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DIELECTRIC RELAXATION IN RARE-EARTH DOPED CALCIUM FLUORIDE CRYSTALS (U)  
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A TRIDENT SCHOLAR  
PROJECT REPORT

NO. 88

"DIELECTRIC RELAXATION IN RARE-EARTH  
DOPED CALCIUM FLUORIDE CRYSTALS"

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UNITED STATES NAVAL ACADEMY  
ANNAPOLIS, MARYLAND  
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"Dielectric Relaxation in  
Rare-Earth Doped  
Calcium Fluoride Crystals"

A Trident Scholar Project Report

by

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Annapolis, Maryland

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Accepted for Trident Scholar Committee

*Robert*

Chairman

*23 May 1977*

Date

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## ABSTRACT

The complex dielectric constant was measured at five audio frequencies ( $10^2$ - $10^4$  Hz) over a temperature range of 5.5-400K for calcium fluoride crystals doped with 13 different rare-earths of the lanthanide series. The results allow an unambiguous labeling of the spectrum for the first time. Five relaxations were observed which are characteristic of the series and five major new trends were observed in these relaxations. Evidence was also uncovered indicating the possibility of a sixth relaxation occurring at high temperatures.

Work was also done on computer models of a dipolar complex in this crystal which led to the proposal of a new model to account for one of the relaxations. Models were also proposed for the other relaxations observed.

By characterizing the dielectric spectrum for all rare-earth dopants this project has laid the groundwork for a future study on the effects of neutron irradiation of the crystals. It is hoped that this will lead to the development of an improved neutron dosimeter.

### ACKNOWLEDGEMENTS

The author would like to thank his advisor, Dr. John Fontanella, for his help in all areas of this project. His continuing amiability, knowledge and support contributed greatly to my enjoyment of and success in the project.

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*Donald J. Link*  
Donald J. Link  
18 May 1977  
Annapolis, Maryland

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## I. Introduction

In a pure calcium fluoride crystal the fluorine ions form a simple cubic lattice while the calcium ions form a face-centered cubic lattice. This implies that one-half of the cubes formed by the fluorine lattice are occupied by calcium ions and the other half are unoccupied. When a rare-earth impurity is introduced it is often present as a triply-charged ion, requiring some form of charge compensation in order to preserve charge neutrality. This charge compensation will often result in the formation of dipolar complexes. These dipolar complexes induce a number of electrical relaxations which lend themselves well to analysis because of their Debye-like behavior.

These crystals have received a great deal of attention in recent years. The challenge is to develop a coherent picture of the observed relaxations and develop models of dipolar relaxations to account for their behavior. At the present time only one relaxation has been studied for several rare-earth dopants in calcium fluoride and there are isolated reports of at least five other relaxations in the literature.<sup>1-5</sup> In this project a study was made of the dielectric spectrum of calcium fluoride crystals with thirteen different rare-earth dopants. This allows for an unambiguous labeling of the dielectric spectrum for the

first time. Five relaxations are observed that are characteristic of the series with a possible sixth relaxation occurring at high temperatures. New observations about their trends of behavior lead to the proposal of models of dipolar relaxation to account for their behavior.



## II. Experiment and Data Reduction

### A. Experimental Procedure

The crystals used in the experiment were calcium fluoride crystals with 0.1 mol-% rare-earth impurities. The rare-earth impurities include the entire lanthanide series with the exception of promethium and lanthanum. The crystals were obtained from Optovac, Inc. in the form of discs 25.4 mm in diameter and about 2.0 mm in thickness. The crystals were first ground to a thickness of 1.5 mm and then polished with 1 micron Metadi diamond polishing compound. Aluminum electrodes were evaporated on in the three-terminal configuration using a shadow ring that gave a guard gap of .01 mm or less. Good boundary conditions were ensured by having the ratio of the width of the guard ring to the thickness of the sample be greater than three. The crystals were then placed in the eight-sample holder of a Cryogenics CT-14 cryostat. The temperature range was from 5.5-400K with an automatic temperature controller using a platinum resistance thermometer at temperatures down to 30K and a germanium thermometer at temperatures below that.

The conductance divided by frequency,  $G/\omega$ , and the capacitance,  $C$ , were measured using a General Radio 1615 capacitance bridge modified to give meaningful results for  $G/\omega$ , and  $C$  at levels of less than 1 ppm at the five

audio frequencies  $10^2$ ,  $10^{2.5}$ ,  $10^3$ ,  $10^{3.5}$ , and  $10^4$  Hz. The generator-detector assembly was designed to allow single-knob switching between frequencies. An interface was designed to give a digital readout after the bridge was manually balanced.

#### B. Analysis of Data

The real part of the dielectric constant,  $\epsilon'$ , was set equal to 6.915 at 300K and 1000Hz for all 0.1 and 1.0 mol-% samples. This is the value given by the two-fluid technique for calcium fluoride with a 0.1 mol-% erbium impurity.<sup>3</sup> This was done for two reasons; first, the difference between this value and the correct value is negligible, and second, most of the important results are derived from relative changes in  $\epsilon'$  and  $\epsilon''$  so a change in the absolute value of the entire curve would have minimal effect on the results.

To determine  $\epsilon'$  for other frequencies at 300K the relationship:  $\epsilon' / \epsilon'_{1000\text{Hz}} = C / C_{1000\text{Hz}}$  was used.  $\epsilon'$  at temperatures other than 300K was determined from:

$$\frac{\epsilon'_T}{\epsilon'_{300}} = \frac{C_T}{C_{300}} \text{EXP}(-\int_{300}^T \alpha_p dT) \quad (1)$$

where  $\alpha_p$  is the isobaric linear thermal expansion coefficient. Since  $\alpha_p$  is unknown for rare-earth doped samples the value of  $\alpha_p$  for pure calcium fluoride was used.<sup>6</sup>

Then the imaginary part of the dielectric constant at each temperature and frequency was calculated using the equation:

$$\epsilon_T'' = \frac{\epsilon_T'' G}{\omega C} \quad (2)$$

Figure 1 contains the graphs of  $\epsilon''$  vs.  $T$  at 100 Hz for 0.1 mol-% impurities of thirteen different rare-earths. They are listed in order of increasing atomic number (and decreasing ionic radius) starting with Ce and going down to Gd on the left and continuing with Tb through Lu on the right. For the other four frequencies the plots are basically the same except that the peaks occur at successively higher temperatures as the frequency increases. It is readily apparent from figure 1 that there are certain peaks which are characteristics of the series. These peaks will be discussed individually in a later section.

Next, at each of the five frequencies the peaks were fit to the Debye equation:

$$\epsilon'' = \frac{A\omega\tau}{T(1+\omega^2\tau^2)} \quad (3)$$

in order to obtain the temperature at which  $\omega\tau = 1$ .  $T$  is the absolute temperature,  $\tau$  is the relaxation time, and  $A$  is the dipole strength, given by:

$$A = \frac{Np^2}{3\epsilon_0 k} \quad (4)$$

where  $N$  is the dipole concentration,  $p$  is the dipole moment,  $\epsilon_0$  is the permittivity of free space and  $k$  is Boltzmann's constant.  $A$  is assumed to be constant for a given peak.

The relaxation time,  $\tau$ , is given by an Arrhenius equation of the form:

$$\tau = \tau_0 \text{EXP}(E/kT) \quad (5)$$

where  $\tau_0$  is the reciprocal frequency factor and E is the activation energy. Equation (5) and  $\omega\tau = 1$  imply:

$$\ln(\omega) = -E/kT - \ln(\tau_0) \quad (6)$$

Finally, the five sets of ( $\omega, T$ ) obtained from equation (3) were fit into equation (6) to give the values of E and  $\tau_0$  for individual peaks. Table 1 gives a listing of activation parameters for the peaks for which fits were obtainable. The activation energy is an almost linear function of the peak position. If an accurate fit of the peak can't be made because of background, a reasonable estimate of the activation energy can be made based on the peak position.

### C. Computer Simulation

Work was also done on designing computer models of the dipolar complex shown in figure 3. The first program was designed to give the difference in potential energy between various sites for an interstitial fluorine ion. The model included the effects of short range repulsion (using the short range repulsion parameters for the  $F^- - F^-$  and  $Ca^{2+} - F^-$  interactions given by Wong<sup>7</sup>) and electrostatic interaction using the Ewald/Evjen method and including ions out to the sixth nearest neighbor. Due to lack of availability of short range repulsion parameters for

$RE^{3+}-F^{-}$  interactions, the  $Ca^{2+}-F^{-}$  parameters were used.

Next, work was done on a computer model to discover how the lattice would relax as the interstitial fluorine ion moved through the saddle point between two equilibrium positions. The technique used was similar to that used for the first program, but the short range repulsion parameters for the  $RE^{3+}-F^{-}$  interactions were varied to simulate the varying sizes of the rare-earth ions. The program is listed in Appendix.A.

### III. Discussion of Results

#### A. $R_I$ Relaxation

The central peak, at about 200K with an activation energy of about .4 eV as seen in table 1, has been the most widely studied. It is the only peak for which a relatively reliable ESR correlation has been made. ESR line broadening experiments show a 0.4 eV process with tetragonal symmetry. The simplest model to account for the known behavior of this peak would be charge compensation by a nearest-neighbor interstitial fluorine ion (as is seen in figure 3). Figure 2 is a graph of  $\mathcal{E}''$  vs. concentration and temperature for 0.1 mol-% Er from a paper by Andeen and Fontanella<sup>3</sup>. As can be seen from the graph, the height of the  $R_I$  peak at first increases with increasing concentration, reaches a peak at a concentration of about 0.1 mol-%, and then decreases.

An explanation for this is that as the concentration increases the number of complexes of this type at first increases, but as the concentration gets too high the crystal becomes crowded with rare-earth ions and clusters predominate.

The activation parameters for this peak compare reasonably well with the values recently obtained by Kitts and Crawford using the ITC technique<sup>1</sup>. However, the first main result of this study indicates that the activation energy is relatively independent of rare-earth ionic radius rather than obtaining a slight increase in activation energy as ionic radius increases as reported in their paper. It is quite possible that their results for Tm and Yb are too low because of the non-Debye-like behavior of the  $R_I$  peaks for Tm, Yb, and Lu. Analysis of present data indicated that this peak is indeed much broader than for the other rare-earths so no activation parameters were obtained for this peak for Tm, Yb, and Lu in the present work.

As mentioned above, this peak has been traditionally associated with the relaxation of a nearest-neighbor fluorine ion as shown in figure 3. This model is supported by the ESR correlation and concentration dependence of the relaxation. However, it is disturbing that a relaxation that occurs so close to a rare-earth ion should have an activation energy so independent of ionic radius.

## B. $R_{II}$ Relaxation

The second major result of this work is the discovery that the  $R_{II}$  peak disappears for all rare-earths with an ionic radius larger than that of  $Gd^{3+}$ . It can also be seen that the size of the peak increases monotonically with decreasing ionic radius. As can be seen from figure 2 this peak has approximately the same dependence on concentration as the  $R_I$  peak, possibly indicating that the associated complexes for both of the peaks have the same number of rare-earth ions. It was difficult to obtain activation parameters because of the complication introduced by the presence of other peaks, but it can be seen from the positions of the peaks in figure 1 that, with the exception of Lu, the activation energy decreases with decreasing rare-earth ion size. Several mechanisms have been proposed for this relaxation, none of which appears to be particularly reliable.

One possible new model for this relaxation is the relaxation of the nearest-neighbor fluorine ion by a different mode than that for the  $R_I$  peak. There have been two possible modes of relaxation proposed for the relaxation of a nearest-neighbor fluorine. Figure 3 shows the direct jump mode, in which the interstitial ion moves directly from one position to another by a route between the two lattice fluorines and a neighboring calcium ion. Figure 4 illustrates the interstitialcy mode, in which

a lattice fluorine moves into the interstitial position and is replaced by the old interstitial ion. The results of the first computer model (unrelaxed lattice) discussed in section II.C. indicated the possibility of a third mode of relaxation, such as is shown in figure 5. In this mode of relaxation the fluorine ion would move directly from one position to another as in the direct jump mode, but via a path between the two lattice fluorines and the rare-earth ion rather than the calcium ion. The results of the the second computer model (relaxed lattice) indicate that this mode of relaxation is not possible if the short range repulsion parameters for the  $RE^{3+}-F^{-}$  interaction are too high. Because of lack of data on the short range repulsion parameters for the  $RE^{3+}-F^{-}$  interaction it was not possible to determine for which of the rare-earth ions this mode of relaxation would disappear. It is possible that the  $R_{II}$  peak is due to this mode of relaxation and that the  $R_I$  peak is due to one of the other modes of relaxation. This would account for the larger dependence of the activation energy on rare-earth ionic radius for the  $R_{II}$  peak in comparison with the  $R_I$  peak. This would also account for the fact that both of the peaks have approximately the same dependence on concentration.

There are three major shortcomings to this proposal. In the unrelaxed lattice computer model it was found that the activation energy for the mode of relaxation shown



in figure 5 is less than the activation energy for the mode of relaxation shown in figure 3. however it must be expected that in a relaxed lattice the activation energy would be larger for the former mode of relaxation. or else it would not disappear with too large a short range repulsion parameter for the  $RE^{3+} - F^{-}$  interaction. So it would be expected that this peak would have a larger activation energy than the  $R_I$  peak, which is not the case. Also, if both of these peaks were due to a single dipolar complex, the peak occurring at a higher temperature would not be expected to appear in ITC data. Once again this is not the case. Finally, it appears that the peaks do not anneal together; the  $R_{II}$  peak increasing approximately three times as much as the  $R_I$  peak after annealing.

### C. $R_{III}$ Relaxation

The third major result of this study is that the  $R_{III}$  peak, discovered recently by Fontanella, et al,<sup>3</sup> disappears for rare-earths with a larger ionic radius than that of  $Tb^{3+}$ . Because of the irregularity of the peak few activation parameters could be obtained. From figure 2 it can be seen that this peak has a very strong dependence on concentration, stronger than for any other peak. Based on this it is generally accepted that this peak is due to a cluster complex, possibly involving four or more rare-earth ions.

#### D. $R_{IV}$ Relaxation

The fourth major result of this work is the discovery of a relaxation with an activation energy which depends strongly on the nature of the rare-earth. In fact, the dependence is almost linear, as is shown in figure 6, a graph of activation energy versus rare-earth ionic radius. Figure 2 shows that this peak has a higher dependence on concentration than the  $R_I$  or  $R_{II}$  peaks, but not as high a dependence on concentration as the  $R_{III}$  peak. Consequently the model proposed for this relaxation involves two rare-earth ions, as is shown in figure 7. The extra fluorine ion required for charge neutrality would have to be trapped elsewhere in the lattice. The fact that the fluorine ion has to pass between two rare-earth ions in order to relax would account for the strong dependence of the activation energy on the rare-earth ionic radius. A second way to account for this strong dependence would be a complex in which the rare-earth ion itself relaxed.

#### E. $R_V$ Relaxation

The fifth major result of this project is the discovery of an additional relaxation which is a characteristic of the series. Little can be said about this peak other than what can be seen in figure 1. This peak is similar to the  $R_{IV}$  peak in its strong dependence of

activation energy on rare-earth ion size although the dependence is not as large.

#### F. High Temperature Tail

Another result of this project is the discovery that the high temperature tail commences at increasingly lower temperatures as the ionic radius of the rare-earth dopant decreases. In the past this feature has commonly been associated with DC conductivity, a phenomenon that is only indirectly associated with defect centers. However the excessively strong dependence of this peak on the rare-earth dopant indicates the possibility that this tail may be due to the beginning of another peak, possibly associated with the relaxation reported by Franklin, et al, with an activation energy of 1.2 eV<sup>5</sup>. The position of the peak would indicate an activation energy in close agreement with this figure.

#### G. Practical Applications

The original purpose of this project was to find a crystal with a zero temperature coefficient for use as the transducer in a high pressure gauge. However, it was soon discovered that these crystals were not suitable for that purpose and attention was directed toward another use of these crystals. It was hoped that the main achievement of this project, the characterization of the dielectric spectrum for almost all rare-earths of the lanthanide series,

would lay the groundwork for a study on the effects of neutron irradiation of these crystals.

The rare-earths have a large absorption cross section, particularly Gd and Eu. So it is expected that neutron irradiation of these crystals will have a large effect on them. (It has already been shown that the  $R_{II}$  peak can be grown in a Eu doped sample by gamma irradiation<sup>3</sup>) And based on the characterization of the peaks provided by this project, it may be possible to determine which new rare-earths are introduced as decay products. The  $R_{IV}$  peak, which occurs at different temperatures for different dopants, will be particularly useful in this work. Midshipman Kolodziejzak has proposed a Trident Project to study the effects of neutron irradiation of these crystals next year. It is hoped that this will lead to the development of an improved neutron dosimeter.

#### IV. Conclusion

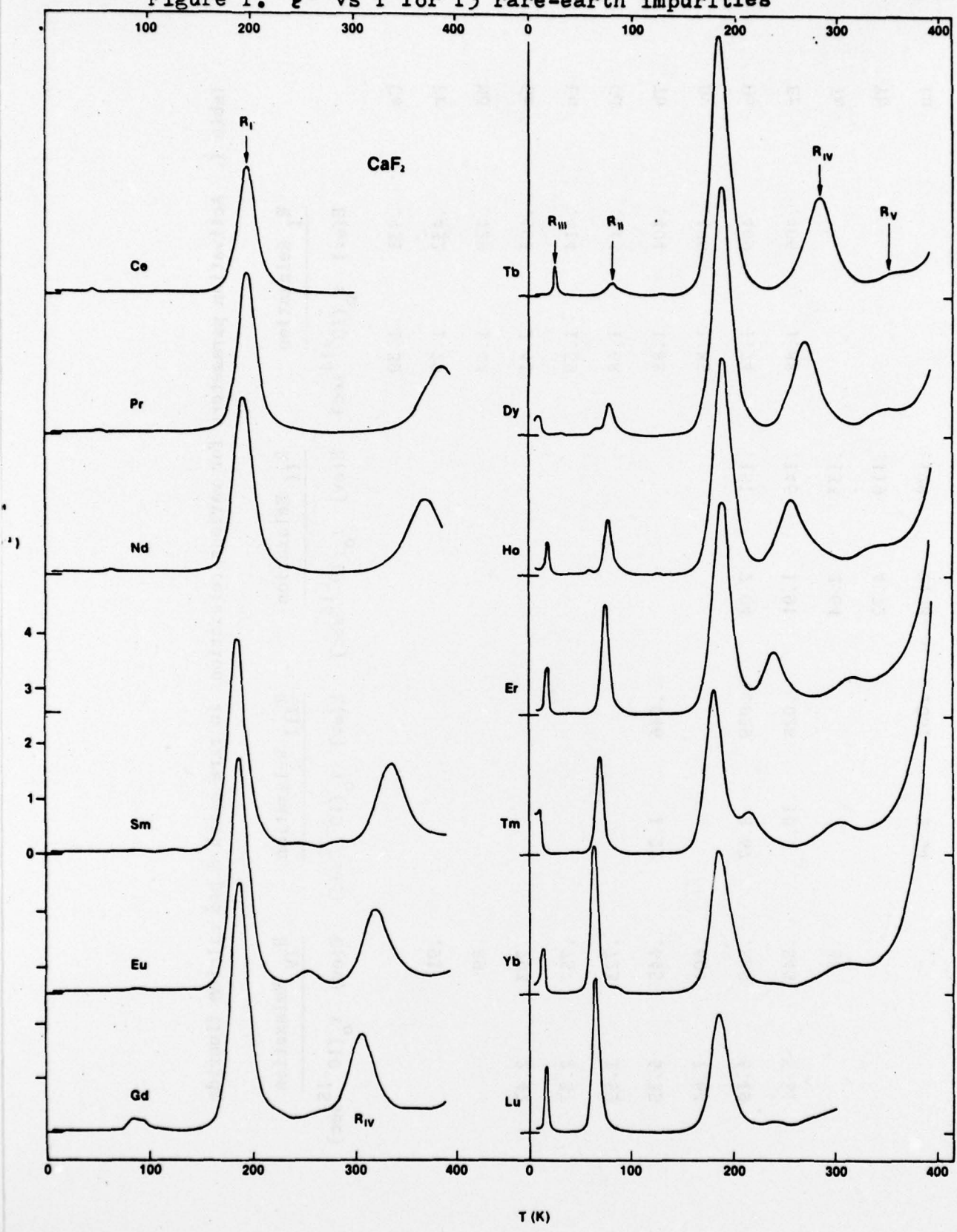
The five major results of this work are the discovery of the independence of the activation energy with respect to rare-earth for the  $R_I$  peak, the disappearance of the  $R_{II}$  and  $R_{III}$  peaks for the lower numbered rare-earths, the extremely strong dependence of activation energy on rare-earth ion size for the  $R_{IV}$  peak, and the discovery of a new relaxation which is a characteristic of the series. Another result is the discovery of the movement of the high temperature tail as a function of the rare-earth dopant, leading to the possibility that it may be due to another relaxation.

However the main achievement of this project is the characterization of the dielectric spectrum for all rare-earth dopants. This characterization has laid the groundwork for a study on the effects of neutron irradiation of the crystals. It is hoped that this will lead to the development of an improved neutron dosimeter.

Table I. Activation parameters for various relaxations in rare-earth doped calcium fluoride.

	<u>R<sub>I</sub> Relaxation</u>		<u>R<sub>II</sub> Relaxation</u>		<u>R<sub>III</sub> Relaxation</u>		<u>R<sub>IV</sub> Relaxation</u>	
	E(ev)	$\tau_0$ ( $10^{-14}$ sec)	E(ev)	$\tau_0$ ( $10^{-13}$ sec)	E(ev)	$\tau_0$ ( $10^{-12}$ sec)	E(ev)	$\tau_0$ ( $10^{-15}$ sec)
Ce	.431	1.39						
Pr	.432	1.29					.91	
Nd	.429	1.42					.89	
Sm	.403	2.41					.793	2.47
Eu	.414	1.59					.757	2.37
Gd	.414	1.68					.723	2.59
Tb	.404	1.88			.046	1.22	.645	5.35
Dy	.406	1.85					.604	7.64
Ho	.409	1.74	.151	2.04	.029	8.67	.580	6.19
Er	.406	1.88	.146	1.91	.028	10.7	.543	5.51
Tm			.133	2.64			.48	
Yb			.119	4.72				
Lu			.128	2.08	.031	2.54		

Figure 1.  $\epsilon''$  vs T for 13 rare-earth impurities



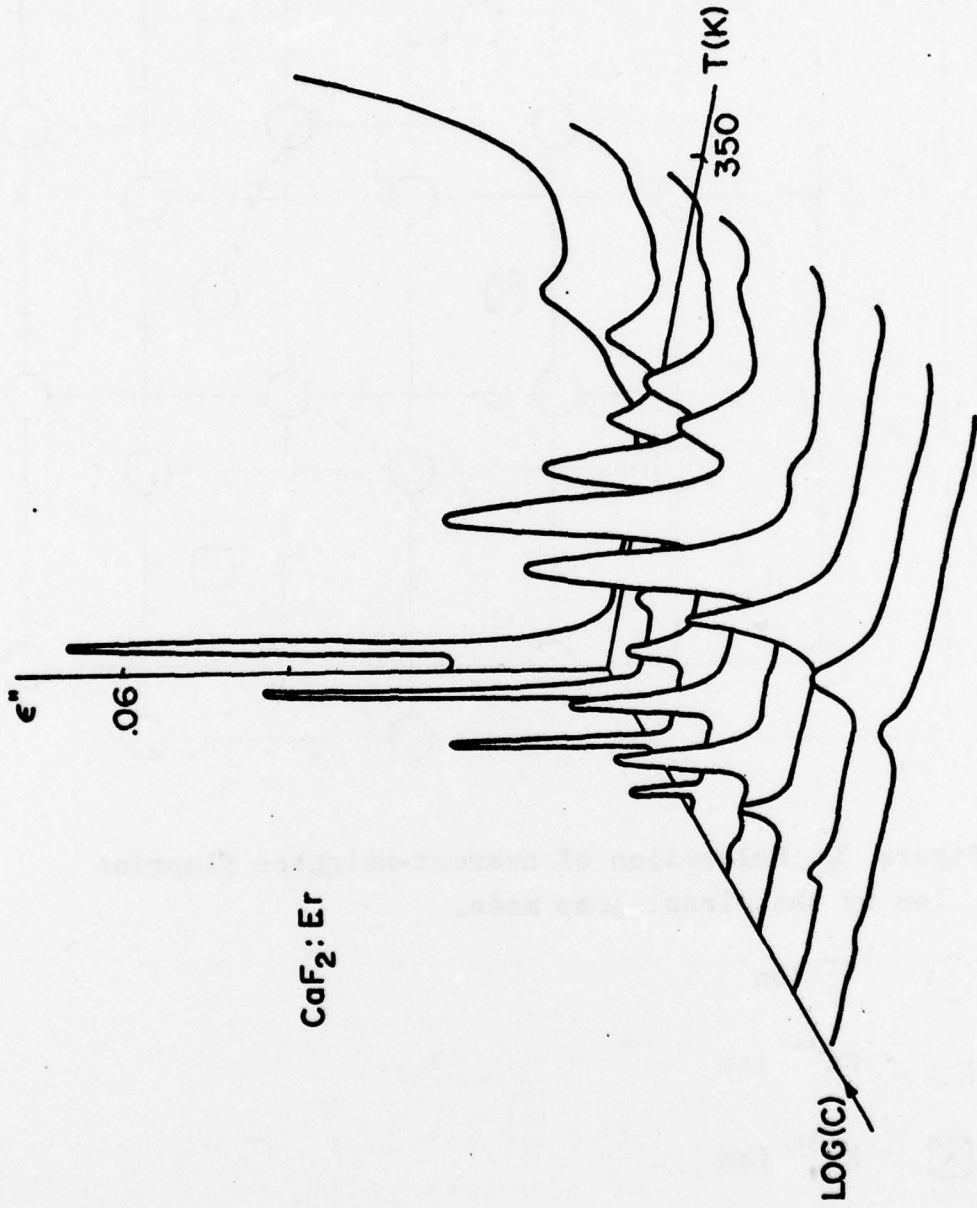


Figure 2. Imaginary part of the dielectric constant,  $\epsilon''$ , at 1000 Hz vs. temperature for all eight concentrations of  $\text{CaF}_2:\text{Er}^{3+}$ .



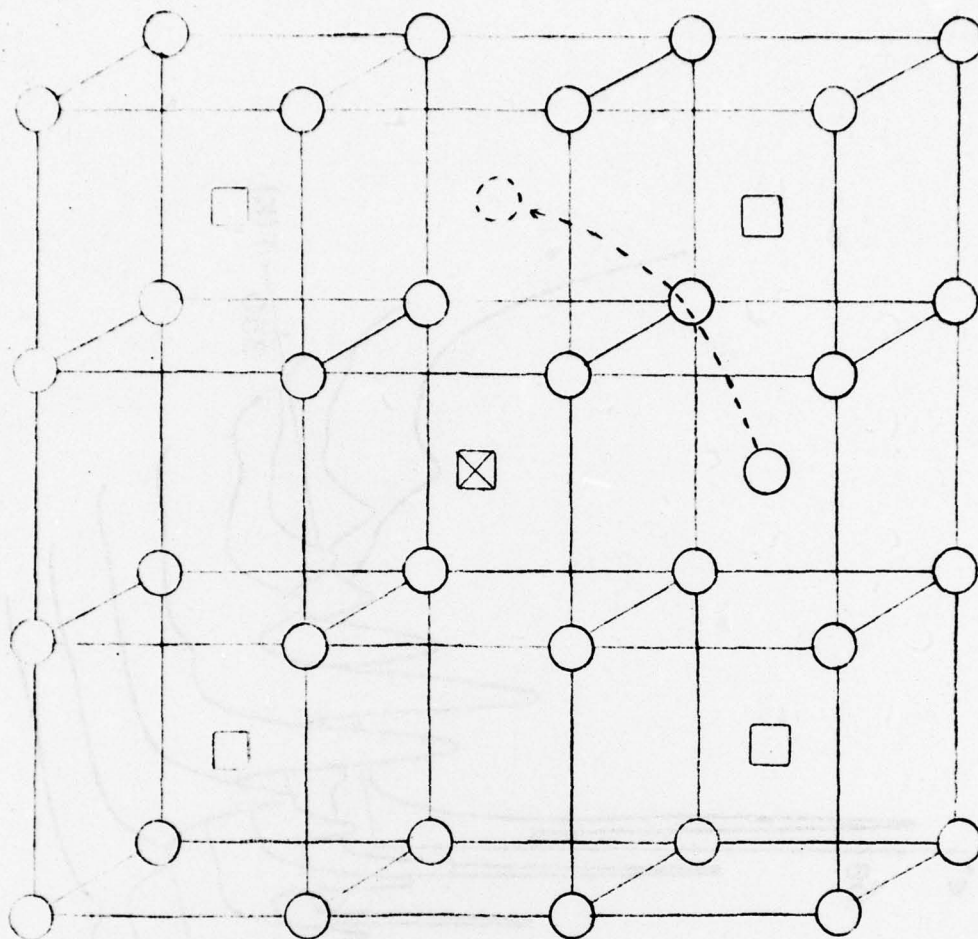
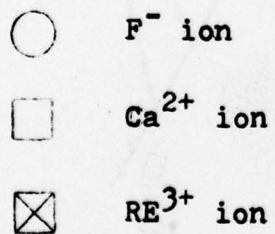


Figure 3. Relaxation of nearest-neighbor fluorine ion by the direct jump mode.



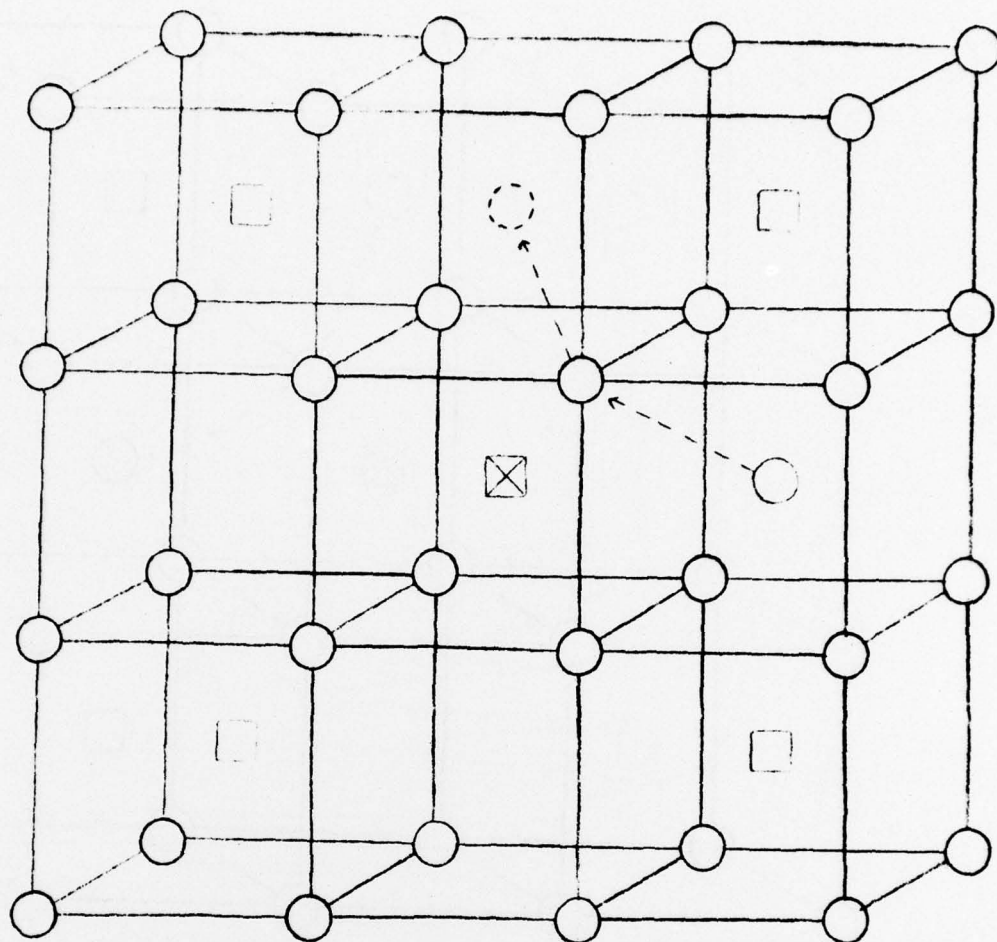
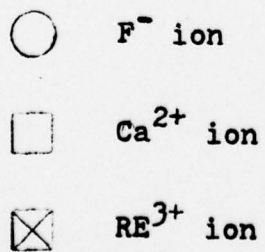


Figure 4. Relaxation of the nearest-neighbor  
fluorine ion by the interstitial mode.



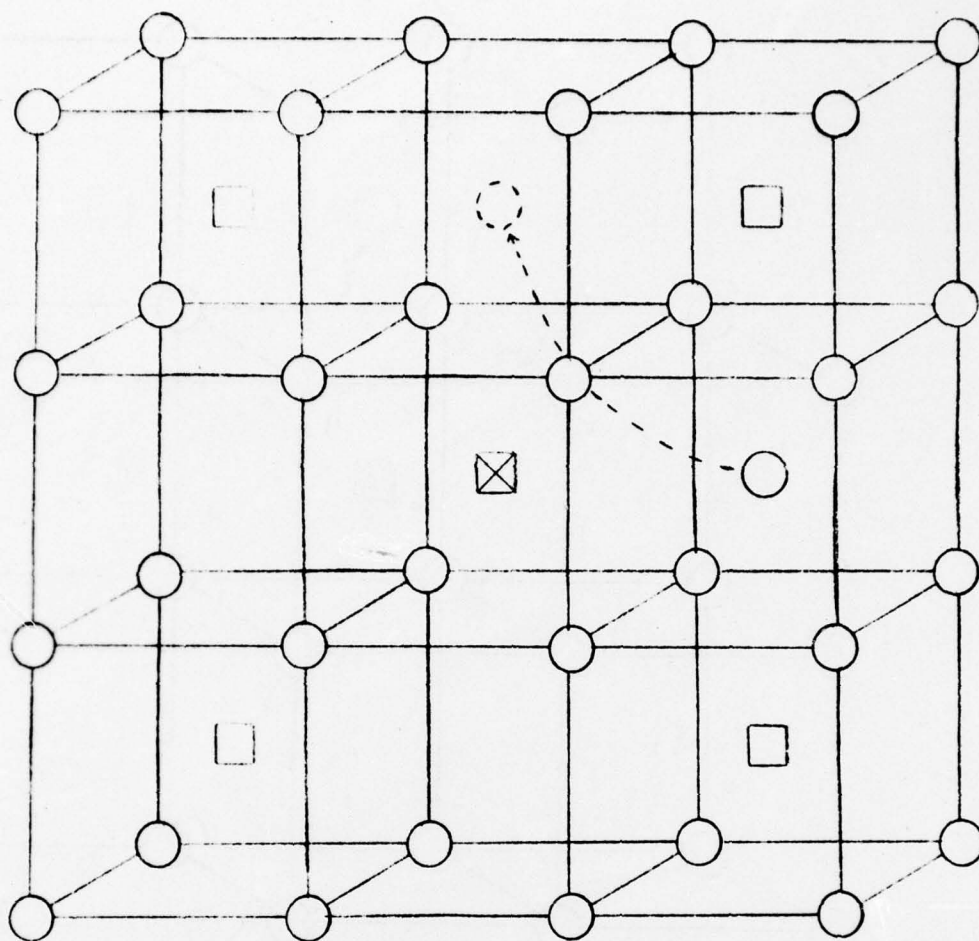


Figure 5. Relaxation of the nearest-neighbor fluorine ion by the alternate direct jump mode.

- $F^-$  ion
- $Ca^{2+}$  ion
- ⊗  $RE^{3+}$  ion

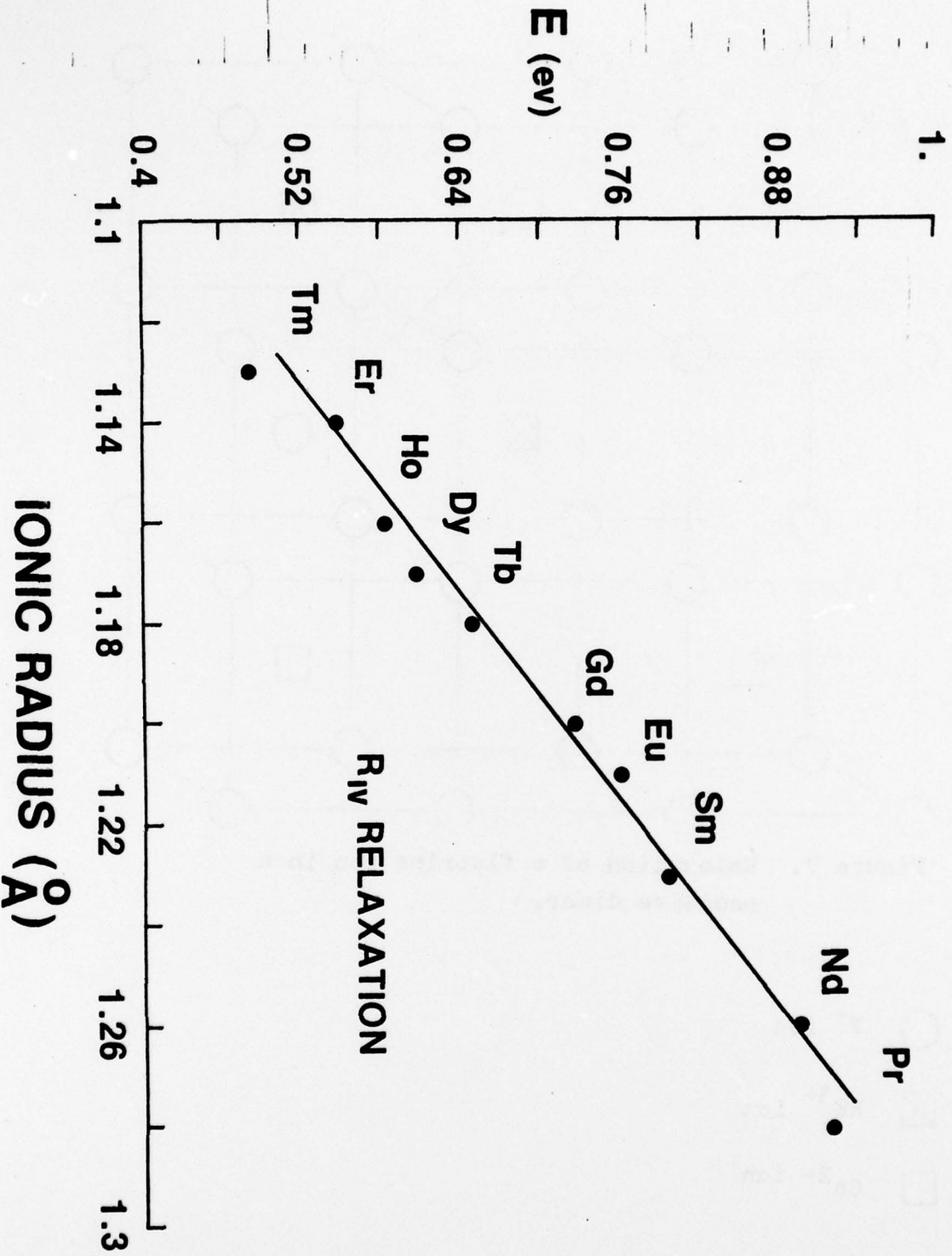


Figure 6. Activation energy vs ionic radius

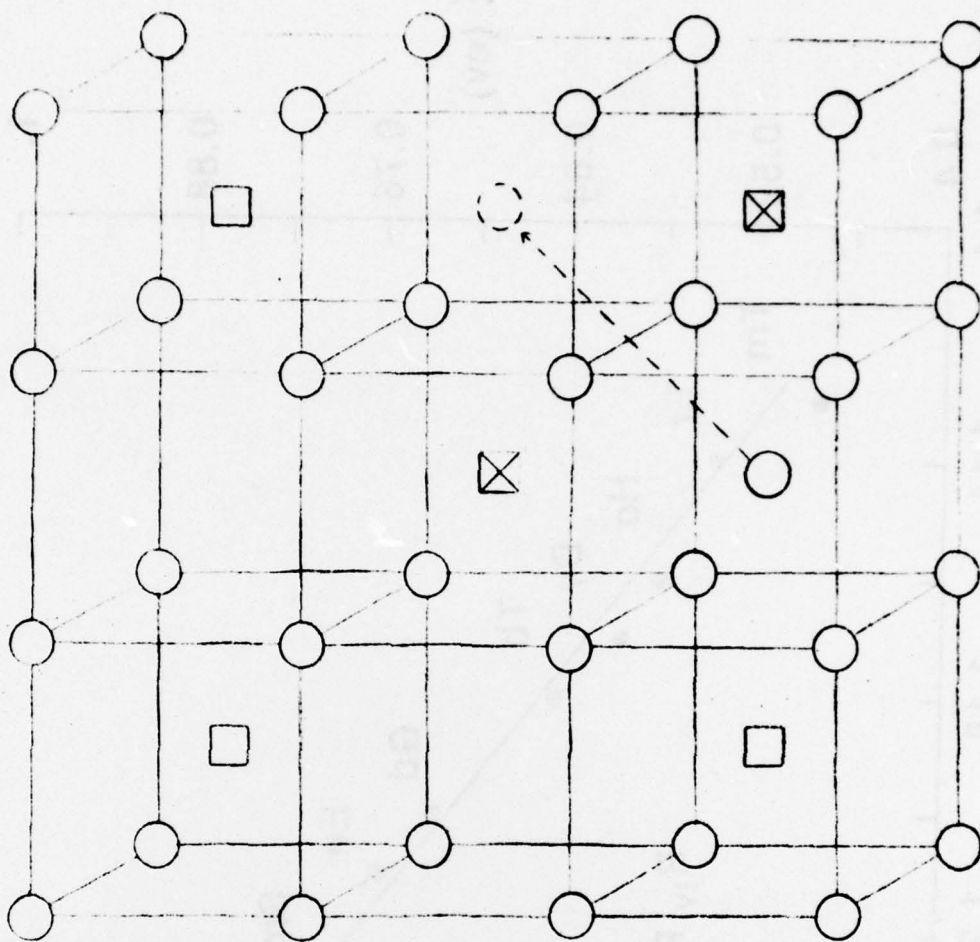


Figure 7. Relaxation of a fluorine ion in a positive dimer.

- $F^-$  ion
- ⊗  $RE^{3+}$  ion
- $Ca^{2+}$  ion

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APPENDIX A

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100 DIMENSION A(-6:6,-6:6,-6:6),B(-6:6,-6:6,-6:6),C(-6:6,-6:6,-6:6)
110 LOGICAL G
120 I1=.85372E+5
130 I2=-9.4014
140 J1=.9695E+3
150 J2=-17.293
160 G=31.031
161 I2=-4.5
162 S1=1E+6
163 15 U=1.4
164 X=0.
165 13 D=.2
17000 1 I=-6.6
18000 1 J=-6.6
19000 1 K=-6.6
200A(I,J,K)=I
210B(I,J,K)=J
220 1 C(I,J,K)=K
230A(2,0,0)=B(2,0,0)=U
270R=10.
290 11 D=.35*G
300 G=.FALSE.
31000 2 L=-1.3
32000 2 M=-1.3
33000 2 N=-2.2
350T1=T2=T3=0.
360IF (100*L+10*M+N .NE. 0) GO TO 7
37000 3 I=-6.6
38000 3 J=-6.6
39000 3 K=-6.6
400IF (100*I+10*J+K .EQ. 0) GO TO 3
410Z3=(A(L,M,N)-A(I,J,K))^2+(B(L,M,N)-B(I,J,K))^2+(C(L,M,N)-C(I,J,K))^2
420Z=SQRT(Z3)
430F=0.
440IF (MOD(I+J+K,2) .NE. 0 .OR. 100*I+10*J+K .EQ. 200) F=-3*G/Z3+S1*EXP(S2*Z)
450IF (MOD(I+J+K,4) .EQ. 0 .AND. MOD((I+1)*(J+1)*(K+1),2) .NE. 0) F=6*G/Z3
460IF (I .EQ. -6 .OR. I .EQ. 6) F=F/2
461IF (J .EQ. -6 .OR. J .EQ. 6) F=F/2
462IF (K .EQ. -6 .OR. K .EQ. 6) F=F/2
470T1=T1+F*(A(L,M,N)-A(I,J,K))/Z
480T2=T2+F*(B(L,M,N)-B(I,J,K))/Z
490T3=T3+F*(C(L,M,N)-C(I,J,K))/Z
500 3 CONTINUE
510GO TO 4
520 7 IF (MOD(L*M*N,2) .NE. 0 .OR. 100*L+10*M+N .EQ. 200) GO TO 5
530IF (MOD(L+M+N,4) .NE. 0 .OR. MOD((L+1)*(M+1)*(N+1),2) .EQ. 0) GO TO 2
54000 6 I=-6.6

```

```

100 DIMENSION A(-6:6,-6:6,-6:6),B(-6:6,-6:6,-6:6),C(-6:6,-6:6,-6:6)
110 LOGICAL Q
120 I=.85372E+5
130 Z2=-9.4014
140 Y1=.9696E+3
150 Y2=-13.293
160 G=31.031
161 S2=-4.5
162 S1=1E+6
163 15 U=1.4
164 X=0.
165 13 D=.2
170 0 1 I=-6.6
180 0 1 J=-6.6
190 0 1 K=-6.6
200 A(I,J,K)=I
210 B(I,J,K)=J
220 1 C(I,J,K)=K
230 A(2,0,0)=B(2,0,0)=U
270 R=10.
290 11 D=.35*U
300 Q=.FALSE.
310 0 2 L=-1.3
320 0 2 M=-1.3
330 0 2 N=-2.2
350 T1=T2=T3=0.
360 IF (100*L+10*M+N .NE. 0) GO TO 7
370 0 3 I=-6.6
380 0 3 J=-6.6
390 0 3 K=-6.6
400 IF (100*I+10*J+K .EQ. 0) GO TO 3
410 Z3=(A(L,M,N)-A(I,J,K))^2+(B(L,M,N)-B(I,J,K))^2+(C(L,M,N)-C(I,J,K))^2
420 Z=SQRT(Z3)
430 F=0.
440 IF (MOD(I+K,2) .NE. 0 .OR. 100*I+10*J+K .EQ. 200) F=-3*G/Z3+S1*EXP(S2*Z)
450 IF (MOD(I+K,4) .EQ. 0 .AND. MOD((I+1)*(J+1)*(K+1),2) .NE. 0) F=6*G/Z3
460 IF (I .EQ. -6 .OR. I .EQ. 6) F=F/2
461 IF (J .EQ. -6 .OR. J .EQ. 6) F=F/2
462 IF (K .EQ. -6 .OR. K .EQ. 6) F=F/2
470 T1=T1+F*(A(L,M,N)-A(I,J,K))/Z
480 T2=T2+F*(B(L,M,N)-B(I,J,K))/Z
490 T3=T3+F*(C(L,M,N)-C(I,J,K))/Z
500 3 CONTINUE
510 GO TO 4
520 7 IF (MOD(L*M*N,2) .NE. 0 .OR. 100*L+10*M+N .EQ. 200) GO TO 5
530 IF (MOD(L*M*N,4) .NE. 0 .OR. MOD((L+1)*(M+1)*(N+1),2) .EQ. 0) GO TO 2
540 0 6 I=-6.6

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△ spectrum for all rare-earth dopants. This characterization has laid the groundwork for a study on the effects of neutron irradiation of the crystals. The writer hopes that this will lead to the development of an improved dosimeter. -

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