NUCLEAR SPIN POLARIZATION OF BETA-RADIOACTIVE NUCLEI CREATED BY MEANS OF TILTED FOIL TECHNIQUE


To cite this version:

NUCLEAR SPIN POLARIZATION OF BETA-RADIOACTIVE NUCLEI CREATED BY MEANS OF TILTED FOIL TECHNIQUE

Y. NOJIRI, S. MOMOTA, A. OZAWA, A. KITAGAWA, M. FUKUDA, K. MATSUTA and T. MINAMISONO

Department of Physics, Osaka University Toyonaka, Osaka 560, Japan

Abstract - The fundamental mechanism of the tilted foil technique has been experimentally studied for its effective application to short-lived beta-emitters. The multi-foil enhancement in $^{12}$B nuclear polarization was measured as a function of the foil number and the foil spacing. The technique was further applied to heavier beta-emitters, $^{20}$F and $^{41}$Sc.

1 - Introduction

Since the first discovery of atomic polarization produced through beam-tilted foil interactions/1/, the tilted foil technique has been applied successfully in a series of various measurements on nuclear physics/2/. In fact, the technique has proved its effectiveness for experimental studies on short-lived radioactive nuclei, particularly in NMR measurements on beta-radioactive nuclei, $^{27}$Si(T$_{1/2}$=4.2 sec)/3/ and $^{33}$Cl(T$_{1/2}$=2.51 sec)/4/. In these experiments, it has played a very crucial role to create nuclear polarizations of the beta emitters produced through nuclear reactions. In order to expand its applicability to a wide range of beta-emitters, the technique was recently applied to the creation of polarized projectile fragments, $^{39}$Ca(T$_{1/2}$=0.86 sec) and $^{43}$Ti(T$_{1/2}$=0.51 sec) produced in high-energy heavy-ion collisions/5,6/.

Essential mechanisms constituting the technique are 1) atomic polarization creation through beam-tilted foil interactions and 2) the atomic polarization transfer to nuclei through possible hyperfine interactions. The mechanism 1) has been well studied experimentally through measurement of atomic polarization, and it is concluded from the studies that the polarization creation is resulted from asymmetric surface collisions between outgoing atoms and and lattice ones. For the mechanism 2), quantum oscillation of atomic polarization was confirmed. Direct evidence of the creation of the nuclear polarization by the mechanism has been shown in the measurement of the nuclear polarization in short lived beta emitter $^{12}$B/7/. Enhancement in the nuclear polarization by use of multi-foil stack was also confirmed in Ref. 7.

Although the mechanism of the polarization transfer and the multi-foil enhancement have been proposed theoretically, it should be confirmed experimentally, in order to use the technique effectively for the wide range of application. In particular, we should know more about the optimum condition for the inter-foil spacing of the multi-foil stack, which is defined as the distance between foils in the direction of beam path, and the foil number, in addition to the tilt angle.

In the present experiment, the fundamental mechanism in the polarization enhancement achieved by use of multi-tilted foils was studied. As a proof of the proposed polarization mechanism, the multi-foil enhancement effect of nuclear polarization in short-lived beta-emitter $^{12}$B($I^e=1^+$, T$_{1/2}$= 20 msec) was measured as a function of distances between two foils and also of numbers of multi-foils. In the following, the technique was further applied to heavier...
short-lived beta emitters, $^{20}$F($I^e = 2^+$, $T_{1/2} = 11.03(6)$ sec) and $^{41}$Sc($I^e = 7/2^-$, $T_{1/2} = 596.3(17)$ msec), to prove the effectiveness of the technique.

2 - EXPERIMENTAL METHODS

The essential part of the present measurement is similar to the previous one/8/. The experimental setup is shown in Fig. 1. Beta emitters, $^{12}$B, $^{20}$F, and $^{41}$Sc, were produced through the nuclear reactions $^{11}$B(d,p)$^{12}$B, $^{19}$F(d,p)$^{20}$F, and $^{40}$Ca(d,n)$^{41}$Sc, respectively. Deuteron beams($E_d = 4$ MeV) were extracted from the Van de Graaff accelerator at Osaka University. Recoil nuclei emerged from the target into the recoil angle $30^\circ$ were selected by a collimator. Nuclear polarization was induced in the nuclei by passing through a multi-foil stack. The stack consists of 1-6 carbon foils of 5 µg/cm$^2$ thick tilted 60° relative to the beam direction. The polarized nuclei were focussed by use of an electrostatic lens and implanted into a catcher. A week magnetic field (~ 10 Oe) was used to maintain the atomic polarization during the flight of the recoil nuclei while a strong magnetic field (~ 2 kOe) was applied to preserve the nuclear spin polarization after the implantation. The stopping materials were a metallic Pt foil, a single crystal CaF$_2$, and fine granular crystals TiC for $^{12}$B, $^{20}$F, and $^{41}$Sc, respectively. The nuclear polarization was determined through measurements of asymmetries in beta-ray emissions from the nuclei by means of beta-NMR technique.

3 - RESULTS

The nuclear spin polarization of $^{12}$B produced with two foils was measured as a function of inter-foil spacing. The induced nuclear polarization showed an exponential increase as the inter-foil spacing increased as shown in Fig. 2. The polarization $P(X)$ was well described by a form,

$$P(X) = P_0 - P_1 \exp(-X/X_0), \quad (1)$$

where $X$ is the inter-foil spacing, $P_0$ is a saturated value of induced polarization, $P_0 - P_1$ is the polarization created by single foil, and $X_0$ is a free distance parameter. From the least $\chi^2$ analysis, the distance parameter was

\[\text{Fig. 1. Schematic view of experimental setup.}\]
Fig. 2. Enhancement of nuclear polarization of $^{12}$B as a function of inter-foil spacing.

Fig. 3. Multi-foil enhancement of $^{12}$B nuclear polarization.

deduced to be $X_0 = 1.26(46)$ mm. The parameter $X_0$ is related to the transfer time $\tau$ of the polarization from atomic spin to the nuclear spin, as $X_0 = v \tau$, where $v$ is the velocity of $^{12}$B after passing through a foil. Using the average velocity $v = 3.1$ mm/nsec of $^{12}$B, the transfer time was deduced to be $\tau = 0.41(15)$ nsec.

On the other hand, the transfer time $\tau$ can be calculated from the known hyperfine interaction strength. Here, we assume that the atomic polarization can only be induced in atomic states with non-zero orbital-angular momentum. Because the boron atoms are populated in a large part in the ground state after passing through foils, the ground state of neutral boron, $^{2}P_{1/2}$ is naturally assumed to take large part in producing the nuclear polarization. From the known hyperfine interaction strength $\omega_{hf} = 1.24 \times 10^9$ (1/sec)/9/, the calculated value for the transfer time was deduced to be $\tau = 1/\omega_{hf} = 0.8$ nsec. A good agreement between the present observation and the calculation shows above assumption to be plausible from the view point of fundamental mechanisms of the polarization production in the beam-tilted foil interaction.

Polarization enhancement of the $^{12}$B by use of multi-tilted foils was observed by changing the foil number from 1 to 6. In this observation, the inter-foil spacing was kept to be 1 mm. The result showed an exponential rise as shown in Fig. 3. According to the discussion in Ref. 10, the data was analyzed using the relation,

$$P(N) = P(\infty)\{1 - (1 - k)^N\}, \quad k = P(1)/P(\infty)$$

where $P(N)$ is induced nuclear polarization by use of $N$ foils, and $P(\infty)$ is the saturated value of the polarization. From the least $\chi^2$ analysis, the optimum value for the parameter $k$ was deduced to be $k = 0.42(7)$. The parameter $k$ is related to the atomic spin $J$ and nuclear spin $I$ as,

$$k = P(I, J)(P_J^+ (1 - P_J)J/I),$$

$$P(I, J) = (1/4\lambda^2)\{(2\lambda^+ (\lambda^2 - 1)ln(1 + \lambda)/(1 - \lambda)),$$

$$\lambda = 2IJ/(I^2 + J^2).$$

(3)

where $P_J$ is the atomic polarization created at the exit surface of the foils. So, the $k$ is determined by the ratio $J/I$. Considering the nuclear spin $I$=1 of $^{12}$B, the average atomic spin $<J>$ which effectively participates in the polarization creation process was deduced to be $<J> = 0.88(20)$ from the experimental value of $k$. This indicates that the excited state $^{2}P_{3/2}$ has another contribution to the polarization creation together with the ground state $^{2}P_{1/2}$ of the neutral boron atom.
In the succeeding experiments, the tilted foil technique has been further applied to heavier beta-emitters, $^{20}$F and $^{41}$Sc. Atomic charge states of both nuclei were mainly neutral and plus one out of the foils in the present experimental conditions. The results are shown in Fig. 4. Six carbon foils with 1 mm inter-foil spacing were used for $^{20}$F. The observed polarization for $^{20}$F induced with tilted foils were 0.7±0.2 %. In the $^{41}$Sc case, the result is for single foil. The observed polarization of $^{41}$Sc was 0.8±0.3 %. The multi-foil enhancement could not be applied in the $^{41}$Sc case due to small kinetic energy.

As a conclusion, the mechanism of polarization transfer became rather clear from present experiment. Further applications of the tilted foil technique to wider variety of radioactive nuclei are expected to achieve new developments in nuclear physics.

Fig. 4. Nuclear spin polarization of $^{20}$F and $^{41}$Sc created by the tilted foil technique.

Open circles O and an open circle with dot O denote the data with carbon foils of 5 µg/cm$^2$ thick and 10 µg/cm$^2$ thick, respectively. Closed circles • denote averages of the separate runs. Six carbon foils were used for $^{20}$F. In the $^{41}$Sc case, the data are for single carbon foil.

REFERENCES