Synchrotron Radiation Experiments under Very Strong Magnetic Fields

A strong magnetic field is indispensable for studying the physical properties of strongly correlated electron systems. A variety of novel phenomena, such as metamagnetism, insulator-metal transition and structural transition, are induced by a strong magnetic field. On the other hand, performing an X-ray experiment using synchrotron radiation is a powerful means of investigating the structural, electronic and magnetic properties of solids. Hence, a combination of strong magnetic fields and synchrotron radiation is one of the most promising experimental techniques for opening up a new area for both synchrotron radiation materials science and high magnetic field physics.

The key to realizing a synchrotron radiation experiment in strong magnetic fields is how to develop a magnetic field generator in or near a synchrotron radiation facility. Although a strong magnetic field of up to 20 T is available with a commercial superconducting magnet at the present, it cannot be used for the X-ray experiment as it is because of its narrow sample space, the small aperture for the access to the sample and other factors. In fact, the world's strongest DC magnet for X-ray diffraction is the 15-T split-pair type magnet installed on beamline **BL19LXU** [1].

Since various kinds of phase transitions or peculiar phenomena were discovered in strong magnetic fields exceeding 20 T, the development of the technique for the synchrotron X-ray experiment under stronger fields is urgently required. A pulsed magnet can generate much stronger magnetic fields than a DC magnet because of its short pulse duration time and hence small heat production. However, the construction of a conventional-type pulsed field generator in a synchrotron radiation facility is still not easy because the generation of strong fields exceeding 30 T requires large electric power, large space and special skills.

Fig. 1. Photograph of miniature split-pair type magnet for X-ray diffraction.

In order to overcome this problem, we have recently developed a very small pulse magnetic field generator for the synchrotron X-ray experiment. It consists of a portable size capacitor bank (~2 kJ) and a miniature pulsed magnet (3 mm inner diameter) [2,3]. A photograph of the magnet is shown in Fig. 1. The capacitor bank only weighs 100 kg and can be readily installed into a synchrotron X-ray facility from the outside. The magnet is small enough to be set in a standard cryostat and cooled together with a sample. The energy of the capacitor bank and the volume of the magnet are roughly two orders of magnitude smaller than those of a conventional pulsed magnet.

We applied this technique to the X-ray diffraction study on a field-induced valence transition of $YbInCu_4$. $YbInCu_4$ is known to show a first-order valence transition at 42 K. At low temperatures the local magnetic moment of the Yb ion is compensated and a Fermi liquid state is realized due to the strong *c-f* hybridization. The valence of the Yb ion becomes fluctuating (v = 2.8+ ~ 2.9+) from an integer valence state (v ~ 3+) with decreasing temperature; the lattice volume increases by 0.45% at the transition, while maintaining C15b cubic structure.

The first-order valence transition is also induced by a strong magnetic field at low temperatures. According to previous papers, the valence fluctuating state (v = 2.8+ ~ 2.9+) is transformed into the integer valence state (v ~ 3+) by a magnetic field of around 30 T at 4.2 K [4]. The distinct metamagnetic transition is observed.

The experiment was performed on undulator beamline **BL22XU**. A split-pair type miniature magnet that can generate 36 T at 1.3 kJ was used. We made a time-resolved measurement using an avalanche photodiode (APD) and a multichannel scalar (MCS). A single crystal of $YbInCu_4$ grown from In-Cu flux was used. The available lowest temperature is 3 K at present.

Figure 2 shows the time dependence of the (220) Bragg reflection peak intensity in $YbInCu_4$ and that of the magnetic field. We see that the (220) reflection intensity suddenly decreases and recovers at the time corresponding to around 30 T. This field dependent behavior of the reflection intensity indicates that the structural transition occurs due to the field induced valence change [3,5].

The (220) reflection peak profiles in magnetic fields are obtained by repeating the measurements at different reflection angles. The field dependence of the (220) reflection profile is shown in Fig. 3. It is found that the new reflection peak denoted as peak A appears at around 26 T and its intensity increases as the field increases. Correspondingly, the reflection peak B from the low-field phase disappears with increasing magnetic fields higher than 26 T. This phenomenon is attributed to the lattice contraction due to the field-induced valence transition. It is worth noting that peak B dose not successively translate to peak A. Hence, it is apparent that the valence state transition of $YbInCu_4$ is of first order.

We carefully analyzed the field dependence of the integrated reflection intensities and the peak positions of peaks A and B. It is found that the intensity of peak B (low-field phase) is nearly scaled with the magnetization. On the other hand, peak A (high-field phase) appears at slightly higher fields than expected from the magnetization. This is most probably because the domain size of the high-field phase at the early stage of the transition is too small to be observed as a well-defined X-ray diffraction peak [5]. Moreover, we found that both peaks (peaks A and B) show a small continuous shift in the vicinity of the transition field (25 T~ 28 T) where the two phases coexist. This may suggest that the lattice is slightly deformed by a kind of internal stress due to the interaction between two domains of different valence states [5].

As shown above, X-ray diffraction in a strong magnetic field is considered to be one of the most interesting means of investigating the field induced phase transitions of strongly correlated electron systems. Our experimental technique can also be applied for other kinds of experiments such as those based on X-ray absorption spectroscopy (XAS) and X-ray magnetic circular dichroism (XMCD). The development of the technique for XAS under strong magnetic fields is now in progress and the preliminary experiment has been conducted at BL22XU up to 51 T using a solenoid-type mini-magnet.

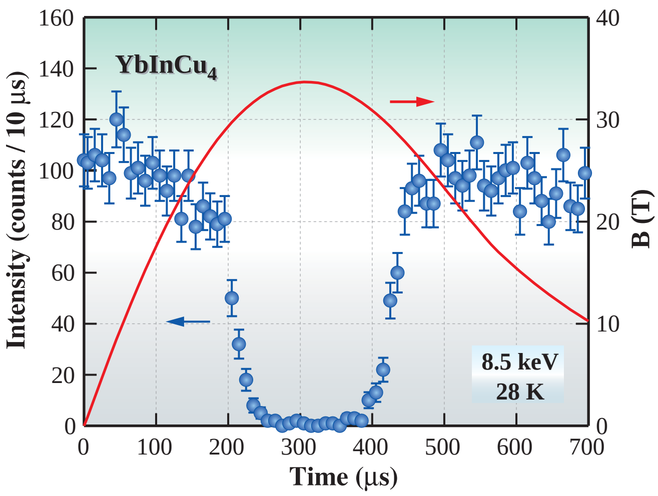

Fig. 2. Time dependences of (220) Bragg reflection peak intensity and magnetic field.

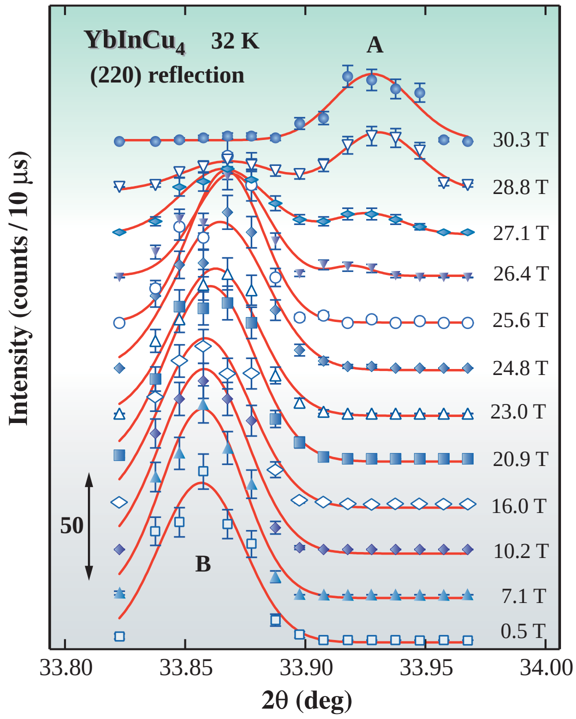

Fig. 3. (220) Bragg reflection peak profiles in magnetic fields. The solid curves are the results of the curve fitting.

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