External Influences on the $^{14}$N NQR of Ferroelectric NaN0$_2$

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External influences on the $^{14}$N NQR of ferroelectric NaN0$_2$, such as changes of the temperature, electric field, stress, gamma-ray irradiation, and impurity doping are reviewed. They normally cause either a frequency shift or a broadening of the $^{14}$N NQR lines and are strongly related to the change of the spontaneous polarization.

**Key words:** $^{14}$N NQR; Ferroelectric NaN0$_2$; Spontaneous Polarization; External Effects; Impurity.

1. Introduction

NaN0$_2$ is a famous ferroelectric material with spontaneous polarization ($P_s$) along the crystallographic $b$-axis, which undergoes an order-disorder transition at $T_c = 437$ K [1 - 3]. The $P_s$, arising from the ordering of NO$_2^-$ and the accompanying shift of Na$, is sensitive to the environment. Information on the local structure in NaN0$_2$ has been obtained by employing $^{14}$N NQR [4 - 5]. A change of the local structure can be achieved by changing the external conditions. The influences of those are reflected in the $^{14}$N NQR. External influences, such as changes of the temperature [6], electric field [7 - 8], stress [9], gamma irradiation [10], and impurity doping [11 - 13], on the $^{14}$N NQR in NaN0$_2$ were studied for a long time in our laboratory. A substitutional impurity A in Na$_{1-x}$A$_x$NO$_2$ ($A = $Ag, K) disturbs the electric field gradient (EFG) at the $^{14}$N site, resulting in line broadening and intensity weakening of the $^{14}$N NQR line [13]. This trend is similar to the effect of gamma irradiation on NaN0$_2$. The $^{14}$N NQR spectra obtained in the presence of an external electric field, stress, or a change of temperature show a frequency shift or line broadening. In this work, the results of previous investigations are reviewed and explained in terms of the spontaneous polarization of NaN0$_2$.

The spontaneous polarization in ferroelectric NaN0$_2$ was derived by Yamada et al. [14] as

\[ P_s = \tanh\left(\frac{T_c}{T}\right)(P_3 + P_3^3\Delta), \]

(1)

where $\Delta$ is an anomalous volume expansion parameter which was found to be 0.39. $P_s$ decreases with increasing temperature and goes to zero at $T_c$, as shown in Figure 1.

2. Experimental Results and Discussion

The employed spectrometers were a CW NQR spectrometer of Robinson type and a pulse NQR spectrometer (Ritec). The CW NQR spectrometer was efficiently employed to measure precisely the change of the lineshape as a function of temperature, elec-

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Fig. 1. Temperature dependence of the spontaneous polarization in NaN0$_2$.
tric field, stress, and gamma irradiation. Meanwhile, a pulsed spectrometer was suitably used for impurity doped samples.

A) Temperature Dependence

For $^{14}$N ($I = 1$) in NaN$_2$ ($\eta \neq 0$), the $^{14}$N NQR spectra consist of two resonance lines,

$$\nu = (3e^2qQ/4h)(1 \pm \eta/3),$$

\begin{equation}
(2)
\end{equation}

where $e^2qQ/h = 2(\nu_+ + \nu_-)/3$ is the quadrupole coupling constant and $\eta$ the asymmetry parameter. It was shown that the temperature dependence of the quadrupole coupling constant of $^{14}$N is directly related to the spontaneous polarization:

$$(e^2qQ/h)_{\text{exp}} = [5.2 - 0.6P^2_s - 0.17f_B(T)] \text{MHz},$$

\begin{equation}
(3)
\end{equation}

where $f_B(T)$ represents the effect of lattice vibrations, based on the Bayer theory, given as $f_B(T) = 2/\left[\exp(h\omega_c/kT) - 1\right]$ with $\omega_c = 153 \text{ cm}^{-1}$ [15]. Consequently, the changes of the quadrupole coupling constant and $^{14}$N NQR frequencies originate from the change of spontaneous polarization due to the temperature by (3) and (1).

B) Electric Field Effect

The NQR line measurements with an applied external electric field were made at 77 K in order to obtain a good signal to noise ratio and to reduce the discharge current across the sample due to the high voltage. The apparatus and method were described in [7-8]. The electric field was applied either parallel or antiparallel to the direction of spontaneous polarization of the ferroelectric NaN$_2$.

For the single domain NaN$_2$ single crystal with spontaneous polarization along the b-axis, a frequency shift of the $\nu_+$ and $\nu_-$ lines of $^{14}$N NQR due to the electric field was observed [7-8]. For the multidomain crystal [7-8] and the powder [8], a broadening of the $\nu_+$ and $\nu_-$ lines due to the external electric field was detected. While the direction of $P_s$ is alternately reversed with a phase difference of 180° between domains in the case of multidomain, the direction of $P_o$ of individual particles is randomly oriented with respect to the applied electric field in the powder sample.

C) Stress Effect

The stress effect on the $^{14}$N NQR in NaN$_2$ powder was investigated by the application of external pressure. In the samples, two extra NQR lines, $\nu_+$, were observed in addition to the two normal NQR lines, $\nu_-$. The frequency of these four lines was found to decrease with increasing applied stress, as shown in Fig. 2, although hardly detectable in the case of $\nu_-$ [9]. The quadrupole coupling constants($Q_{cc}$ and $Q'_{cc}$) arising from two sets of lines $\nu_{\pm}$ and $\nu'_{\pm}$, respectively, were found to decrease with increasing applied stress [9]. This anomaly and shift in NQR frequency, and the quadrupole coupling constant of $^{14}$N may be attributed to the change of the spontaneous polarization caused by deformation of the ions due to the external stress.

D) Irradiation Effect

The NaN$_2$ fine powder samples used here were irradiated at room temperature up to a maximum of
Influences on the $^{14}$N NQR of Ferroelectric NaN$\text{O}_2$

**E) Impurity Effect**

$^{14}$N NQR spectra in NaN$\text{O}_2$ are usually affected by doping impurities. In this study, impurity effects on $^{14}$N NQR in isomorphic mixed systems NaN$_{1-x}$A$_x$NO$_2$ (A = Ag, K) and anisomorphic mixed systems NaN$_{1-x}$BO$_3$, NaN$_{1-x}$BO$_4$, and NaN$_{1-x}$BO$_5$ were investigated and compared to each other. All mixed systems investigated here were obtained by slow evaporation of aqueous mixed solutions. The sample preparation, characterization, and measurement were described in detail [11].

In the isomorphic systems NaN$_2$-[AgNO$_2$] (A = Ag, K) and anisomorphic systems NaN$_2$-[BNO$_3$] (B = K, Na) and NaN$_2$-[BNO$_4$] (B = K, Na) [12], and NaN$_2$-[BNO$_5$] [13], the $^{14}$N NQR line positions remained unchanged independent of the concentration and kinds of impurity, as shown in Figure 3. This implies that introducing impurities into NaN$_2$ host crystal do not cause any ordered change in the EFG-configuration at the $^{14}$N-site [11-13].

Figure 4 shows a comparison of the relative line width (normalized with respect to that in the pure host crystal) obtained with three kinds of mixed systems, NaN$_2$-[AgNO$_2$] [11], NaN$_2$-[BNO$_3$] (B = K, Na) [12], and NaN$_2$-[BNO$_4$] [13]. The line width is the full width at half maximum (FWHM) of the NQR line. The line width for the isomorphic mixed systems increases rapidly with increasing AgNO$_2$ concentration. This implies that the substitutional Ag impurity ions at Na ion sites are static in nature.

On the other hand, the line width in anisomorphic mixed systems NaN$_2$-[BNO$_3$] (B = K, Na) [12] and NaN$_2$-[BNO$_4$] [13] is more or less constant regardless of the impurity concen-
The defects may then diffuse into the matrix inside the cluster. The relatively narrow and constant line intensity in the anisomorphic mixture is associated with the fast motion of lattice defects produced by introducing impurities, as shown in Fig. 5, where the line intensity is taken by integrating the area of the NQR line. In Fig. 5, the line intensity of the anisomorphic systems \( Na_{1-x}Ag_xNO_2 \) (\( A = Ag, K \)) decreases more rapidly than that of the anisomorphic system \([NaN0_2]_{1-x}[(CH_2)_6N_4]_x\). The decrease of \( T_c \) in the anisomorphic mixture \([NaN0_2]_{1-x}[(CH_2)_6N_4]_x\) is found to decrease roughly in proportion to the content of the corresponding structure, as shown with the solid line in Fig. 5 [13]. Because of the fast motion of the lattice defects, the local field is spatially homogeneous within the cluster, leading to the motional narrowing. Thus the point defects do not smear the resonance line as the static impurities do in the isomorphic system.

The transition temperature \( T_c \) between the ferroelectric to paraelectric phase due to the Ag-impurity in the anisomorphic mixed system \( Na_{1-x}Ag_xNO_2 \) is found to increase with \( x \) by measuring the \( ^{23}Na \) NMR spin-lattice relaxation [17]. Equation (1) shows that an increase of \( T_c \) causes an increase of \( P_s \) below \( T_c \). The increase of \( P_s \) in \( Na_{1-x}Ag_xNO_2 \) may be caused by substitution of \( Ag^+ \) at the \( Na^+ \) site. The \( Ag^+ \) ion is larger in size and electronegativity than the \( Na^+ \) ion. The increase of \( T_c \) in \( Na_{1-x}Ag_xNO_2 \) with \( x \) contrasts the general trend of impurity effects in other systems and that observed in gamma-ray irradiated \( NaNO_2 \) crystal [16, 18].

Meanwhile, the decrease of \( T_c \) in an anisomorphic mixture \([NaNO_2]_{0.8}[KNO_3]_{0.2}\) was observed. The decrease of \( T_c \) in the mixed system can be explained by the decrease of \( P_s \) in (1). As already mentioned, the anisomorphic mixture is characterized by mismatch between the starting materials due to the absence of structural similarity. Thus the impurity effect in the anisomorphic mixture is associated with the fast motion of lattice defects produced by introducing impurities into the host crystal. Consequently, the decrease of \( P_s \) may be attributed to the fast motion of mobile defects in the mixture, disturbing the correlated motion.

### 3. Summary

The external effects on \( ^{14}N \) NQR in the ferroelectric \( NaNO_2 \) have been reinvestigated in terms of the spontaneous polarization. The frequency shift due to temperature, the line broadening and frequency shift due to electric field, the anomaly and frequency shift due to external stress, and the change of \( T_c \) as well as line intensity loss/line broadening due to gamma-ray irra-
Radiation and impurity doping have been observed. The examination of the results leads to a conclusion that the change of transition temperature, the line broadening and frequency shift of $^{14}$N NQR line due to the external effects are originated from the change of the spontaneous polarization of the NaN0$_2$ system as a macroscopic quantity.

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