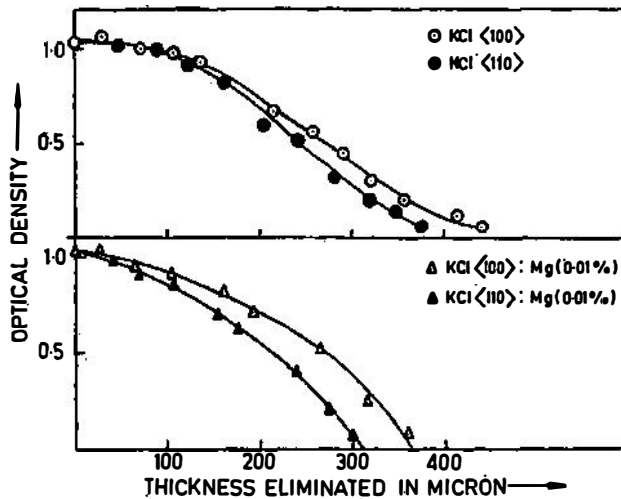


Fig. 1. Variation of optical density below the surface of pure and magnesium doped KCl crystals.
 $E_{\alpha} = 30 \text{ MeV}$, dose = $0.12 \mu\text{C}$.

As the alpha particles moving through the crystal produce colour centers along their path, the depth of colouration may be regarded as the range of alpha particles within the crystal. So the range may be expressed as the distance below the surface of the crystal where the optical density becomes zero¹¹⁾. Thin surface layers were successively eliminated from the coloured crystal using wet-cut process¹¹⁾, and the optical density was measured after each elimination. This process was continued until the optical density was found to be negligible. The optical density was plotted against the thickness of the surface eliminated (Fig. 1). In the case of pure samples the tails of the curves of Fig. 1 were fitted to an equation of the type $y = Ae^{-Bx} + C$, where A , B and C are constants. The range values (x) were computed from the equation when y becomes zero. However the ranges of alpha particles in impurity doped crystals were estimated directly from the graphs. The values of the ranges for all the samples are shown in Table 1.

TABLE 1.

Specimen	Range estimated from Bethe's Equation mg cm^{-2}	Range $(\text{mg cm}^{-2}) \pm 0.22$	Efficiency (η) keV/center
KCl <100>	105.01	97.30	31.55
KCl <110>		78.80	31.78
KCl <100> : Mg (0.01%)		72.80	31.01
KCl <110> : Mg (0.01%)		61.60	31.28

Range of alpha particles in pure and impurity doped KCl crystals.
 $E_{\alpha} = 30 \text{ MeV}$, dose = $0.12 \mu\text{C}$.

3. Results and discussion

It is known that the electron density at the mid-channel is considerably lower than that at the channel-edge. So the particles incident near the channel-edge will be scattered more strongly than those incident at the mid-channel^{15,16}. The position of the entrance-point of the particles thus determines the magnitude of channeling. However every particle entering the channel is known^{11,17} to have a probability of close encounter with nuclei along their path in the channel and may undergo a transition from channeled beam to random beam. This transition, known as dechanneling, can be attributed to the effects of thermal vibrations, impurities, defects etc. on particle motion.

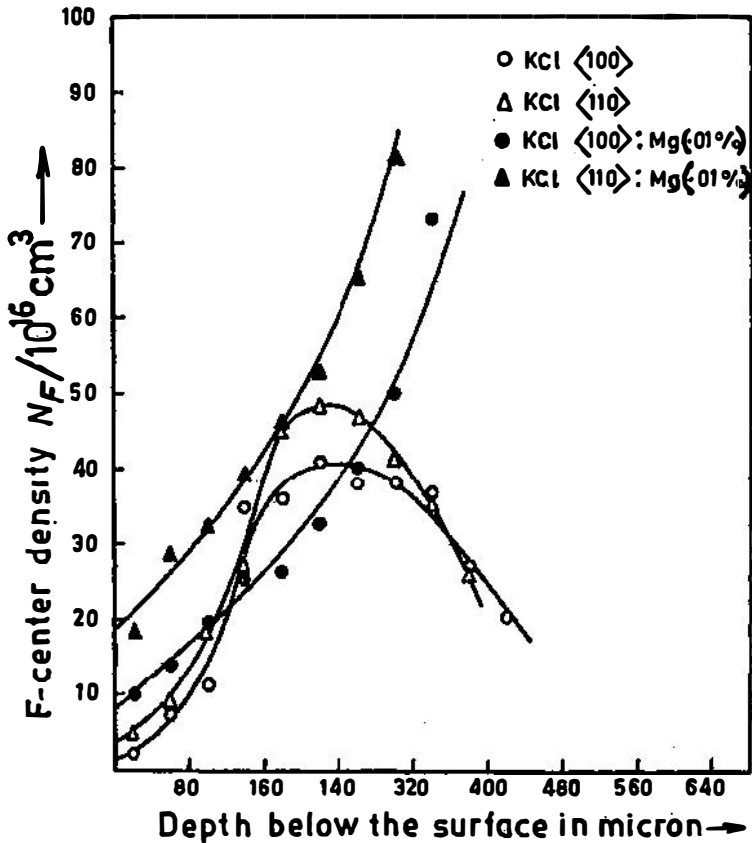


Fig. 2. Variation of F center/cm³ as a function of depth below the surface in pure and magnesium doped KCl crystals.

The total transverse energy of an ion of energy E and incident on a crystal at an angle ψ has three components — (i) a transverse kinetic energy $E\psi^2$, (ii) a transverse potential energy φ at its point of entrance into the channel and (iii) transverse energy (E_{\perp}) due to multiple scattering by electrons, lattice vibrations

and imperfections^{18,19}). The alpha particle dechanneled due to multiple scattering dominantly suffer energy loss producing F centers in the medium. From Fig. 1, a F center concentration (N_F/cm^3) curve was produced by using the slope $\Delta O.D./\Delta x$, where $\Delta O.D.$ is the change in optical density corresponding to a change Δx . The number of F center/ cm^2 for $\Delta O.D.$ can be estimated from Smakula's equation. The results are shown in Fig. 2.

From Table 1 may be noted that the range of 30 MeV alpha particles in KCl crystal is somewhat less than the value calculated from Bethe's energy loss equation. For 30 MeV alpha particles, the range as calculated from Bethe's equation assumed the value 105 mg cm^{-2} for KCl crystal. The experimentally observed value is 97 mg cm^{-2} . Another type of discrepancy, particularly for KCl crystal, has been reported by Price and Kelly²⁰. They have shown that the back scattering yield (κ_{min}) for 1 MeV alpha particles in KCl is anomalously high, whereas in the case of NaCl, NaF, LiF, etc. the experimentally observed values for κ_{min} agree fairly with the theoretical values^{21,22}). As the back scattering yield (κ_{min}) is inversely related to the transparency of the channel²³), an anomalous reduction in range value compared to that as calculated from Bethe's equation, may arise in case of KCl crystal only. No report on theoretical investigation has been available regarding this discrepancy and it awaits further attention in future works.

From Fig. 2 the variation of F center density with the thickness traversed appears to be exponential in nature up to a distance of 240 micrometers in KCl $\langle 100 \rangle$. The value of E_{\perp} for trajectories bounded by a particular potential energy contour²⁴) is assumed to have an exponential distribution^{18,19}), the dechanneling and hence the F — center density is expected to bear a similar relation with the distance traversed by the particles. The nature of the curve beyond the distance of 240μ in KCl $\langle 100 \rangle$ crystal shows that a group of incident particles, having comparatively low energy loss, has penetrated deeper into the matrix. The results obtained in case of KCl $\langle 110 \rangle$ (Fig. 1) indicate a reduction of range values compared to those of KCl $\langle 100 \rangle$. Although the range values measured for both $\langle 100 \rangle$ and $\langle 110 \rangle$ directions are shorter than the calculated value using Bethe's equation, yet their relation with interplanar distance d^{20}) is found to be satisfactory as given below.

$$\text{KCl}_{d\langle 110 \rangle} / \text{KCl}_{d\langle 100 \rangle} \cong 0.71 \text{ (Theory)}$$

$$\text{KCl}_{R\langle 110 \rangle} / \text{KCl}_{R\langle 100 \rangle} \cong 0.80 \text{ (Expt.)}$$

The curves of Fig. 2 further depict the effect of the introduction of Mg^{++} impurities in the crystal matrix in both $\langle 100 \rangle$ and $\langle 110 \rangle$ directions. In case of doped crystals, F center density is found to increase with the distance below the surface. It is a redeeming feature that the tail as observed in the case of pure crystals is absent in the case of doped crystal. From Table 1 it is also evident that the range values are reduced considerably due to doping for the both $\langle 100 \rangle$ and $\langle 110 \rangle$ directions of KCl crystal. This effect may be explained as due to the effects of lattice structure on the ion-atom potential^{18,19}). The lattice structure is also being distorted by the presence of impurities and vacancies^{25,26}). Moreover, a long-range constriction or curvature of a crystallographic channel near a point defect may cause a transition from channeling to dechanneling²⁵).

From Table 1 it is also seen that the efficiency i. e. the amount of energy necessary to produce an F - center is of the order of 31 keV/center and is independent of the nature of the doped or undoped crystals. This value of efficiency is found to corroborate well the results obtained by others²⁷, for irradiation with high energy particles like protons, etc.

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DOSEG 30 MeV ALFA-ČESTICA U ČISTIM I DOPIRANIM KCl
KRISTALIMA

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Čisti i Mg-dopirani kristali KCl su ozračivani sa 30 MeV alfa-česticama. U kristalu nastaju *F*-centri i određena je brzina njihovog stvaranja. Nađeno je da je brzina stvaranja nezavisna od nečistoća i orijentacije kristala. Doseg alfa-čestica je kraći u kristalima sa nečistoćama nego u čistim kristalima. Rezultati su interpretirani u skladu sa postojećim opažanjima.