Development of On-Line Perturbed Angular Correlation *

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The on-line time differential perturbed angular correlation technique has been developed for the first time. The quadrupole interaction of ^{19}F in Cd was measured.

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The time differential perturbed angular correlation (TDPAC) has been known for half a century. The conventional TDPAC measurement is divided into two steps. Firstly, probe nuclei are introduced into the sample in question by nuclear reactions at an accelerator or reactor, implantation, diffusion or alloying. Secondly, the sample is removed from the vicinity of probe introduction for the TDPAC measurement. This is called the off-line TDPAC. So far, no on-line TDPAC (TDPACOL) has been performed. For a long time, researchers have wished to develop TDPACOL that has a strong background of potential use in industry and medicine as well as applications in nuclear physics, condensed matter physics, and lifetime science, etc.

In this present work, we aim to develop a TDPACOL technique. The key point is to have short-lived mother nuclei with a lifetime of several tens of seconds or less. We have found a suitable mother nucleus ^{19}O having a half-life of 26.9 s and decaying to the daughter nucleus ^{19}F that is a nice perturbed angular correlation probe. This pair of nuclei $^{19}O/^{19}F$ was used by Phillips *et al*[1] to determine the magnetic moment of the intermediate state, $^{19}F(I^{\pi} = 5/2^+, T_{1/2} = 89\,ns)$, by the off-line TDPAC. In their experiment the ^{19}O nucleus was produced by irradiating an HF target with neutrons from the cyclotron and then removed from the vicinity of the cyclotron for the TDPAC observation. The intermediate state $^{19}F(0.197\,MeV{:}I^{\pi} = 5/2^+, T_{1/2} = 89\,ns)$ was also used in the time differential perturbed angular distribution (TDPAD) measurements.[2,3] Here we develop a TDPACOL technique with this unstable nucleus ^{19}O. As an example, the first TDPACOL experiment has been performed to determine the quadrupole interaction of ^{19}F in Cd.

The TDPACOL technique is based on an accelerator that delivers a pulsed beam. The beam line of the TDPACOL is schematically shown in Fig. 1. The technique consists of the production of probe nuclei and the *in situ* measurement of perturbed angular correlation.

The ^{19}O nucleus with a half-life of 26.9 s was produced through the nuclear reaction $^{18}O(d,p)^{19}O$ using a 3 MeV deuteron beam from the 2×1.7 MV tandem accelerator at the China Institute of Atomic Energy (CIAE).[4] The ^{19}O-producing target was a $Ti^{18}O_2$ target of $100\,\mu g\,cm^{-2}$ prepared by oxidizing a 0.5 mm Ti plate with ^{18}O. The ^{19}O nuclei that recoiled out of the target at the angles between 32° and 48° with respect to the beam direction defined by a Cu collimator were implanted into the $\phi 20\,mm \times 0.5\,mm$ sample in question. The recoil nuclei were almost homogeneously distributed in the implanted layer of 1–2 μm. The ^{19}O nucleus decays to the excited states of ^{19}F that successively de-excites to the ground state by a γ-γ cascade emission of 1.357 and 0.197 MeV via the intermediate states (1.554 MeV, $I^{\pi} = 3/2^+$, $T_{1/2} =$ 3.5 fs) and (0.197 MeV, $I^{\pi} = 5/2^+$, $T_{1/2} = 89$ ns).[5]

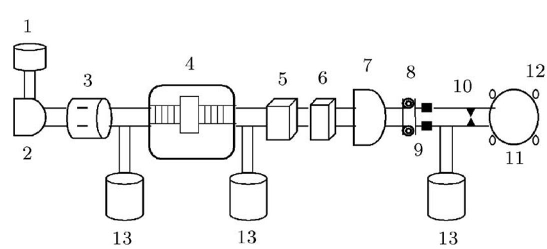

Fig. 1. Schematic view of the beam line for on-line time differential perturbed angular correlation at the CIAE 2×1.7 MV tandem accelerator: 1, ion source; 2, analysing magnet; 3, beam chopper; 4, 2×1.7 MV tandem; 5, quadrupole lens; 6, beam steering; 7, switching magnet; 8, beam profiling sensor; 9, slits; 10, collimator; 11, TDPAC chamber; 12, detectors; 13, turbo molecular pump).

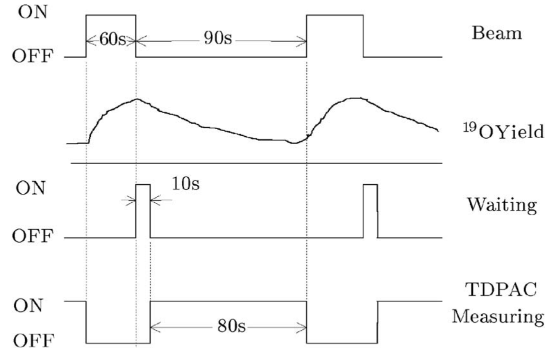

Fig. 2. Time sequence for an on-line time differential perturbed angular correlation measurement.

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The deuteron beam was chopped to a pulsed beam of 60 s duration and 150 s repetition interval. The ^{19}O nucleus was produced in the beam pulse duration of 60 s. After 10 s from a beam pulse the TDPAC measurement started and lasted to the next beam pulse. During this waiting time of 10 s, unwanted shorter-lived nuclei decayed out. The data acquisition was blocked in the beam duration and the waiting time, as schematically shown in Fig. 2 by the drawn time sequence program of TDPACOL.

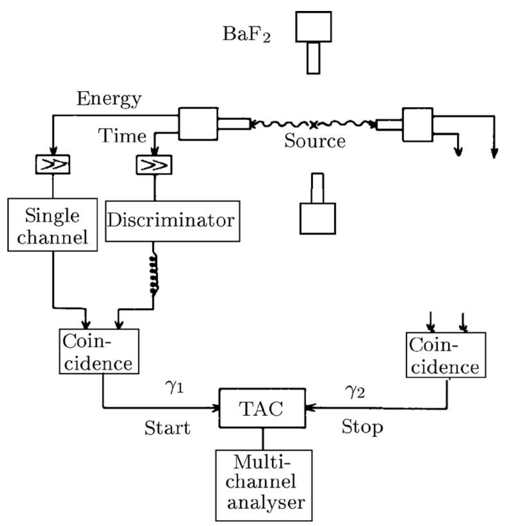

Fig. 3. Schematic diagram of the experimental set-up for an on-line time differential perturbed angular correlation measurement.

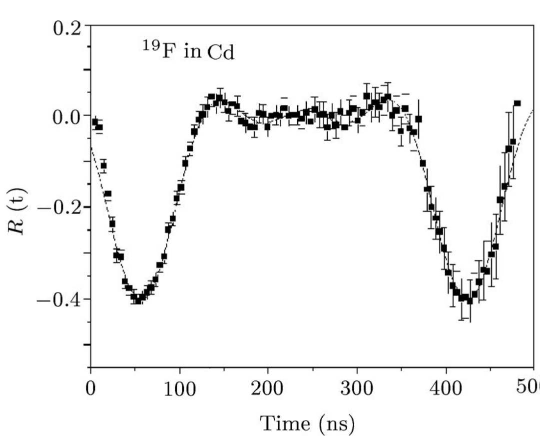

Fig. 4. Spin rotation function measured by on-line time differential perturbed angular correlation for ^{19}F in Cd. The dashed line indicates the fit to the data.

A standard four-BaF$_2$-detector system was employed for the TDPAC measurement, in which the normal fast–slow coincidence electronics was adopted (for details of TDPAC, see Ref. [6]). Figure 3 schematically shows the experimental set-up for the on-line time differential perturbed angular correlation measurement, the time resolution of which is generally 0.5 ns. The TDPAC measurement was carried out on the 1.357 and 0.197 MeV cascade of ^{19}F implanted into the sample. Great care should be taken to prevent the γ rays, which originate from the Ti^{18}O$_2$ target and Cu collimator, from entering the detectors

The first TDPACOL measurement has been carried out for ^{19}O/^{19}F in a well-annealed polycrystalline Cd at room temperature. The ^{19}O nuclei were recoil-implanted into the Cd of ϕ20 mm×0.5 mm. In a one-way coincidence measurement, i.e. two detectors reject one of the two γ-rays, four coincidence time spectra of $N(\theta, t)$ were obtained for $\theta = 90^\circ$ and $\theta = 180^\circ$. A normal spin rotation function $R(t)$ was formed with the four background subtracted coincidence time spectra. The experimentally measured $R(t)$ for ^{19}F in Cd is shown in Fig. 4.

The least-squares fitting of the experimental spin rotation function with a theoretical formula

$$R(t) \approx A_2 G_2(t) = A_2 \sum S_{2n} \cos(n\omega_0 t) \qquad (1)$$

gives the quadruple interaction frequency $\omega_0 = 17.12\,\mathrm{Mrad{\cdot}s^{-1}}$ and coupling constant $\nu_Q = eQV_{zz}(^{19}\mathrm{F})\ /h = 18.16\,\mathrm{MHz}$. Using the presently known quadrupole moment ^{19}F $(Q) = (0.11 \pm 0.02)$ b for the 0.197 MeV state ($I^\pi = 5/2^+$, $T_{1/2} = 89$ ns),[7] the electric field gradient (V_{zz}) was determined to be $(6.8 \pm 1.4) \times 10^{17}\,\mathrm{Vcm^{-2}}$. This value was compared with the theoretical value given by the *ab initio* band structure calculation in the framework of the Korringa–Kohn–Rostoker (KKR) method.[8] The theoretical value of $V_{zz} = 6.17 \times 10^{17}\,\mathrm{Vcm^{-2}}$ for ^{19}F in a substitutional site of Cd agrees well with the present experimental value. On the other hand, if we assume the reliability of the theoretical V_{zz}, the quadrupole moment of $Q = (0.121 \pm 0.005)$ b was obtained for $^{19}\mathrm{F}(I^\pi = 5/2^+,\ T_{1/2} = 89$ ns), which is consistent with the known value (0.11 ± 0.02) b measured by Sugimoto *et al.*[7]

In summary, the on-line time differential perturbed angular correlation technique with the ^{19}F probe has been developed for the first time. The quadrupole interaction of ^{19}F in Cd has been measured. The obtained electric field gradient is in good agreement with that given by the KKR calculation and the deduced quadrupole moment of $^{19}\mathrm{F}(I^\pi = 5/2^+,\ T_{1/2} = 89\,\mathrm{ns})$ is consistent with the previously measured value.

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