Quadrupole Moment of the Second Excited State of F^{19}

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The differential anisotropy of the delayed angular distribution of the 198-keV gamma radiation following the inelastic scattering of protons by F^{19} has been investigated using various chemical forms of target materials. While in the case of a KF target, no appreciable time variation of anisotropy was observed within the time interval measured, in the cases of a ClF target and a $(C_2F_4)_n$ target the characteristic patterns for the static quadrupole coupling of the polycrystalline state were observed. It was found to be necessary to interpret the patterns on the basis of a frequency distribution in the range of about ten percent. The mean values for the fundamental frequency of quadrupole coupling were found to be 12.4 ± 0.6 Mc/sec for ClF and 9.0 ± 0.4 Mc/sec for $(C_2F_4)_n$. The strength of the electric field gradient q of the nuclear environment in ClF was estimated as $q=1.07\times10^{16}$ esu, following the empirical rule of Townes and Dailey. The nuclear quadrupole moment Q was deduced to be $|Q(F^{19},\frac{5}{2}^+)|=0.11$ b. The uncertainty due to various causes of the moment Q obtained was estimated to be about 20%.

1. INTRODUCTION

THE relatively long lifetime[1] (125 nsec) of the second excited state (198 keV, $\frac{5}{2}^+$) of F^{19} together with the fairly large anisotropy of the angular distribution of de-excitation radiations following the inelastic scattering of protons[2] made it possible to investigate the time-dependent angular distribution in detail. The time-dependent angular distribution in the present case can be expressed as

$$W(\theta,t)=1+A_2G_2(t)P_2(\cos\theta),$$

where $G_2(t)$ is the time-dependent attenuation factor caused by the effect of the nuclear environment. The theory of the extranuclear perturbations on angular correlations has been treated by Abragam and Pound,[3] and the attenuation factor for static quadrupole coupling of the polycrystalline case is calculated as follows,

$$G_2(t)=\frac{1}{5}\left(1+\frac{13}{7}\cos\omega_0t+\frac{10}{7}\cos2\omega_0t+\frac{5}{7}\cos3\omega_0t\right)$$

for nuclear spin $I=\frac{5}{2}$, where $\omega_0=[3/2I(2I-1)](eqQ/\hbar)$ is the fundamental angular frequency by the pure quadrupole coupling with an axially symmetric electric field gradient q of nuclear environment. A large q can be expected by a fluorine atom which is bounded covalently in a molecule. In the present work, an attempt has been made to observe a pattern in the differential anisotropy of angular distribution due to the quadrupole coupling. The target materials of polytetrafluoroethylene $(C_2F_4)_n$, ClF and SF_6 were investigated. KF was also examined because of its ionic bonding. Preliminary results have been reported previously.[4]

2. EXPERIMENTAL PROCEDURE

The time spectrum of the gamma radiation was observed using a pulsed-beam technique. A block diagram of the experimental setup is shown in Fig. 1. A beam of protons accelerated by the static generator of Osaka University up to 1.40 MeV was chopped to a pulsed beam of 4-nsec duration and 500-nsec repetition interval. The gamma radiation was detected by a NaI(Tl) scintillation spectrometer, whose output was fed to a time-to-pulse-height converter and the time spectrum was displayed on a 400-channel pulse-height sorter. The over-all resolving time was 7~8 nsec full width at half-maximum for 200-keV prompt radiation. The time spectra were taken in the direction of 0 and 90° relative to the incident protons. A typical example of the time spectrum is shown in Fig. 2. The geometrical centering of the system for angular distribution has been checked by measuring the 430-keV gamma radiation from the $B^{10}(p,\alpha\gamma)Be^7$ reaction, which should be isotropic in the center-of-mass system, and the eccentricity was determined with an accuracy of $\pm0.5\%$.

The targets were prepared by plating or depositing the target materials on an aluminum disc 1 mm in thickness, whose surface was covered with a copper layer of about 10 mg/cm² by evaporation. This aluminum disc was mounted on a target support and the system was coolable by liquid nitrogen. The thickness of target was selected so that the energy loss of 1.4-MeV protons was about 200 keV, and the main contribution to the intensity of the 198-keV radiation came from the

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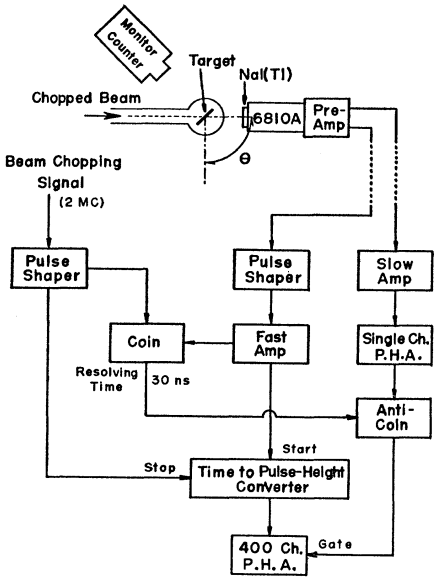

FIG. 1. Block diagram of the experimental setup.

resonances of 1.37 and 1.35 MeV. For the case[5] of ClF or SF_6, the preparation of target[6] was performed as follows. The target backing was cooled by liquid nitrogen, then a sample gas was sprayed on the backing through a thin nozzle; thus a thin layer of target material was deposited as a molecular crystal. The control of thickness was difficult for these cases and the effective thickness ranged up to about 400-keV equivalent energy loss of protons. ClF is extremely active chemically, so that special precautions were necessary. The composition of the sample gas was analyzed by measuring the vapor pressure as a function of temperature just before depositing on the target backing. Only the part vaporized up to -120°C was deposited as a target, thus excluding Cl_2 and HF, which were considered as the main contaminants. After a series of measurements, the yield of gamma rays due to fluorine as a function of temperature was measured, and more than ninety percent of target material was identified as ClF.

The time-scale calibrations of the time-to-pulse-height converter were performed with calibrated cables just before and after each series of measurements. The consistency of the time scale between different series of measurements was checked by calculating the lifetime of the 198-keV level. As a byproduct of the present measurement, the lifetime of the second excited state of F^{19} was found to be 128 ± 2 nsec. This value is consistent with previous measurements.[1]

The magnitudes of A_2G_2 as a function of delay time were computed from the time spectra of 0 and 90°. There were strong contributions due to higher energy gamma rays around the prompt event, so that no computation was performed up to 15 nsec delay. The time-independent background was estimated by measuring the time spectrum with a gate opened to a slightly higher energy than normal, and found to be less than 1% intensity compared to the 198-keV spectrum up to 250-nsec delay. No correction was considered for the background. A small correction due to finite solid angle sustained by the detector was applied.

3. RESULTS AND DISCUSSION

The values of A_2G_2 obtained as a function of time are shown in Fig. 3.

In the case of KF, no appreciable time variation in A_2G_2 was observed within the time interval measured. The chemical bond of KF is ionic and the crystal structure is cubic, so that there should be no perturbation if an excited nucleus sat in a normal site. The value $A_2G_2\sim0.25$ obtained in the region of early time was about 60% of the theoretical value[2] $A_2\sim0.4$. It was therefore suggested that a perturbation whose relaxation time was less than a few nanoseconds existed.[7] On the other hand, the almost time-independent behavior of the result was considered to reveal the order of magnitude of the perturbation due to imperfection of the lattice or intersticial location of a recoil, after quenching such a quick perturbation.

In the case of $(C_2F_4)_n$, a characteristic pattern for the static quadrupole coupling of polycrystalline state was observed. There was no difference of $A_2G_2(t)$ exceeding the statistical error between the measurements at 10°C and at -196°C. The recovery in anisotropy of

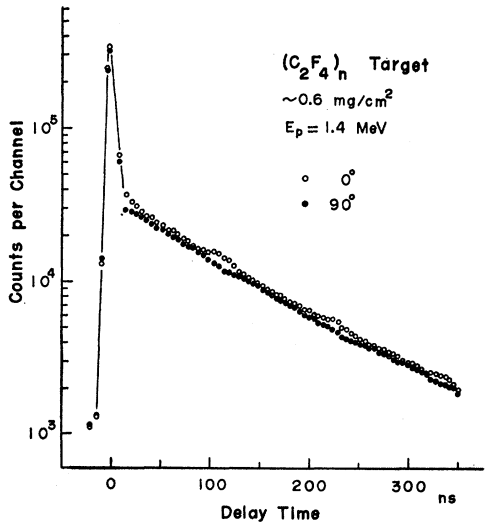

FIG. 2. Typical time spectrum of the 198-keV gamma rays from $F^{19}(p,p'\gamma)F^{19}$ reaction. The open and the closed circles are indicating the counting rates of the measurements in the direction of 0 and 90° relative to the incident protons, respectively.

[5] The sample gas of ClF was kindly supplied by the Daikin Kogyo Company, Ltd., Osaka, Japan.

[6] K. Sugimoto, A. Mizobuchi, and K. Nakai, Japan J. Appl. Phys. **3** (1964).

[7] P. B. Treacy, Nucl. Phys. **2**, 239 (1956/57).

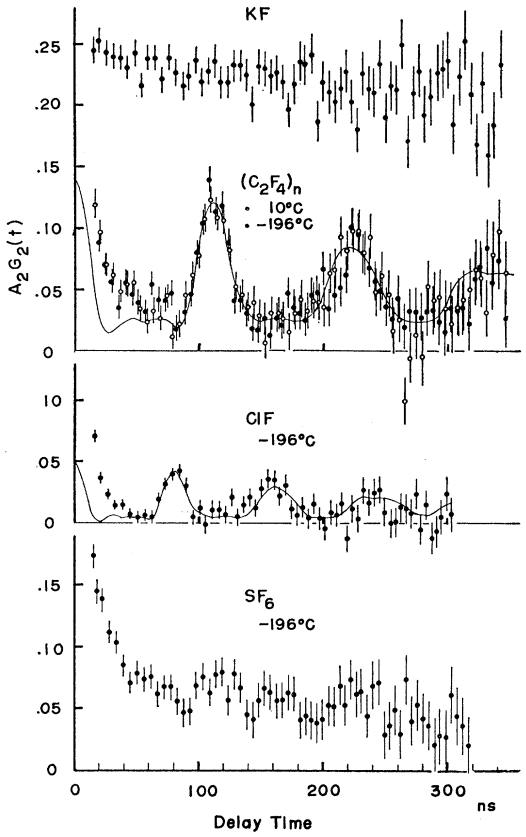

FIG. 3. Differential anisotropy in $A_2G_2(t)$ as a function of delay time. Errors indicated are only statistic. The curves fitted to the experimental points in the cases of $(C_2F_4)_n$ and ClF were calculated under an assumption that the quadrupole coupling frequency was distributed uniformly in a frequency range of $\pm 10\%$.

the second maximum at 110 nsec was about 40% compared with the case of KF. If one postulates that the coupling frequency is distributed uniformly in a frequency range of $\pm 10\%$, then the essential feature of the pattern can be reproduced, except the behavior in the region of very early time and a constant level of $0.02 \sim 0.03$ in the A_2G_2 scale. The unnatural square frequency distribution was not essential, but a frequency distribution whose width was about 10% was required to interpret the result. The distribution of the coupling frequency was probably due to local variation of the field.[8] The calculated curve with square frequency distribution was compared with the experimental points and the mean frequency for the coupling was determined to be $\omega_0/2\pi = (9.0 \pm 0.4)$ Mc/sec.

In the case of ClF, the characteristic behavior was similar to the case of $(C_2F_4)_n$, but the amplitude of pattern was smaller and the coupling frequency was higher. The recovery in anisotropy of the second maximum at 80 nsec was about 20% compared with the case of KF. The essential feature of the pattern was reproduced again by a postulation of square frequency distribution of $\pm 10\%$. The mean coupling frequency was determined to be $\omega_0/2\pi = (12.4 \pm 0.6)$ Mc/sec.

In the case of SF_6, a severe time dependence in A_2G_2 compared to the case of KF was observed but no definite structure could be identified. Thus a suitable choice of target material was essential to observe a definite pattern.

The magnitude of the electric field gradient q due to Cl-F bond in ClF was estimated as $q = 1.07 \times 10^{16}$ esu following the empirical rule of Townes and Dailey[9] using the Barnes and Smith[10] value of $\langle r^{-3} \rangle$ for the $2p$ electron. In view of the consistency between the quadrupole coupling constants of halogens, especially for diatomic molecules, the estimation was believed to be reliable with an accuracy of a few percent.[9] The empirical rule, however, is formally applicable to a free molecular state, and the present measurement was performed with a molecular solid state, so that the field gradient could be smaller than the estimated value by a few percent.

A reliable estimation of the electric field gradient q for the case of $(C_2F_4)_n$ was difficult with the present state of knowledge, but the lower coupling frequency obtained compared with the case of ClF was qualitatively expected. From the coupling frequencies obtained and q estimated for ClF, the electric field gradient q for fluorine in $(C_2F_4)_n$ was deduced to be $q = 7.8 \times 10^{15}$ esu.

From the coupling frequency obtained for the case of ClF and the electric field gradient q estimated, the nuclear quadrupole moment was deduced to be

$$|Q(F^{19}, \tfrac{5}{2}^+)| = 0.11 \text{ b}.$$

The uncertainty of this value was estimated to be about 20%, and the various factors contributed are summerized as follows:

(1) Probable error of the mean coupling frequency determined: 5%.

(2) Uncertainty in the estimation of the electric field gradient q by the empirical rule: $\lesssim 10\%$.

(3) Uncertainty due to the Sternheimer effect: $\sim 10\%$.

On the Sternheimer effect,[11] it was remarked that the electric field gradient q due to Cl-F bond was mainly intra-atomic, so that the main effect was due to the angular mode and the resulted shielding effect was about 10%. No correction owing to the Sternheimer effect was applied.[12]

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[12] The shielding factor R for atomic fluorine has been calculated to be $R = 0.110$ by Sternheimer [C. H. Townes, in *Encyclopedia of Physics*, edited by S. Flügge (Springer-Verlag, Berlin 1958), Vol. 38, p. 414]. When the correction was applied for the present case, the nuclear quadrupole moment was deduced to be $|Q(F^{19}, \tfrac{5}{2}^+)| = 0.12$ b.

The quadrupole moment obtained is larger than the single particle estimate $|Q|\sim 0.05$ b. The $E2$ transition probability for the second excited state ($\frac{5}{2}^+$) to the ground state ($\frac{1}{2}^+$) transition is known to be strongly enhanced compared with the single particle estimate. The nucleus F^{19} has been treated on the rotational model by Paul[13] and Rakavy.[14] On the strong coupling theory of the rotational model, the $E2$ lifetime and the quadrupole moment are interrelated by an intrinsic quadrupole moment Q_0, and the quadrupole moment was calculated to be $|Q|\sim 0.091$ b from the measured lifetime under an assumption that the levels belong to a $K=\frac{1}{2}$ band and the particle part of the transition probability can be neglected. Paul has shown, however, that a mixture of two rotational bands is necessary to interpret the level structure of F^{19} and also that the collective part and the particle part of the $E2$ transition probability are of comparable importance.

On the other hand, Inoue, Sebe, Hagiwara, and Arima[15] have treated, recently, the s-d shell nuclei on the intermediate coupling shell model, and predicted the quadrupole moment of the state to be $Q\sim -0.097$ b by taking the effective charge $\beta\sim 0.5$.

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Nilsson Model Calculations of Mu Capture Rates in $2s-1d$ Nuclei*

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Theoretical calculations of mu capture rates in $2s$-$1d$ nuclei are compared with experiment in the hope of elucidating the coupling constants of the interaction. Working from Primakoff's closure-approximation expression for the total average capture rate, the nuclear matrix element is treated in the context of the Nilsson unified model. A Hill-Wheeler integration must be performed to avoid extraneous coordinates in the A-particle wave function. The one- and two-particle parts of the matrix element are broken up into the various shell contributions, since all of the angular momentum properties reside in the shell wave function for the nucleons outside the O^{16} core. The closed-shell matrix elements are easily treated with standard angular-momentum techniques. The method for reducing the outer-shell matrix elements to a form amenable to evaluation by a computer is given in an appendix. Radial integrals are obtained from the Ford-Wills muon wave functions. The average neutrino momentum $\bar{\nu}$ is chosen on the basis of Kaplan's Fermi-gas model for the capture process and the subsequent comparison with neutron evaporation rates. The choice of nuclear parameters for F^{19}, Ne^{20}, Si^{28}, Cl^{35}, and Cl^{37} is discussed and numerical results are given. Comparing with experimental rates, one cannot exclude the possibility that the Fermi part of the interaction is absent. If a $V-A$ theory is assumed, however, we conclude the induced pseudoscalar coupling is probably present. The induced pseudoscalar with the "wrong" sign, $g_P=-8g_A$, is definitely excluded, and the "large" pseudoscalar, $g_P=16g_A$, seems to fit the data better at $\bar{\nu}=0.75$.

I. INTRODUCTION

THE mu-capture interaction, $\mu^-+p\rightarrow n+\nu$, like beta decay and mu decay, is presumably described by the universal Fermi interaction (UFI)[1,2] given in the refined $V-A$ form of Feynman and Gell-Mann.[3] It is not very well understood experimentally, however, and we can only say at this time that it fits the UFI hypothesis to within 20% or so.[4] In this paper we present a theoretical study of this capture process in certain of the light $2s-1d$ nuclei to see whether existing

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