Phase Transfer in Time-Delayed Interferometry with Nuclear Resonant Scattering

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In x-ray interferometry accompanying nuclear resonant scattering with some time delay, interference was observed under the condition that a phase shifter was set in front of a nuclear scatterer. The observed interference pattern clarified that the phase information is transferred to the reemitted beam through the intermediate state in nuclear resonance. A storing of phase information in time-delayed scattering is discussed in a system consisting of a quantized radiation field combined with a nucleus state.

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The time-delayed scattering in 14.4 keV Mössbauer resonance at ^{57}Fe has been studied for more than a decade using a pulsed synchrotron radiation (SR) source and a delayed coincidence technique [1–3]. The mean lifetime $\tau = 140$ nsec of the excited state of ^{57}Fe, the time delay in this scattering, is physically deduced from the narrow bandwidth $\Delta E = 5 \times 10^{-9}$ eV of this nuclear resonance. This resonant scattering exhibits intensity modulations in subsequent decays due to the coherently excited hyperfine split energy levels of nuclei [4–8]. An analogous coherent phenomenon of the radiation field emitted after pulsed excitation is known as free induction decay in the lower optical energy regime [9] and in the radio-frequency (RF) regime [10].

In the visible light region, a single photon state has been shown to have remarkable features of anticoincident detection in quantum optics [11,12]. In the x-ray regime, photon statistic phenomena can hardly be observed due to the low brilliance of the source [13], which enables us to consider essentially only the contribution from the single photon state in x-ray interferometry. In addition, the nuclear resonance demands considering the combined state between the radiation field and the nucleus. Combined systems are known in other regimes, e.g., the combination between two particles [14,15] as well as that between the radiation field and an atom in a cavity [16]. They show a notable correlation and/or interference of the probability amplitudes of the combined states.

X-ray interferometry is normally accomplished with the use of a monolithic perfect crystal [17]. It has been utilized as a powerful tool for experimental studies of interference in the higher frequency electromagnetic spectrum. The general mixture of interfering beams in x-ray interferometry was examined as a modified version of the double-slit experiment [18]. We have already applied a triple Laue interferometer to a pulsed excitation of nuclei by SR, where interference was observed between the beams reemitted with a certain time delay by different nuclei in nuclear resonance [19]. In addition, the amplitude modulation on the time evolution of nuclear forward scattering was investigated utilizing time-delayed interferometry [20]. These time-delayed interferometry experiments represent the observation of interference between freely decayed beams.

In this Letter, we demonstrate the dependence of the interference pattern on the phase shift *before* the nuclear resonance. The observed interference pattern implies that the intrinsic phase information be transferred to the reemitted beam through the absorption and time-delayed reemission in the resonance. Since the essential contribution of the incident photon state to the obtained results is the single photon state, the photon state after the absorption to excite nuclei has good justification to be regarded as the vacuum state. We discuss the possibility of storing the intrinsic phase information in the vacuum state of the quantized radiation field combined with the state of the nucleus in nuclear resonance.

The experiments were carried out by the use of an undulator source at the 6.5 GeV accumulation ring for TRISTAN at the National Laboratory for High Energy Physics (KEK) [21]. A schematic view of the experimental setup is shown in Fig. 1. The delayed coincidence measurement

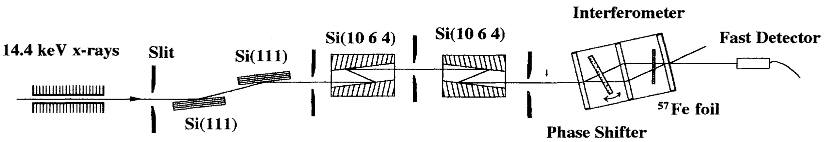

FIG. 1. Schematic view of the experimental setup. The incident beam is monochromatized by successive reflections in the monochromator system and falls on the interferometer. In the triple Laue interferometer, a Si wafer is inserted as the phase shifter before a ^{57}Fe foil of the nuclear resonant scatterer. The interference oscillations were observed due to the phase shift before the nuclear resonance with certain time delay.

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system as well as the monochromators were the same as those from our earlier work [20]. A fast plastic scintillation detector with a time-to-amplitude converter (TAC) system enabled us to select the yield in any delayed time windows of the nuclear resonant scattering.

The symmetric triple Laue interferometer was the same device used in our other works [18–20]. This interferometer was adjusted to give 220 reflections. The cross section of the incident beam was reduced to 5.0×0.2 mm^2 before the interferometer. In the present experiment, we intended to demonstrate the interference due to the phase shift before the nuclear resonance with a certain time delay. Thus, while a phase shifter was inserted between the first and the second plates of the interferometer, a nuclear resonant scatterer was inserted between the second and the third plates. As a phase shifter, a parallel sided Si wafer of 290 μm in thickness was used, and a relative phase was introduced by rotating this Si wafer [18,22]. A highly enriched (95.5%) ^{57}Fe foil about 4 μm thick was used as a nuclear resonant scatterer. The fast detector was set for the interfering O beam.

Only the yields resonantly scattered with some time delay were to be counted in the following interference experiments by removing the transmitted prompt radiation, which was not affected by the nuclear resonance [19]. After measuring the time spectrum of the interfering beam after the interferometer with given ^{57}Fe foils, we set the delayed time window for the measurements between 37 and 47 nsec. Under these conditions, the interference oscillations were measured by shifting a relative phase with the phase shifter. For reference, we measured the same interference oscillation for the beams off resonance by tuning the monochromator some 156 meV away from the resonance energy. The collected data with least square fits are shown in Fig. 2. Though only the fluctuation of the background is seen for counts off resonance, a clear sinusoidal oscillation above the background is seen for counts on resonance. The contrast was as high as the instrumental property of the interferometer.

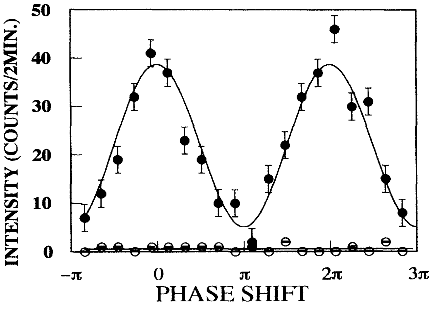

FIG. 2. Interference oscillations with least squares fits for the energy on (●) and off resonance (o). A high visibility interference oscillation is observed on resonance, while only the background fluctuation is observed off resonance.

In the earlier work, we demonstrated the coherence of two beams emitted at different times by different nuclei through the nuclear resonance [19]. The present experimental results show, moreover, that the phase information before the absorption in the nuclear resonance is transferred to the reemitted radiation field after the nuclear resonance. Since reemission occurs with some time interval after the absorption of the incident photon in the nuclear resonance, the phase transfer demands that phase information should be stored in the intermediate state in this time interval, say, 40 nsec.

It should be stressed here that the typical Bose phenomena of the photon statistics in the x-ray regime can hardly be observed even with our SR of high brightness due to its low brilliance [13]. Therefore, contributions other than from the single photon state are negligibly small in x-ray interferometry. With this reasoning, the incident photon state can be considered as the single photon state. (Strictly speaking, the essential contribution to our experimental results is the single state.) We have already shown an interpretation of collective excitations of nuclei by a single photon state in the earlier experiment of time-delayed interferometry [19]. There, many nuclei are excited in principle, but each one has only a small probability amplitude. We deal here with the phase information transfer through successive absorption and reemission processes with some time interval by a single nucleus. Since the intermediate photon state between the absorption and reemission in the nuclear resonance can be considered as the vacuum state, particular attention is paid to the possibility of storing the phase information in the intermediate vacuum photon state that transfers the phase information to the reemitted radiation field.

We used ^{57}Fe foils in our experiments and the state of the iron nucleus in practice splits into several levels due to the Zeeman effect. For simplicity, we consider the interaction of the quantized field with two-level nuclei [23]. We denote the pulsed incident radiation field and the nuclei by $|\Psi_i\rangle$. If one photon is present in mode $\mathbf{k}_0$ and the nuclei are in the ground state, this combined state, $|1_{\mathbf{k}_0};\{g_i\}\rangle$, can be written in the form of a direct product given by

$$|\Psi_i\rangle = |1_{\mathbf{k}_0};\{g_i\}\rangle = e^{i\phi}|1_{\mathbf{k}_0}\rangle \otimes |\{g_i\}\rangle, \qquad (1)$$

where ϕ represents the intrinsic phase of the radiation field. A similar notation is used for the combined system of atom plus radiation field in the cavity experiments [16].

The Hamiltonian of the total system H is expressed as the sum of the nuclear H_N, the radiative H_R, and the interactive H_I parts. For simplicity, the concerned nucleus is assumed to be placed at the origin, which results only in the omission of the exponential terms $\exp(\pm i\mathbf{K} \cdot \mathbf{R})$. In the rotating wave approximation, we then have

$$H = H_N + H_R + H_I\,, \tag{2}$$

where

$$\begin{aligned} H_N &= \hbar\omega_0 \pi^\dagger \cdot \pi\,, \\ H_R &= \sum_{\mathbf{K}} \hbar\omega_{\mathbf{K}} a^\dagger \cdot a\,, \\ H_I &= i\sum_{\mathbf{K}} \hbar g'_{\mathbf{K}}\{\pi^\dagger \cdot a_{\mathbf{K}} - \pi \cdot a^\dagger_{\mathbf{K}}\}\,. \end{aligned} \tag{3}$$

Here, $\hbar\omega_0$ and $\hbar\omega_{\mathbf{K}}$ represent the resonance energy of the two-level nucleus and the energy of the radiation field of mode $\mathbf{K}$, respectively. The operator $\pi^\dagger$ describes the transition of the nucleus from the ground state to the excited state, and π denotes the reverse process. The operators $a^\dagger_{\mathbf{K}}$ and $a_{\mathbf{K}}$, respectively, describe creation and annihilation of a photon in mode $\mathbf{K}$. And $g'_{\mathbf{K}}$ is defined as the coupling constant of the magnetic-dipole interaction. The first and second terms of the interaction Hamiltonian H_I represent the cases when the photon is absorbed, and it excites the nucleus, as well as when the excited nucleus returns to the ground state by emitting a photon.

In our nuclear resonance experiments, the incident single photon is absorbed, and it excites the nuclei when it falls on the resonance absorber. The excited nuclei reemit the photon with a characteristic decay time. This is treated in perturbation theory of quantum electrodynamics [24]. Since the nuclear resonance has some finite time interval between the absorption and the reemission, not a virtual but a real intermediate state can be assumed. In what follows we give a simple treatment by means of a two-step perturbation, i.e., we include primary absorption and reemission.

The primary absorption is expressed by the operation of the first term of the interaction Hamiltonian H_I in Eq. (3). The intermediate state $|\Psi_m\rangle$ between the absorption and the reemission of the photon is given by

$$\begin{aligned} |\Psi_m\rangle &= i\sum_{\mathbf{K}} \hbar g'_{\mathbf{K}} \pi^\dagger \cdot a_{\mathbf{K}} |\Psi_i\rangle \\ &= i\sum_{\mathbf{K}} \hbar g'_{\mathbf{K}} \pi^\dagger \cdot a_{\mathbf{K}} (e^{i\phi}|1_{\mathbf{k}_0}\rangle \otimes |\{g_i\}\rangle) \\ &= i\hbar g'_{\mathbf{k}_0} e^{i\phi} |0_{\mathbf{k}_0}\rangle \otimes \{g_{i(\neq j)}\}, e_j\rangle\,. \end{aligned} \tag{4}$$

This clearly shows that, while the nucleus is excited, the phase information before the absorption is stored in the combined system of nucleus plus radiation field.

With some time interval after the primary absorption, reemission occurs. The exact time evolution of the intermediate state demands the inclusion of additional factors, which describe radiative damping. We neglect these factors, since we only intend to show how the phase information is transferred from the initial to the final state of the radiation field. The reemission is expressed by the operation of the second term of the interaction Hamiltonian. The final state $|\Psi_f\rangle$ is then given by

$$\begin{aligned} |\Psi_f\rangle &= -i\sum_{\mathbf{K}} \hbar g'_{\mathbf{K}} \pi \cdot a^\dagger_{\mathbf{K}} |\Psi_m\rangle \\ &= -i\sum_{\mathbf{K}} \hbar g'_{\mathbf{K}} \pi \cdot a^\dagger_{\mathbf{K}} (i\hbar g'_{\mathbf{k}_0} e^{i\phi}|0_{\mathbf{k}_0}\rangle \otimes \{g_{i(\neq j)}\}, e_j\rangle) \\ &= (\hbar g'_{\mathbf{k}_0})^2 (e^{i\phi}|1_{\mathbf{k}_0}\rangle \otimes |\{g_i\}\rangle)\,. \end{aligned} \tag{5}$$

This shows that the intrinsic phase factor $e^{i\phi}$ is transferred to the final state through some time interval in nuclear resonance as was expected.

With Eqs. (4) and (5), the phase information of the incident radiation field is shown to be transferred to the reemitted beam in time-delayed nuclear resonant scattering. Let us discuss this phase information transfer in more detail. One may think that the phase information is stored in the system of the radiation field *plus* in the nucleus in the intermediate state. This combined system is described as the direct product of the states of the two subsystems, and it is natural that the initial phase information to be transferred belongs to the state of the radiation field. In addition, the annihilation operator $a_{\mathbf{K}}$, which describes the absorption of the incident photon, operates only on the state of the field. One may therefore consider the intermediate state of the radiation field as the vacuum state accompanied by the phase information to be transferred. Figure 3 shows how in this scheme the

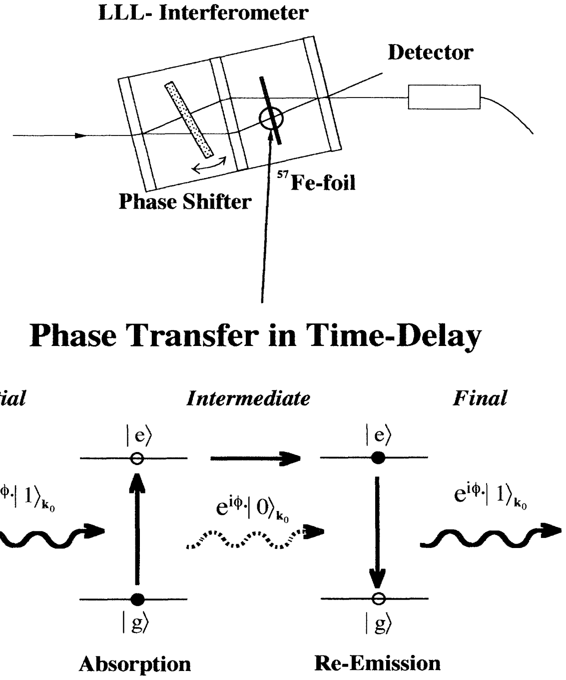

FIG. 3. A model of phase information transfer in time-delayed nuclear resonant scattering. An incident single photon is absorbed and excites the nucleus. After some interval, the excited atom reemits the photon. The phase information is stored in the vacuum photon state in the interval.

intrinsic phase is transferred through the vacuum photon state in the nuclear resonance. It is important to note that, in this scheme, the vacuum state defined by the absence of any photons can have its phase. Another argument of the direct observation of the stored phase in the vacuum photon state will be presented elsewhere in connection with the vacuum effects on interference [25,26].

In summary, we have successfully demonstrated the interference of the beams due to the phase shift before the nuclear resonance. This experiment confirmed that the intrinsic phase information is stored in the intermediate state between the absorption and the reemission and is then transferred to the reemitted beam. It was shown that the phase information is stored in the combined state of quantized radiation field plus nucleus state in time-delayed nuclear resonant scattering.

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