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学位論文要約

題目 : Development of measuring method of gamma-ray waveform transmitted through vibrating nuclear resonant absorber for study of quantum applications

The recoilless nuclear resonant scattering, known as the Mössbauer effect and developed into spectroscopy, extend the concepts of quantum optics into the range of X-rays or gamma rays with an extremely narrow bandwidth. For example, the natural linewidth of the first excited state of ^{57}Fe is 4.6 neV, which corresponds to a linewidth-to-transition-energy ratio of approximately 10^{-13} for the 14.4 keV transition. X-ray quantum optics has advanced rapidly with the emergence of remarkable X-ray sources such as synchrotron radiation and X-ray free electron lasers. X-ray quantum optics is attractive because these photons, with their ultrashort wavelength, have several advantages over visible or infrared light which are primarily applied in quantum optics. However, there are still many challenges to controlling X-rays or gamma rays other than the source limitation. The technique of the vibrating absorber including the Mössbauer nuclide is one efficient method for controlling X-rays or gamma rays.

This thesis describes the development of a method to control the gamma rays using the vibrated resonant absorber. This technique utilizes the frequency modulation of gamma rays, where the frequency-modulated gamma rays can be represented as a superposition of spectral components equally spaced by the vibrational frequency centered at the carrier frequency of the gamma rays. The intensity of these components depends on the vibrational amplitude. Since the wavelength of the gamma rays in the 10 to 100 keV range is on the order of sub-nanometers, it is necessary to control the vibrational amplitude in the sub-nanometer scale to achieve the desired sideband intensities. Furthermore, efficient control of gamma rays requires high-frequency vibration with minimal amplitude variance in the nuclei within the sample.

If the vibrational amplitude depends on the positions of the sample and the nucleus in the small area vibrates with a uniform amplitude and phase, it is possible to avoid the problem due to the variance of the amplitude for coherent control of the gamma rays. To investigate the position dependence of the vibrational amplitude, the ^{57}Fe synchrotron Mössbauer spectroscopy was performed with X-ray focusing optics. It was confirmed that the nuclei in the stainless-steel foil glued on the PVDF film vibrated with almost zero

amplitude variance in 100 μm diameter region. Therefore, focused synchrotron radiation can make it possible to control the gamma rays without the influence of the variance of the vibrational amplitude.

Moreover, to develop the study on the coherent gamma radiation, the method was developed that allows post-measurement analysis by recording all relevant information such as photon detection and the external parameters for measuring the pulse train of the gamma rays emitted by a radioisotope source. A series of pulses in the time domain of the gamma rays can be generated by transmitting the gamma rays through a vibrating single-line absorber. For the case of using the radioactive ^{57}Co , the observation of a 14.4 keV gamma-ray waveform in the time domain utilizes a cascade scheme in which ^{57}Fe nuclei sequentially emit 122 keV and 14.4 keV gamma rays. In this scheme, the 122 keV photon emission leads to the origin of the 14.4 keV gamma-ray waveform. The vibrational phase of the absorber at the origin of the waveform determines the phase of the pulse train. Therefore, synchronization of gamma-ray emission timing with the vibration phase is important. The measuring method developed in this thesis mitigates the limitation of the time intervals for accepting the signals of 122 keV gamma rays. The 14.4 keV gamma-ray pulse train was experimentally generated at a frequency of 15 MHz by transmitting the gamma rays through the single-line absorber vibrating at a frequency of 15 MHz. Furthermore, the results successfully confirmed that the phase of the gamma-ray pulse train shifted with respect to the initial phase of the vibrating absorber. By recording all relevant data from detected photon, experimental results under the different conditions could be obtained without the need to repeat similar experiments.

The method of coherent control of gamma rays using frequency modulation and the experimental technique developed in this work can be applied to the future studies of X-ray quantum optics using the synchrotron radiation or X-ray free electron lasers. This work is expected to accelerate the progress of X-ray quantum optics and quantum technology applications involving photons with the energy of 10 to 100 keV.