rigid rotor embedded in a lattice would satisfy the requirement of having a large temperature-independent charge displacement, changes in which could be effective in relaxing a paramagnetic center somewhere nearby. The energy levels of a rigid rotor are proportional to $n(n+1)$ which for large n resembles the square-well energy-level distribution.

The E' center in quartz,[7] which is an electron trapped at a silicon atom next to an oxygen divacancy may behave like a particle in a square well. The two missing oxygen atoms free the silicon atom to swing in a large arc about the line joining the remaining two oxygens. For the E' center and for complex defects in general, it is probable that the frequency of the localized motion gets lower and lower, the motion becomes more and more like a particle in a square well. It is clear that the amplitude cannot remain harmonic for extremely low frequencies because the amplitude of a harmonic oscillator is proportional to $\omega^{-1/2}$ as $\omega \rightarrow 0$. Large anharmonicities must therefore become important at very low frequencies.

SUMMARY

A paramagnetic center which is involved in a vibration whose amplitude is independent of temperature, e.g., a particle moving in a large square well, or a particle tunneling through a barrier between two stable positions, can have a spin-lattice relaxation rate that varies linearly with temperature at high temperatures and drops off exponentially with the reciprocal of the temperature at low temperatures. The linear temperature dependence for the tunneling model is a consequence of a single excited vibrational state. The process is analogous to an Orbach process. The temperature dependence differs from that of an Orbach process because spins in the excited state are observed while in the Orbach process one observes only ground-state spins. If the relaxation mechanism in the square-well case is due to a magnetic interaction with some other nearby dipole, the relaxation rate is linear in temperature at high temperatures. In order to obtain a linear variation in a Kramer's system using an electric-field modulation, it is necessary to require that the external magnetic field couple the excited states of the defect together resulting in spin-flip matrix elements that are not proportional to the frequency of the participating phonons. If this is not probable then the electric-field modulation in a Kramers system leads to a T^2 dependence at high temperatures.

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Density Effect for the Ionization Loss of Charged Particles*

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The reduction in the ionization loss of charged particles due to the polarization of the medium (density effect) has been evaluated for several substances. An approximate semiempirical expression for the mean excitation potential I as a function of the atomic number Z has been obtained.

THE density effect correction for the ionization loss of charged particles[1-6] has been previously evaluated for various substances.[4-6] The purpose of the present paper is to give the results of additional calculations for the following materials: silicon, germanium, liquid hydrogen, propane and freon (CF_3Br). The first two substances are of interest in connection with solid-state detectors, while an evaluation of the density effect for liquid hydrogen, propane, and freon should be useful in connection with the observation of ionization densities in bubble chambers. We have also obtained a semiempirical expression for the mean excitation potential I (as a function of Z) which enters into the Bethe-Bloch formula for the ionization loss.[7,8]

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The procedure of the calculation of the density effect followed along the same lines as in Refs. 4–6. Thus the calculated values of δ have been expressed in the form:

$$\delta=4.606X+C+a(X_1-X)^m, \quad (X_0<X<X_1) \quad (1)$$

$$\delta=4.606X+C, \quad (X>X_1) \quad (2)$$

with $X\equiv\log_{10}(p/m_0c)$, where p and m_0 are the momentum and the rest mass of the incident particle. In Eqs. (1) and (2), C, a, m, X_0, and X_1 are constants which are characteristic of the substance considered. In particular, C is given by

$$C=-2\ln(I/h\nu_p)-1, \quad (3)$$

where I is the mean excitation potential for the electrons of the substance, and $h\nu_p$ is the corresponding plasma energy, with ν_p defined by

$$\nu_p=(ne^2/\pi m_e)^{1/2}, \quad (4)$$

where n is the electron density (number of electrons per cm^3), and m_e= electron mass. From Eq. (4), we obtain

$$h\nu_p=2.118(\rho_0 Z/A_0)^{1/2}\ \mathrm{Ry}, \quad (5)$$

for the value of $h\nu_p$ in Rydberg units; here ρ_0 is the density of the material (in g/cm^3) and Z, A_0 are the atomic number and atomic weight, respectively.

We will now discuss the choice of the values for the mean excitation potential I. For the cases of Si, Ge, and Br (in CF$_3$Br), we used the following semiempirical expression proposed by Sternheimer[9] for $Z\geqq 13$:

$$I/Z=9.76+58.8Z^{-1.19}\ \mathrm{eV}. \quad (6)$$

This gives: $I=172$ eV for Si, 343 eV for Ge, and 372 eV for Br.

Equation (6) is based on the fact that the experimental values of I/Z decrease slowly with increasing Z from a value $\sim$12.5 for Al to $\sim$10 for Pb. We have therefore fitted the following I values: $I=163$ eV for Al,[10] $I=826$ eV for Pb,[11] and $I=314$ eV for Cu, 314 being the average of the result of Barkas and von Friesen[11] (323 eV) and the value obtained by Zrelov and Stoletov[12] (305 eV). It is easily seen that Eq. (6) reproduces these three values of I, and gives a smooth behavior of I/Z in the region considered ($Z\geqq 13$).

For hydrogen, we used the value $I=18.7$ eV given by Berger and Seltzer.[13] For C and F, the value of I was taken as $13Z$ eV, giving $I=78$ eV for C and 117 eV for F.

Table I. Data used to calculate the density effect. The values of $h\nu_i$, $h\nu_p$, and I are in Rydberg units. For CF$_3$Br, only the constants ($h\nu_i$, l_i, f_i) for F are listed, as discussed in the text.

Material	Si	Ge	Liq. H	C$_3$H$_8$	CF$_3$Br
$h\nu_1$	135.4	817.6	1.0	21.0	50.6
$h\nu_2$	8.26	93.7		3.0	4.0
$h\nu_3$	3.00	8.8		1.0	2.0
$h\nu_4$	0.88	3.0		1.0	
$h\nu_5$		0.82			
l_1	103.1	382.9	2.602	28.22	52.1
l_2	6.29	43.88		4.04	4.12
l_3	2.28	4.12		1.34	2.06
l_4	0.378	1.41		1.28	
l_5		0.25			
f_1	2/14	2/32	1	6/26	6/68
f_2	8/14	8/32		6/26	6/68
f_3	2/14	18/32		6/26	15/68
f_4	2/14	2/32		8/26	
f_5		2/32			
ρ	1.774	1.522	1.374	1.442	1.800
$h\nu_p$	2.33	3.25	0.528	1.073	1.75
I	12.65	25.22	1.374	3.70	15.05

For the case of compounds (C$_3$H$_8$ and CF$_3$Br), the value of I is given by the logarithmic average of the I values of the constituent atoms, with weights proportional to the corresponding numbers of electrons of the various atoms. Thus, we obtain

$$\ln I=\textstyle\sum_k f_k \ln I_k, \quad (7)$$

where f_k is the fractional number of electrons of the kth atomic species with excitation potential I_k. For C$_3$H$_8$, with $f_{\mathrm{C}}=18/26$, $f_{\mathrm{H}}=8/26$; $I_{\mathrm{C}}=78$ eV, $I_{\mathrm{H}}=18.7$ eV, we find $I=50.3$ eV. Similarly, for CF$_3$Br, we have: $f_{\mathrm{C}}=6/68$, $f_{\mathrm{F}}=27/68$, $f_{\mathrm{Br}}=35/68$; $I_{\mathrm{C}}=78$ eV, $I_{\mathrm{F}}=117$ eV, and $I_{\mathrm{Br}}=372$ eV, giving $I=204.7$ eV.

The density-effect correction δ is obtained from[4–6]:

$$\delta=\textstyle\sum_i f_i \ln[(l_i^2+l^2)/l_i^2]-l^2(1-\beta^2), \quad (8)$$

where l is the solution of the following equation:

$$1/\beta^2-1=\textstyle\sum_i f_i/(\bar{\nu}_i^2+l^2). \quad (9)$$

In Eqs. (8) and (9), β is the velocity of the particle (in units c), f_i is the oscillator strength pertaining to the ith shell of the atom, l_i and $\bar{\nu}_i$ are (dimensionless) frequencies pertaining to i, which are obtained as follows: We start with the experimental ionization potentials for the various shells which will be denoted by $h\nu_i$. In a conductor, it has been previously shown[4,6] that the effective ionization potential pertaining to the conduction electrons (oscillator strength f_c) is given by the corresponding plasma frequency, which is $\nu_p f_c^{1/2}$. Thus we obtain for the conduction electrons: $h\nu_i'=h\nu_p f_c^{1/2}$, where the prime of ν_i' indicates that we are dealing with an effective ionization potential, which can be used to obtain the l_i of Eq. (8) (see below).

The geometric mean of the effective excitation potentials $h\nu_i'$ must be equal to the mean excitation potential I as determined above [Eq. (6)]. In general, as already discussed in Refs. 4 and 6, the mean of the $h\nu_i$ will be somewhat less than I. Therefore, we assume that the effective $h\nu_i'$ values are given by $h\nu_i\rho$, where ρ is a

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common multiplicative factor ($\rho > 1$) for all shells i, except the conduction electrons. Thus ρ is determined by the condition:

$$\sum_{i=1}^{j-1} f_i \ln(h\nu_i\rho) + f_j \ln(h\nu_p f_j^{1/2}) = \ln I , \tag{10}$$

where j is the total number of dispersion oscillators used in the calculation, and $f_j(=f_c)$ pertains to the conduction electrons. We have thus obtained: $\rho = 1.774$ for Si, 1.522 for Ge, 1.374 for H, 1.442 for C, 1.800 for F, and 1.497 for Br. The result that $\rho > 1$ probably reflects the fact that for excitation of the atomic electrons to continuum states, the excitation energy is larger than the ionization potential for the shell considered.

Finally, the constants l_i and $\bar{\nu}_i$ of Eqs. (8) and (9) are given by

$$\bar{\nu}_i = h\nu_i'/h\nu_p = h\nu_i\rho/h\nu_p \ (i<j) , \tag{11}$$

$$l_i = (\bar{\nu}_i^2 + f_i)^{1/2} . \tag{12}$$

For all but the conduction electrons, the difference between $\bar{\nu}_i$ and l_i is usually negligible. For $i=j$, we have $l_j = f_j^{1/2}$.

The basic ionization potentials $h\nu_i$ were obtained by means of standard tabulations.[14,15] For both Si and Ge, it was assumed that only the two outermost p electrons ($3p$ and $4p$, respectively) are conduction electrons in the solid. For Si, the energies $h\nu_1$, $h\nu_2$, $h\nu_3$, $h\nu_4$ pertain to the K, L, $M_I(3s)$, and $M_{II}(3p)$ electrons, respectively. Similarly, for Ge, $h\nu_1$, $h\nu_2$, $h\nu_3$, $h\nu_4$, and $h\nu_5$ pertain to the K, L, M, $N_I(4s)$, and $N_{II}(4p)$ electrons, respectively.

The values of $h\nu_i$, f_i, and the resulting l_i are given in Table I. At the bottom of the table, we have also listed the values of ρ, $h\nu_p$, and I. We note that all energies (i.e., $h\nu_i$, $h\nu_p$, I) in this table are in Rydberg units.

For C_3H_8, the energies $h\nu_1$, $h\nu_2$, and $h\nu_3$ pertain to the C atoms ($1s$, $2s$, and $2p$, respectively), while $h\nu_4$ pertains to the hydrogen. The value of ρ given in the column for $C_3H_8(\rho = 1.442)$ pertains to the carbon.

In Table I, the values of $h\nu_i$, l_i, and f_i listed for CF_3Br pertain to the F atoms only ($h\nu_1$ for $1s$, $h\nu_2$ for $2s$, $h\nu_3$ for $2p$). The pertinent value of ρ_F ($=1.800$) is given at the bottom of the table. The values of $h\nu_i$ and ρ for C were the same as those listed in the column for C_3H_8. Finally, for Br, we used $h\nu_1 = 993$ Ry ($n=1$), $h\nu_2 = 120$ Ry ($n=2$), $h\nu_3 = 12$ Ry ($n=3$), and $h\nu_4 = 2$ Ry ($n=4$), with $\rho_{Br} = 1.497$. The resulting values of l_i for C and Br, which are not listed in Table I, are as follows: $l_i = 17.30$, 2.47, and 0.824 for C (with $f_i = 2/68$ for each of the three dispersion oscillators), and $l_i = 849.4$, 102.6, 10.26, and 1.71 for Br (with $f_i = 2/68$, 8/68, 18/68, and 7/68, respectively). Thus, altogether 10 terms were used in Eqs. (8) and (9) for CF_3Br.

Table II. Values of the constants which enter into the expression for the ionization loss [Eq. (13)] and the density effect correction δ [Eqs. (1) and (2)]. The mean excitation potential I is in electron volts and A is in units MeV/g cm^{-2}. The values of C, a, m, X_0, and X_1 enter into Eqs. (1) and (2).

Material	I (eV)	A	B	$-C$	a	m	X_0	X_1
Si	172	0.0766	16.66	4.38	0.0874	3.586	0.10	3
Ge	343	0.0677	15.28	5.10	0.1666	3.136	0.10	3
Cu	323	0.0701	15.40	4.43	0.109	3.39	0.20	3
Pb	826	0.0608	13.53	6.21	0.355	2.64	0.40	3
Liq. H_2	18.7	0.1524	21.10	2.91	0.0569	6.224	0.415	2
C_3H_8	50.3	0.0906	19.12	3.48	0.555	2.567	0.241	2
CF_3Br	204.7	0.0701	16.32	5.30	0.179	3.097	0.423	3

In obtaining $h\nu_p$ for liquid hydrogen, we have used the density $\rho_0 = 0.0626$ g/cm^3 obtained by Burnstein *et al.*[16] For Si and Ge, the values of ρ_0 ($=2.42$ and 5.35 g/cm^3, respectively) were taken from Ref. 14. The value of ρ_0 used for propane, namely 0.435 g/cm^3 was obtained from an article by Tenner.[17] Finally, the density $\rho_0 = 1.5$ g/cm^3 for CF_3Br was obtained from a paper by Bingham *et al.*[18] If the densities of the bubble chamber liquids differ slightly from the above values under actual operating conditions, the results for δ can be evaluated for the actual density $\rho_1(\neq\rho_0)$ by means of a simple procedure which will be given below.

The values of δ calculated from Eqs. (8) and (9) were fitted by means of the expressions (1) and (2), in the same manner as in our previous work.[4–6] For Si and Ge, we employed a value of $X_0 = 0.10$ with $\delta(X_0) = 0.06$. These values are the same as those previously used for Mg in Ref. 6 (see p. 514). For H, $X_0 = 0.415$ is the value of X for which $\delta = 0$, according to Eqs. (8) and (9). Similarly, for C_3H_8 and CF_3Br, we obtain: $X_0 = 0.241$ and 0.423, respectively.

The resulting values of C, a, m, X_0, and X_1 are presented in Table II. This table also gives the constants A and B which enter into the Bethe-Bloch formula for the ionization loss, in our previous notation[4–7]:

$$-(1/\rho)dE/dx = (A/\beta^2)[B + 0.69 + 2\ln(p/m_0c) + \ln W_{\max,\mathrm{MeV}} - 2\beta^2 - \delta] , \tag{13}$$

where $W_{\max,\mathrm{MeV}}$ is the maximum energy transfer to an atomic electron. Equation (13) applies for the average energy loss for heavy particles. Alternative expressions which pertain to the energy loss of electrons or the restricted energy loss are given in Ref. 7. The constants A and B are defined by

$$A \equiv 2\pi n e^4/m_e c^2 \rho_0 = 0.1536(Z/A_0)\ \mathrm{MeV/g\ cm^{-2}} , \tag{14}$$

$$B \equiv \ln[m_e c^2 (10^6\ \mathrm{eV})/I^2] . \tag{15}$$

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In addition to the results for the substances discussed above, we have also given in Table II values for the density effect for Cu and Pb. In obtaining these values, we used the results for I obtained by Barkas and von Friesen,[11] namely $I_{\mathrm{Cu}}=323$ eV and $I_{\mathrm{Pb}}=826$ eV. The values of δ were obtained by interpolation of the results of Refs. 4 and 6, which pertain to different values of I. Thus, if we denote the two values of I for a given substance by I_1 and I_2, and the corresponding values of δ by δ_1 and δ_2, respectively, then the value of δ appropriate to an intermediate value I $(I_1<I<I_2)$ is obtained by logarithmic interpolation:

$$\delta_I=\delta_1\xi+\delta_2(1-\xi)\,, \tag{16}$$

where ξ is defined by

$$\xi\equiv\log_{10}(I_2/I)/\log_{10}(I_2/I_1)\,. \tag{17}$$

For Cu, we have: $I_1=20.5$ Ry (Ref. 4), $I_2=27.7$ Ry (Ref. 6), so that $I_{\mathrm{Cu}}=323$ eV gives $\xi=0.514$. Similarly, for Pb, $I_1=55.6$ Ry, $I_2=86.8$ Ry, whence $\xi=0.801$ for $I_{\mathrm{Pb}}=826$ eV.

The calculated values of δ_I for Cu and Pb were fitted by means of Eqs. (1) and (2); the resulting values of the coefficients a, m, X_0, and X_1 are given in Table II. For X_0 and $\delta(X_0)$, we used the same data as in Ref. 6 (see p. 514), i.e., $X_0=0.20$ for Cu and $X_0=0.40$ for Pb, with $\delta(X_0)=0.04$ in both cases. We note that the present values of δ were used in the recalculation of the proton range-energy relations[19,20] for Cu and Pb, which has been published in Ref. 20.

Concerning the results for liquid hydrogen, we note that an approximate value of δ could be obtained from the expression for H_2 gas at normal pressure, given in Ref. 6 (see Table II), by substituting in place of X a value $\bar{X}\equiv X+\log_{10}(70/2.602)=X+1.430$, where 70/2.602 is the ratio of $(I/h\nu_p)$ for the two cases. Note that in Ref. 6, $I=1.40$ Ry, $h\nu_p=0.020$ Ry, giving $I/h\nu_p=70$, as compared to $l_1=2.602$ in Table I.

It should also be mentioned that if the density of the liquid hydrogen ρ_0 departs slightly from the value[16] 0.0626 g/cm^3 assumed in the present work, and with $\eta\equiv\rho_0/0.0626$, the density effect correction δ for the density ρ_0 at the momentum p can be obtained from

$$\delta_\eta(p)=\delta_1(p\eta^{1/2})\,, \tag{18}$$

where the subscript of δ indicates the value of η. The correction δ_1 (to be evaluated for the momentum $p\eta^{1/2}$) is given by Eqs. (1) and (2) with the constants C, a, m, X_0, and X_1 listed in Table II. Equation (18) can be deduced directly from Eq. (10c) of Ref. 4.

The same comment concerning the evaluation of δ for the actual density ρ_0 applies, of course, to any other substance. In particular, if the density ρ_0 of the C_3H_8 or CF_3Br differs from the values used in the preceding calculations, one can again use Eq. (18) to obtain $\delta_\eta(p)$, in which η is now defined as $\eta\equiv\rho_0/0.435$ for propane and $\eta\equiv\rho_0/1.5$ for freon.

The density effect for liquid helium can be directly obtained from the results given in Ref. 6 for helium bas at normal pressure. Thus according to Ref. 17, the density of liquid helium under bubble chamber operating conditions is $\sim$0.125 g/cm^3, which gives according to Eq. (5): $h\nu_p=0.529$ Ry. Since $h\nu_p=0.020$ Ry for He gas,[6] the ratio of the $h\nu_p$ values and hence $\eta^{1/2}$ equals 26.45. Upon inserting this result in Eq. (18), we obtain

$$\delta_{\mathrm{liq.He}}(p)=\delta_{\mathrm{gas}}(26.45p)\,, \tag{19}$$

where δ_{gas} is obtained from Ref. 6 (with $I=44$ eV). The constants which enter into Eqs. (1) and (2) for δ_{gas} have the following values: $a=2.13$, $m=3.22$, $C=-11.18$, $X_0=2.21$, $X_1=3$ (see Table II of Ref. 6). In view of Eq. (19), the effective value of X_0 for liquid helium is given by

$$X_0=\log_{10}(p_0/m_0c)=2.21-\log_{10}26.45=0.788\,, \tag{20}$$

so that $p_0/m_0c=6.13$. For smaller values of the momentum, $p<p_0$, we have $\delta_{\mathrm{liq.He}}=0$.

Note added in proof. We have also obtained the density-effect correction δ for the case of lithium fluoride. Upon using the value $I=13Z$ eV for both Li and F ($I_{\mathrm{Li}}=39$ eV, $I_{\mathrm{F}}=117$ eV), one finds: $I_{\mathrm{LiF}}=88.9$ eV, giving $B=17.98$. With $\rho_0=2.601$ g/cm^3, one obtains $h\nu_p=2.32$ Ry. The constants A and C have the values $A=0.0711$ MeV/g cm^{-2}, $C=-3.07$. The ionization potentials $h\nu_1$, $h\nu_2$, and $h\nu_3$ for F and the corresponding value of ρ $(=1.800)$ have been listed in Table I in connection with CF_3Br. For Li, we used $h\nu_1=4.0$ Ry for the 1s electrons, and $h\nu_2=0.4$ Ry for 2s. The resulting value of ρ (required to give $I_{\mathrm{Li}}=39$ eV) is $\rho_{\mathrm{Li}}=1.544$. Thus altogether five dispersion oscillators were used in Eqs. (8) and (9) for LiF.

The calculated results for δ are well fitted by Eqs. (1) and (2) with the following values of the constants: $X_0=-0.072$ $[\delta(X_0)=0]$, $X_1=2$, $C=-3.07$, $a=0.456$, and $m=2.757$.

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