論 文 の 内 容 の 要 旨

論文題目　Particle-irradiation effects on pairing and vortex states in iron-based superconductors
（鉄系超伝導体の対状態および磁束状態に対する粒子線照射効果）

氏　　名　　田縁　俊光

Since iron-based superconductors (IBSs) have relatively high superconducting transition temperature (T_c), high upper critical field (H_{c2}), and high critical current density (J_c), this system attracts researchers from fundamental and technological aspects of view. From a fundamental aspect, it is known that the superconductivity in this system cannot be understood by the conventional theory, as in the case of cuprates, so that some nontrivial pairing mechanisms are under debate. To understand why the superconductivity appears, it is quite important to clarify the superconducting gap structure. For applications, on the other hand, the vortex properties such as pinning and dynamics should be understood for enhancing J_c. Based on the arguments above, we have examined the two themes; (1) pair-breaking effects and (2) vortex pinning and dynamics under the effect of point or columnar defects (CDs). We elaborate these two themes in terms of particle irradiations.

(1) Pair-breaking effects by 3-MeV proton (H^+) irradiation

To explain the superconducting properties in IBSs, some pairing mechanisms are proposed such as mediated by spin fluctuations or orbital fluctuations, and the corresponding gap symmetry is predicted as so-called $s_{\pm}$-wave and s_{++}-wave, respectively. These states are characterized by the sign reversal of the order parameter between the hole and electron Fermi surfaces (FSs). To determine which state is realized, a phase-sensitive probe is required. The impurity effect has played a key role for this purpose. According to the Anderson's theorem, non-magnetic impurities do not work as pair-breaker in isotropic single-gap superconductors. By contrast, fast suppression of T_c is expected in superconductors with a sign change such as *d*-wave. In IBSs, to determine the sign reversal between the hole and electron FSs, some impurity effects are performed by chemical substitutions. On the other hand, a peculiar way to introduce disorders is the energetic particle irradiation. In sharp contrast to chemical substitutions, light-particle irradiations enable us to introduce point-like defects in a given sample systematically. Another advantage is that the problems in chemical substitution, like structurally unstable and inhomogeneous properties and/or possible change in carrier density and FS topology, can be overcome. The central issue of this study is to clarify the relationship between the evolution of ρ_0 and the reduction of T_c, where ρ_0 is the residual resistivity. For this purpose, we have employed *in situ* resistivity measurements right after the introduction of scattering centers by 3-MeV H^+ irradiation in $Ba_{1-x}K_xFe_2As_2$ (x=0.23, 0.42, and 0.69). The introduced impurity scattering rates are estimated by $\Delta\rho_0 = \rho_0^i - \rho_0^0$, where ρ_0^i is ρ_0 of *i*th irradiation. Figure 1 represents T_c (main panel) and T_c/T_{c0} (inset) as a function of $\Delta\rho_0$, where T_{c0} is T_c in the as-grown sample. The linear extrapolation, drawn by broken lines in Fig. 1, gives the critical residual resistivity value $\Delta\rho_0^{cr}$ to fully suppress T_c. These values of $\Delta\rho_0^{cr}$ are similar to previous reports in chemically substituted samples (100-1000 μΩcm). For

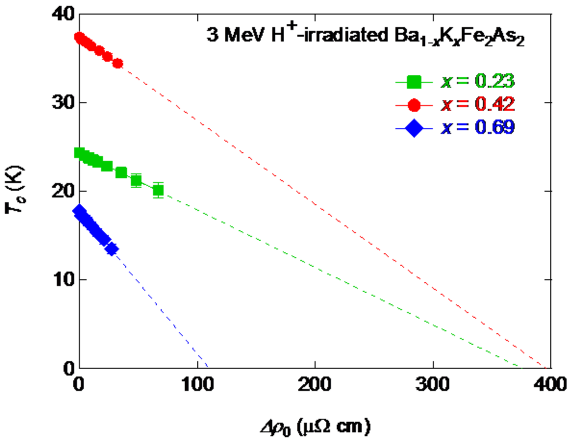

FIG. 1: T_c as a function of $\Delta\rho_0$ in $Ba_{1-x}K_xFe_2As_2$.

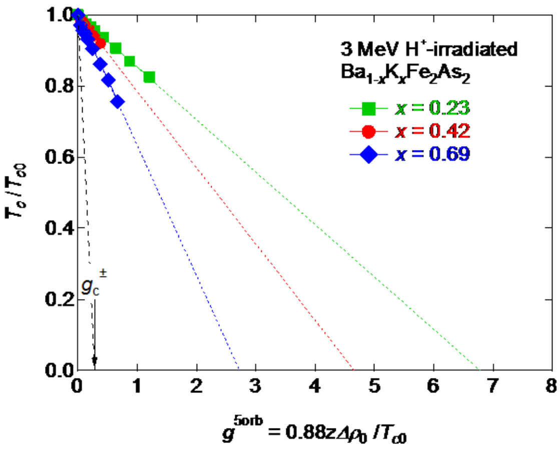

FIG. 2: T_c/T_{c0} as a function of a normalized relaxation rate evaluated by the five-orbital model g^{5orb} in $Ba_{1-x}K_xFe_2As_2$. The linear extrapolations are shown by dotted lines. Dashed line indicates the critical scattering rate $g_c^{\pm}$= 0.3 for the $s_{\pm}$-wave scenario.

quantitative discussion of pair-breaking effects by nonmagnetic scatterings, we evaluate the normalized scattering rate. According to the linear response theory based on the five-orbital model, we can obtain one of estimations $g^{5orb} = 0.88z\,\Delta\rho_0/T_{c0}$, where the renormalization factor $z = 1/2$ is reported in the angle resolved photoemission spectroscopy measurement. The obtained T_c/T_{c0} as a function of g^{5orb} is shown in Fig. 2. The critical values of g (= g_c) where the linear extrapolation of T_c/T_{c0} goes to zero are comparable to g_c = 4-8, obtained for chemical substitutions in $Ba_{0.5}K_{0.5}Fe_2As_2$. These results should be compared with the $s_{\pm}$-wave scenario with equal gap magnitudes of opposite signs on the different FSs, where the obtained critical g is $g_c^{\pm}$= 0.3, as shown by the broken line in Fig. 2. By contrast, it is expected that the rate of T_c suppression is much smaller in the s_{++}-wave scenario. Consequently, our results strongly suggest that the realization of $s_{\pm}$-wave state is unlikely in K-doped $BaFe_2As_2$.

(2)The evolution of vortex states in H^+- and heavy-ion irradiated systems

From the view of applications, high J_c performance is expected as well as high T_c. However, even if high J_c is realized, sizable suppression of screening current density with time, so-called a “giant flux creep” is possibly observed, as pointed out in cuprates. Not only high J_c but also reasonably small flux relaxation rates are required for applications. In addition, it is interesting to know the relaxation process to the equilibrium state and how pinning sites affect to it. In such a point of view, effects of artificial defects on vortex pinning and dynamics are interesting for fundamental and technological aspects. We have employed particle irradiations since the amount and the morphology of defects are controllable. As mentioned in the previous section, H^+ irradiation introduces point defects but does not largely suppress superconductivity, so that the effect of random point pinning sites can be examined. On the other hand, heavy-ion irradiation introduces columnar defects (CDs), which work as one-dimensional strong pinning sites. To clarify the optimal pinning condition, we have carried out several kinds of particle irradiations, and observed J_c by magnetization measurements. Besides, by tracing magnetization (M) with time (t), the vortex dynamics are examined. In H^+-irradiated $Ba_{0.6}K_{0.4}Fe_2As_2$, the value of J_c at low temperature (T) is significantly enhanced by a factor of 5-10 and reached

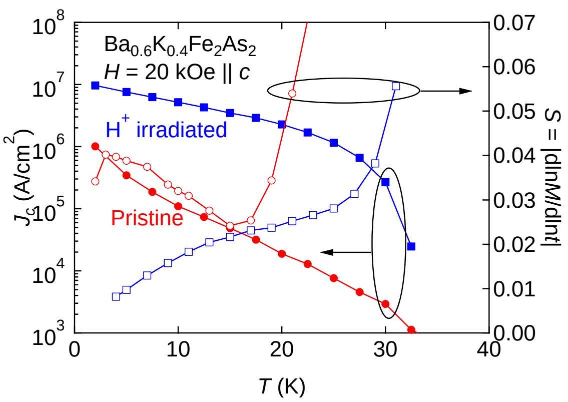

FIG. 3: J_c and S as a function of T under H = 20 kOe parallel to c-axis in the pristine and H^+-irradiated $Ba_{0.6}K_{0.4}Fe_2As_2$.

to the order of 10^7 A/cm^2, as shown in Fig. 3. This value is the largest reported ever in IBSs and greatly exceeds the technologically required values of 10^5 A/cm^2. The vortex creep rates are evaluated by $S = |d\ln M/d\ln t|$. In pristine $Ba_{0.6}K_{0.4}Fe_2As_2$, S at low T non-monotonically behaves with T up to 0.04. With elevating T, the vortex matter crosses over to the plastic creep phase characterized by fast creep at relatively low T (~ $T_c/2$). These behaviors are drastically changed by H^+ irradiation. The monotonic and low value of S is observed up to $T = 0.8T_c$, and a plateau-like feature at intermediate T is identified, which is a fingerprint of so-called "collective creep". As a result, the artificial introduction of weak pinning sites works well to enhance J_c and suppress S at any T and field (H). These behaviors shed light on the clarification of vortex-defect interactions.

In the case of heavy-ion irradiation, the realization of a peculiar vortex phase ("Bose glass" phase) in IBSs is examined. Under the pinning potential of CDs, the vortex hopping among CDs can be mapped on the motion of two-dimensional Bosons, so that some nontrivial vortex dynamics are expected. Indeed at $T = T_{dp}$, a drop in J_c and the acceleration of S as a function of T is observed in cuprates. However, such features have not been observed in IBSs. Another approach is to detect the lock-in phase. Namely, the angular-independent M is identified in the vicinity of H ||CDs. We therefore explore the angular dependent M at low T in 2.6-GeV U-irradiated $Ba(Fe_{0.93}Co_{0.07})_2As_2$. As shown in Fig. 4, the plateau in M is observed around H || CDs and the width of plateau $2\theta_L$ is proportional to $1/H$. This behavior manifests that the lock-in transition is realized, and is the first observation of Bose glass phase in IBSs.

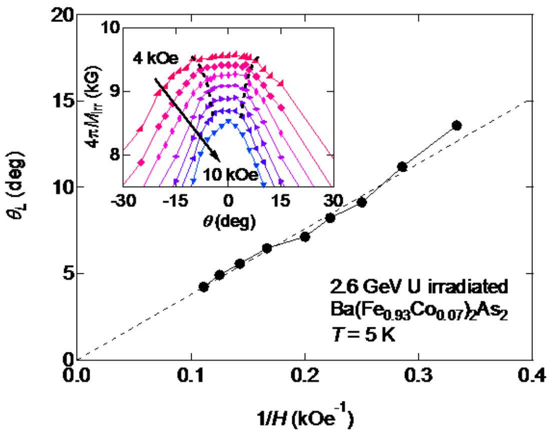

FIG. 4: The half width of the plateau θ_L in M as a function of $1/H$ in U-irradiated $Ba(Fe_{0.93}Co_{0.07})_2As_2$. Inset: the angle dependence of M under several H. Broken lines are guide to the eye for the plateau.

In summary, we have investigated the particle-irradiation effects in IBSs in terms of pairing and vortex states. The small suppression rates of T_c manifests the inconsistency with the superconductivity mediated by spin fluctuation. The vortex states are largely affected by artificial defects. The J_c are largely enhanced as to reach to 10^7 A/cm^2 in H^+-irradiated system. The Bose glass phase is realized in CD-introduced system. Both of them are first observation in IBSs. These findings contribute to optimize pinning properties and understand the vortex-defect interactions.