I. 4 Level-Crossing Resonance of $\gamma$-Ray Anisotropy for the 398-keV $9/2^+$ State of $^{69}$Ge in Zn Single Crystal

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In a previous experiment, we have been successful in observing the in-beam level-crossing resonance for the 398-keV $9/2^+$ isomeric state of $^{69}$Ge produced in a Zn single-crystal target by the $^{66}$Zn($\alpha$,n)$^{69}$Ge reaction; it has been observed that the anisotropy of the time-integrated $\gamma$-ray angular distribution perturbed by collinear magnetic dipole and electric quadrupole fields shows a resonance behavior as a function of the magnetic field. In the present report, we give the results of further study of this resonance: i) effects of non-collinearity of the two perturbation fields, or those of a non-vanishing angle $\beta$ between the direction of magnetic field and the c-axis of Zn crystal, and ii) the temperature dependence of the resonance magnetic field.

A calculation shows that the non-collinearity of the two perturbation fields has a large effect on the level-crossing resonance; it causes rapid smearing of the resonance, increase in width and decrease in amplitude, with increasing $\beta$. The smearing of the resonance for $\beta$=0 can be interpreted as a result of repulsion between the sub-levels that cross each other for $\beta$=0, and the smearing remains insignificant as far as the closest distance between the sub-levels $\Delta E_{\text{rep}}$ is smaller than the natural width $\Gamma_{\text{nat}}$ of the relevant level. The calculation shows that $\Delta E_{\text{rep}}$ is equal to $\Gamma_{\text{nat}}$ at $\beta=2.6^\circ$ in the case of the level-crossing resonance for the 398-keV $9/2^+$ state of $^{69}$Ge in Zn single crystal. The effect of non-vanishing $\beta$ on the resonance curves is shown in fig. 1, where closed circles are the experimental data for $\beta=0^\circ$ and open circles are those for $\beta=5^\circ$ ($\Delta E_{\text{res}}=3\Gamma_{\text{nat}}$).

Since the resonance magnetic field $B_{\text{res}}$ of the level-crossing resonance is highly sensitive to the ratio between the basic quadrupole frequency $|\omega_0|$ and the nuclear g-factor, the experimental determination of $B_{\text{res}}$ is expected to be useful for study of the hyperfine interactions. It is sufficient for the determination of $B_{\text{res}}$ to measure singles $\gamma$-ray spectra with a continuous beam from accelerator, which is a distinct advantage of the present method over other popular ones, e.g. measurement of time-differential perturbed angular distribution or stroboscopic observation of perturbed angular distribution. As an example of application, we have used the level-crossing resonance technique to measure the temperature dependence of the hyperfine electric quadrupole interaction of $^{69}$Ge in Zn single crystal. Quadrupole frequencies $\nu_Q$ of the 398 keV state of $^{69}$Ge in Zn single crystal measured at different temperatures $T$ are shown in fig. 2, where closed circles are the results of the present work, and open circles, squares and crosses
are the results obtained by Christiansen et al.\textsuperscript{2}), Haas et al.\textsuperscript{3}) and Schatz et al.\textsuperscript{4}), respectively. The time-differential method was used in refs. 2) and 3), and the stroboscopic method in ref. 4).

References
Fig. 1. Level-crossing resonance for the 398-keV 9/2+ state of 69 Ge in Zn single crystal; a) 0°-90° and b) 45°-135° anisotropies for the 398-keV γ-ray as a function of magnetic field. Closed circles are the experimental data for β=0° and open circles are those for β=5°. Solid curves are the theoretical ones fitted to the experimental data for β=0°.

Fig. 2. Temperature dependence of the quadrupole frequency ν_Q of the 398 keV state of 69 Ge in Zn single crystal.