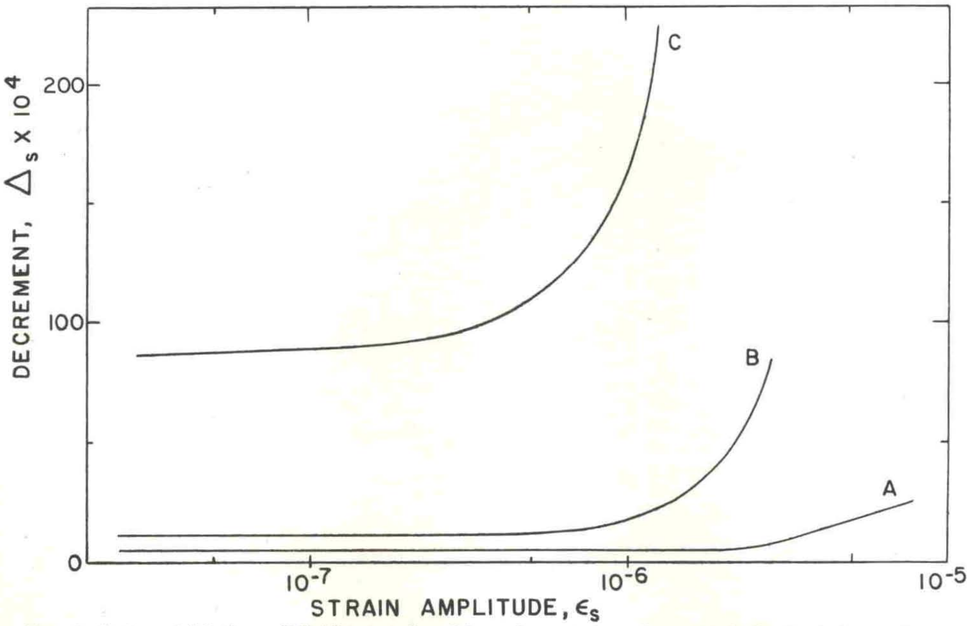

FIG. 2. Internal friction of NaCl crystals subjected to various degrees of plastic deformation. (A) fully annealed; (B) compressed 0.04%; (C) compressed 2.3%.

and a small modulus increase upon irradiation. In the as-received condition the modulus-change upon irradiation and the damping prior to irradiation are again higher than in the annealed condition. Table 1 lists some of the changes in resonant frequency produced by irradiation.

When one of the specimens used for modulus measurements is compressed in the direction of its length, slip takes place on two sets of the {110} planes. Both the decrement and modulus of the crystal are changed as a result of such deformation. Curve *B* in Fig. 2 shows the decrement as a function of strain amplitude observed after a carefully annealed crystal has been compressed 0.04%, while Curve *C* corresponds to this same crystal after a compression of 2.3%.

TABLE 1. Total change in resonant frequency produced in various NaCl crystals by X-irradiation

Crystal number	Treatment	Re-covery time (min)	Re-covery tempera-ture (°C)	Total Δf_s (c.p.s.)
1	annealed	—	—	0
1	quenched from 500°C	—	—	34
1	(as received)	—	—	175
8	deformed 4.07%	150	100	123
7	deformed 4.40	150	100	129
9	deformed 2.00	5760	20	212
5	deformed 2.14	180	20	434
6	deformed 4.20	1700	20	720
12	deformed 3.08	1936	20	1945
10	deformed 4.08	1440	20	2150
13	deformed 3.24	119	20	2870

It is evident that the internal friction is increased markedly by small deformations and that the strain amplitude at which the decrement becomes dependent on the amplitude of vibration is simultaneously decreased. This behavior is similar to that of deformed metal crystals.[14, 15]

The elastic modulus of the compressed crystals is lowered as a result of the deformation. This change is not conveniently observed by direct measurement, because of the dimensional changes that accompany the deformation; it becomes apparent, however, from the fact that the modulus increases spontaneously with time after deformation. Correspondingly, internal friction decreases on standing at room temperature. Similar changes in modulus and damping following plastic deformation have also been observed in deformed metals,[16] and are collectively known as the Köster effect, after their discoverer. The course of the recovery of the Köster effect is such that over a large time-interval the modulus increase is approximately linear with the logarithm of time after deformation, as is shown in Fig. 3. The decrement at large strain amplitudes decreases with time more rapidly than that at small amplitudes, while both decrement curves have the inverted *S* shape characteristic of a recovery phenomenon involving a broad spectrum of recovery times.

Exposure of the deformed crystals to X-rays increases the modulus and decreases the damping in the same way as it does in the as-received and quenched crystals, but the magnitude of the effects produced is

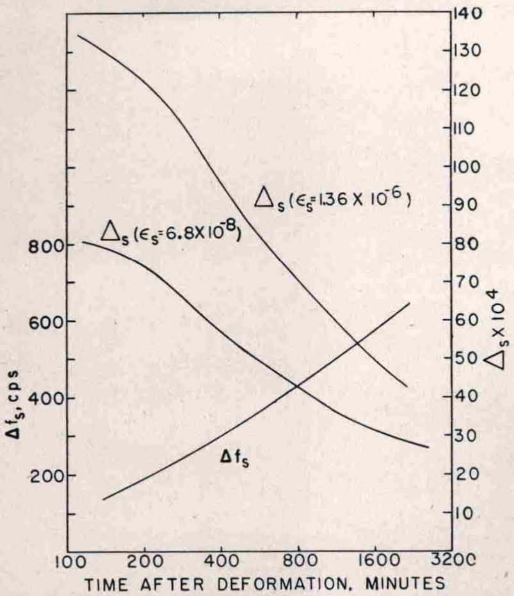

FIG. 3. Spontaneous recovery of the resonant frequency (measured from an arbitrary reference frequency) and decrement of a plastically deformed NaCl crystal (No. 6) at room temperature. The crystal was compressed 4.2% at zero time.

very much greater. The total changes in the resonant frequency of a number of crystals subjected to different deformation and recovery treatments prior to irradiation are listed in Table 1. It should be noted that the largest changes reported correspond to modulus changes of nearly 7%. It is evident from the data presented in the table that the total modulus change produced by irradiation is greater, the greater the prior deformation and the less the prior recovery time. In addition to the amount of deformation and the recovery time, the modulus change observed in any particular crystal apparently depends on other factors, such as the rate at which the crystal was deformed and/or the particular configuration of slip planes which happened to be active during the deformation (varying amounts of double slip were seen in all the crystals).

The data on crystals 7 and 8 presented in Table 1 show that recovery at 100°C prior to irradiation substantially reduces the modulus effect produced by the irradiation. It has also been shown that no modulus effect is observed when carefully annealed crystals are irradiated. These observations suggest that *irradiation can only raise the modulus in crystals where the modulus has been previously lowered by deformation and not allowed to recover fully.* In other words, the sum of the modulus increases resulting from recovery and irradiation should be the same in crystals which have been deformed the same amount, provided that care is taken to deform the crystals in exactly the same manner.

An experimental test of the above hypothesis was carried out as follows. Two crystals (Nos. 12 and 13) were carefully deformed by nearly the same amounts and then allowed to recover for different lengths of time before exposure to X-rays. The resulting resonant-frequency changes on recovery and on irradiation are shown in Fig. 4 and in Table 2. The X-irradiation was

TABLE 2. Comparison of frequency changes in two similarly deformed crystals

Crystal No.	12	13
Per cent deformation	3.08	3.24
Recovery time at 20°C (min)	2936	119
Δf_s in recovery (c.p.s.)	1007	193
Δf_s on irradiation (c.p.s.)	1931	2872
Total Δf_s	2938	3065
Corrected to 3.08% deformation	2938	2950

for two hours in both cases. The total changes in resonant frequency of the two crystals agree to within 4%. Even better agreement is obtained if a correction is made for the small difference in initial deformation of the two crystals, assuming a linear dependence of Δf_s on per cent deformation. This correction is made in the last line of Table 2 as well as in the plotted data for crystal No. 13 in Fig. 4. The excellent agreement obtained for the total modulus change of the two crystals, after correction, is undoubtedly somewhat fortuitous in view of the difficulty in deforming two different specimens in exactly the same way.

The manner in which the modulus changes with X-ray dosage has been demonstrated thus far only in Fig. 1. It is now of interest to compare such modulus vs. dose curves for crystals subjected to different prior treatments. For this purpose it is convenient to define the *modulus defect*, Φ, as

$$\Phi = \frac{M^{\infty} - M}{M^{\infty}} = 2\frac{f_s^{\infty} - f_s}{f_s^{\infty}} \qquad (4)$$

where M^{∞} and f_s^{∞} are the "saturation values" of the modulus $M = s_{11}^{-1}$, and of the resonant frequency f_s, of the specimen attained after prolonged irradiation. The quantity Φ_0 will represent the modulus defect at the start of irradiation. The relation between the modulus vs. dose curves for specimens deformed different amounts is shown in Fig. 5, where the relative modulus defect, Φ/Φ_0, is plotted against the logarithm of the irradiation time. It is seen that during the major part of the modulus change these curves are straight lines; also, within experimental error, curves for the different crystals differ from one another only