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The Scaling Behaviors of Pinning in TlBaCaCuO Superconducting Thin Films

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The scaling behaviors of global pinning force density in dc sputtered TlBaCaCuO superconducting thin films as functions of both reduced magnetic fields and temperatures were investigated by direct transport measurements with applied fields perpendicular to the film surface. The pinning mechanisms which were depicted by the scaling behaviors of the Tl-based thin films were found to be strongly dependent on the superconducting properties of the films. For films with high critical current densities the conventional flux line shear pinning appeared to be the predominant limiting mechanism for the current carrying capability. Whereas in more granular film that did not scale well when normalized by the extrapolated H_{c2}, an astonishing scaling behavior by taking a reversible field H* as the normalization parameters was observed.

I. INTRODUCTION

In ideal type II superconductors which are free of extended lattice defects, the flux line assembly present in the mixed state will begin to move whenever a force acts on it. The motion of vortex lines generates electric fields in the superconductor and results in dissipative effects. Thus, the ideal type II superconductors in the mixed state are not able to carry transport currents without losses.* The critical current density (J,) of the type II superconductors, including the high-T, systems, is determined by the pinning force that provided by the extended defects. Consequently, it is of interest to investigate the origin of the flux pinning of the high-T, superconducting thin films which typically exhibit very high critical current densities to understand the underlying mechanisms for the preparation of possible applications for these materials.

Comparing the field dependence of the global pinning force density ($F_p = J_c \times B$) measured at different temperatures for a type II superconductor, one found for many samples a striking similarity of the shape of these curves. This suggested plotting the results as a function of the reduced field $h = H/H_{c2}$ (H_{c2} is the upper critical field) so that they all coincide at h =

1. If one furthermore normalizes the curves of pinning force ($F_p(h)$) to their maximum values, a single curve is obtained in most cases. Such a scaling law with the form

$$F_p(h) = C \times H_{c2}^n(T) \times f(h) \tag{1}$$

where C is a material parameter and f(h) is a function of h, was first introduced by Fietz and Webb" for a phenomenological description of experimental results on cold-worked Nb-based alloys. Since then, it has been shown (see e.g. Ref. 3) that such a scaling law holds for a large variety of hard superconductors ranging from model systems such as Pb-In[4] or Nb-Ta[5] to the commercial material Nb-Ti[6] and Nb_3Sn[7].

The recognition of scaling laws for the pinning force is important for two reasons. The first is a practical one because that one needs only to measure $F_p(h)$ at one temperature and then the F_p curves for other temperatures are predictable by scaling the results. The second benefit of plotting normalized F_p curves as a function of h is that sometimes qualitative informations about the pinning mechanism can be explored from the simple scaling law.

Currently, the studies of scaling in high-T, superconductors were carried out by D.P. Hampshire et al.[8] for the LaSrCuO material, and K. Matsumoto et al.,[9] V. M. Pan et al.[10] and R. Wördenweber et al.[11] for the polycrystalline YBaCuO superconductor. They have conjectured that from the experimental results, the pinning mechanism of the flux line shear theory which was found in the Nb-based materials by E. J. Kramer[12] should be responsible for the pinning mechanism in the YBaCuO -material.

In this article, the global pinning force density of the TlBaCaCuO thin films has been estimated with multiplying the transport critical current density by the applied field in order to examine the scaling behavior of flux pinning in the Tl-based superconducting thin films. It was found that the well scaling behavior of pinning was not a certain result for the Tl-based thin films by using the extrapolated H_{c2} as the normalization parameter, and the function form of f(h) in Eq. (1) was dependent on the superconducting properties of the samples investigated.

II. EXPERIMENTAL DETAILS

TlBaCaCuO thin films with a typical thickness of 1 μm were prepared by a single target dc sputtering method previously reported.[13] Despite of the as-deposited stoichiometric composition was used for preparing the targets ($Tl_2Ba_2Ca_2Cu_3O_x$), the final quality of the films obtained was found to have a strong dependence cn the subsequent annealing conditions employed.[13,14] It is interesting to note that although the final film properties can be varied vastly by the detailed annealing conditions all the films produced exhibit c-axis oriented characteristics as revealed by thin film X-ray diffractions.

All the films used in this study were patterned into a 10-μm-wide, 125-μm-long bridge by standard lithographic processes[15] for subsequent transport measurements by the usual fourprobe method with the magnetic field applied perpendicularly to the film surface. To determine the critical current densities of the films a practical criterion of 1 μV has been adopted in all cases.

III. RESULTS AND DISCUSSIONS

The magnetic field dependent pinning force density for different temperatures of sample A is shown in Fig. l(a) as an example. To explore the scaling of the pinning, the H_{c2} was obtained by extrapolating the F_p values with data in the range of H $> H_p$, where H_p was the field where the maximum pinning force (F_{pmax}) occurred. Then the field dependent pinning forces were normalized by the H_{c2}'s and the Fpmax ' s at various temperatures, and the results are plotted in Fig. l(b). It is clear from Fig. l(b) that the data are all fallen in one curve, which indicates a good scaling behavior of pinning in this sample. The similar procedure has been carried out on separate thin films with different critical current densities as listed in Table I. Figure 2 shows the normalized pinning force of sample B for four temperatures, a well scaled pinning as observed in Fig. l(b) was also exhibited. For the normalized pinning force for samples C and D, shown in Fig. 3(a) and Fig. 3(b), respectively, the scaling behaviors were again presented in these two films, except that the data were more scattered and consequently were not scaling as well in temperature as those in the two films with much higher critical current densities. However, for the film E with the same normalization method, the pinning behaves in a totally different manner, as shown in Fig. 4, which can not be fitted by the conventional fitting function (see below).

After the normalization process, the function forms of f(h) in Eq. (1) for samples A to D were tried to be found to investigate the prevalent pinning mechanism. For the reason that there is no mature pinning theory for the TlBaCaCuO superconductors at the present time, the following function

$$f(h) = a \times h^b \times (1 - h)^c \tag{2}$$

TABLE I. The current carrying capability of the films investigated in this paper.

Sample	JC
A	$J_c(77K) > 10^6$ A/cm'
B	$J_c(77K) > 10^7$ A/cm"
C	$J_c(20K) \sim 10^5$ A/cm^2
D	$J_c(20K) \sim$ 10 " A/cm^2
E	$J_c(20K) \sim 10^5$ A/cm"

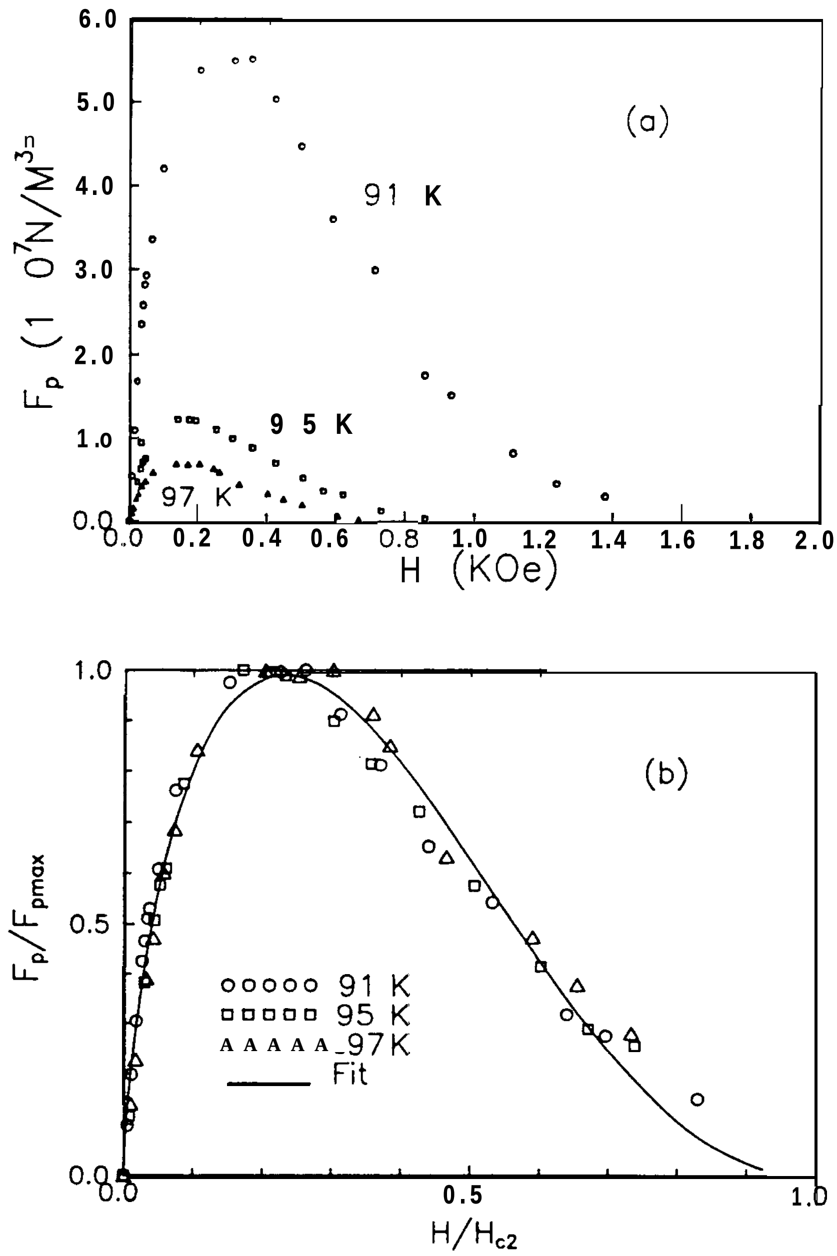

FIG. 1. (a) The magnetic field dependent pinning force densities for sample A at 91, 95 and 97K. (b) The reduced pinning force densities (symbols) of sample A together with the best fitted curve (solid line).

where a, b and c are constants, was adopted to fit the reduced pinning force, because that Eq. (2) is a general result of the pinning in conventional type II superconductors (see e.g. Ref. 3, 12, 16, 17). The fitting was carried out by the least square method and the results are plotted

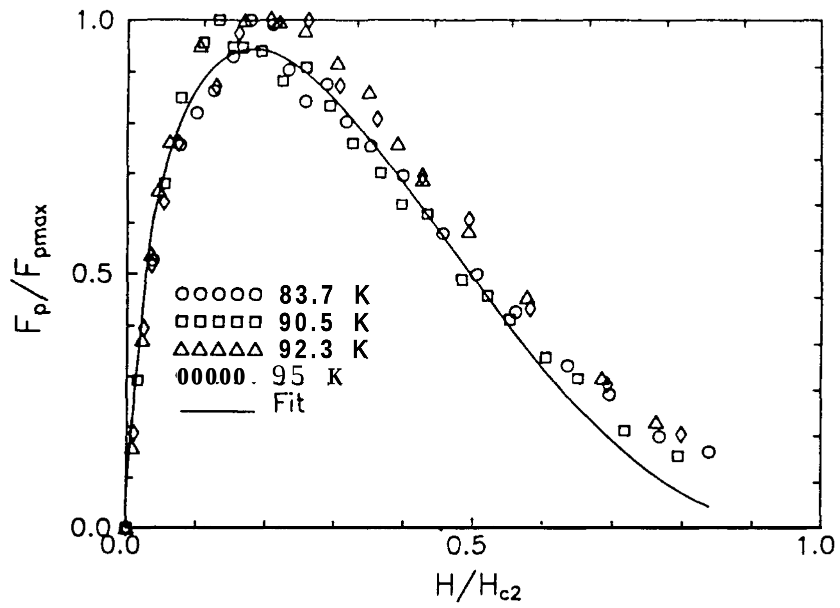

FIG. 2. The reduced pinning force densities (symbols) of sample B together with the best fitted curve (solid line).

by solid curves in Figs. 1 to 3. For the films with high critical current densities (J_c(77K) > 10^6 A/cm^2), the scaling functions obtained (f(h) $\sim h^{0.6}(1-h)^{2.3}$) were close to the result of the flux line shear pinning mechanism[12] which has

$$f(h) = K \times h^{0.5} \times (1 - h)^2 \tag{3}$$

where K is a constant related to the material properties. Such results indicate that the same pinning mechanism may be responsible for the high J_c TlBaCaCuO thin films as those found in the YBaCuO material. However, for the two films (samples C and D) with lower values of J,, the proper pinning mechanism which accounts for their scaling functions f(h) is still unclear. The discrepancy is supposed to come from the more granular structure (the origin of the lower critical current density) of the two samples.

In addition to the study as introduced above, we have made further investigation on film E whose pinning force density normalized by the extrapolated H_{c2} was failed to be scaled into one cuve of the form of Eq. (2). An alternative method was proceeded to determine the effective normalization constant of this sample. The temperature dependent J_c was measured in a fixed applied field both in the zero-field-cooled (ZFC) and field-cooled (FC) conditions, and it was found that the measured J_c's coincided with each other above a temperature where the J_c was not zero. Figure 5 shows such result for the applied field of 1008 Oe, and the temperature where the zero-field-cooled J_c equal to the field-cooled one is 53.5 K. From this result, we defined an

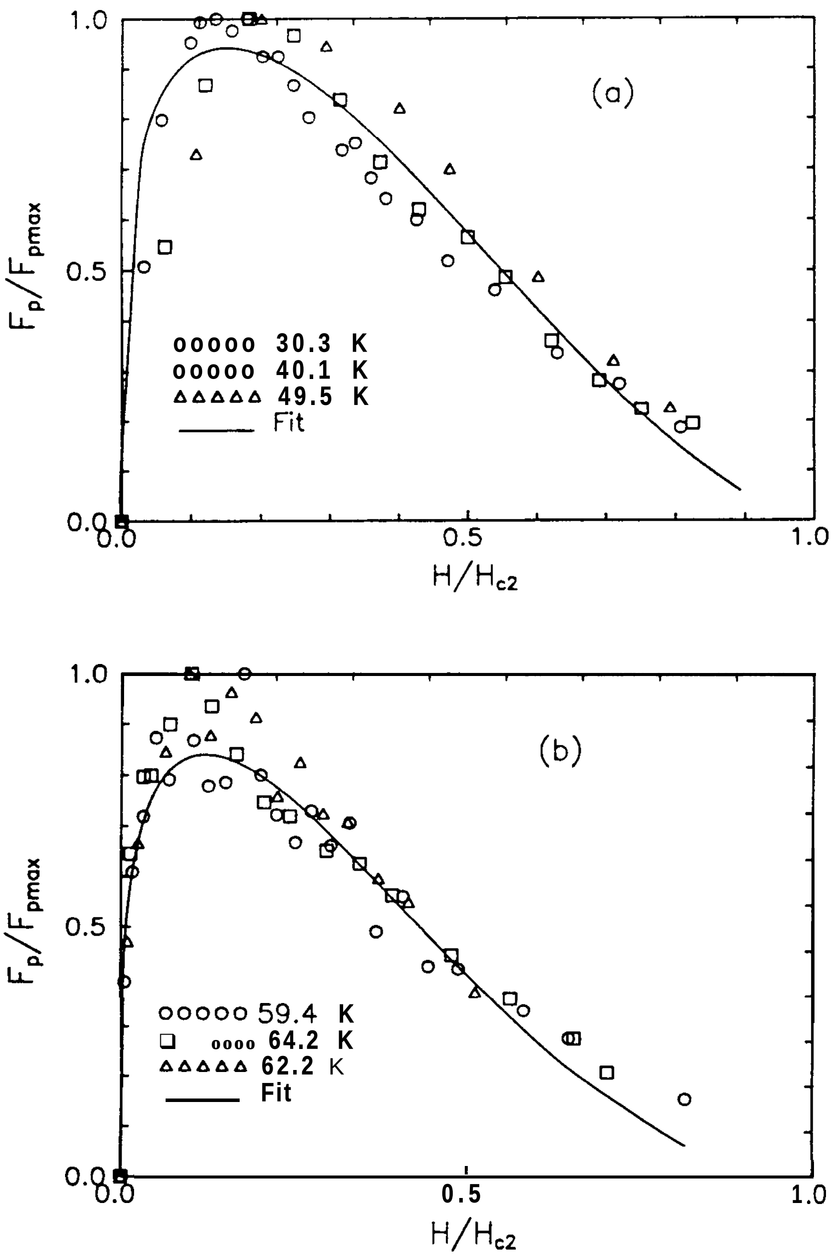

FIG. 3. The reduced pinning force densities (symbols) for various temperatures plotted with the best fitted curves (solid lines) for (a) sample C and (b) sample D.

H* = **1008 Oe at** T = **53.5** K. The same process was repeated at various applied field until series of H*'s were obtained for different temperatures. The pinning force density for sample E was then normalized by using the H* as an effective upper critical field instead of the extrapo-

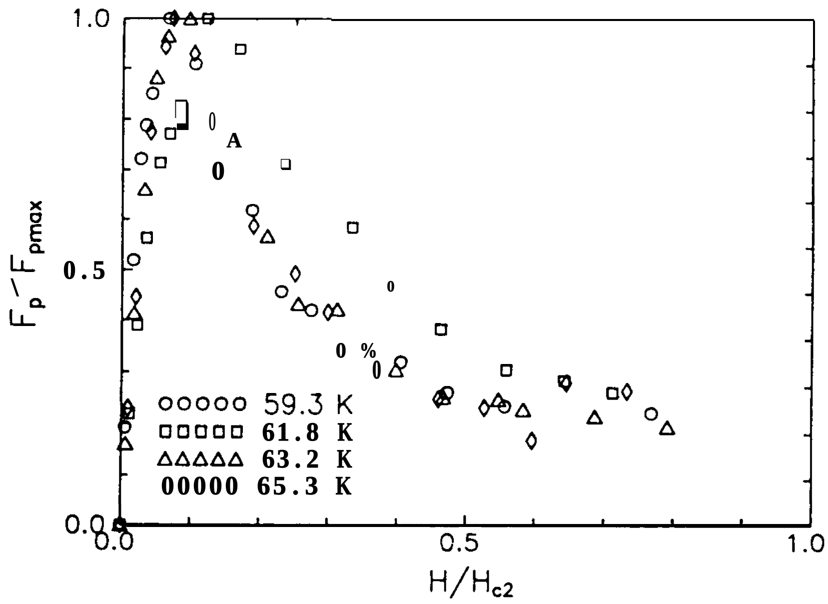

FIG. 4. The reduced pinning force densities which normalized by the extrapolated H_{c2} of film E.

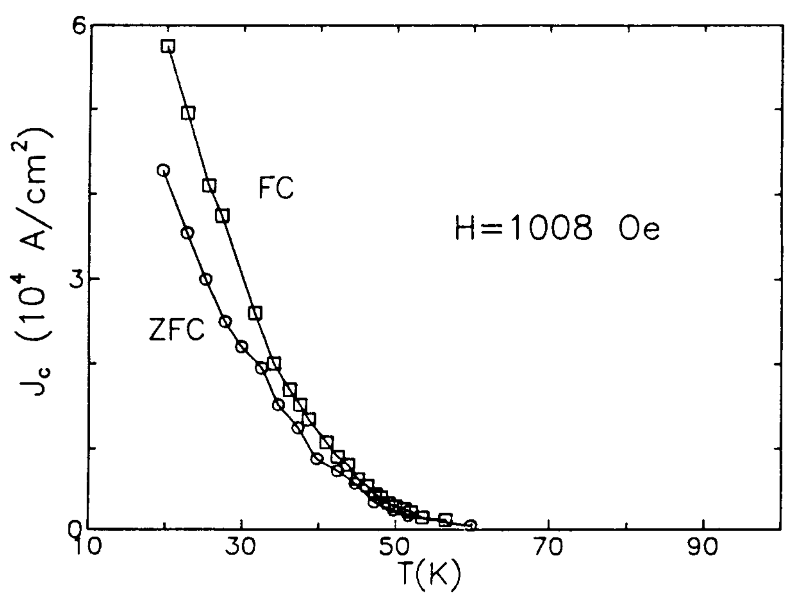

FIG. 5. The zero-field-cooled and field-cooled J_c measured in 1008 Oe for sample E.

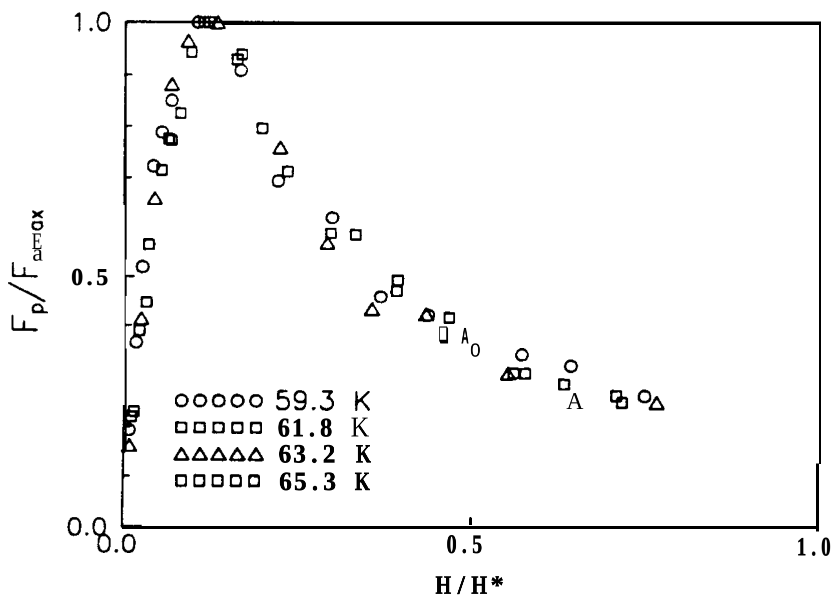

FIG. 6. The reduced pinning force densities that were normalized by the F_{pmax} and the reversible field H* for sample **E.**

lated H_{c2} and plotted in Fig. 6. It is clear in Fig. 6 that the pinning force for different temperatures can be scaled well by taking H* as the effective upper critical field. Moreover, it is interesting to compare such result with that of the magnetization (M) measurement, which reported by R. Wordenweber et al. that the critical current density and consequently the F_p obtained by the hysteresis of M (using the Bean model ' *) exhibited a good scaling rule by using the H^*_{c2} as the normalization constant,[11] with H^*_{c2}, the irreversibility field[19] measured for their sample. There is an noticeable similarity between the scaling of sample E and that reported in Ref. 11, for the H* was obtained from the FC and ZFC measured J_c and the H^*_{c2} in Ref. 11 was obtained from the FC and ZFC measured M. A granular nature in both the intragrain and intergrain characteristics of the high-T, superconductors was implied from such results. In any case, the true mechanism involved in such scaling behavior is worth investigation in advance and is currently undertaken.

IV. SUMMARY

The global pinning force of the Tl-based thin films obtained from multiplying the transport J_c by applied field was investigated. The scaling behaviors of the pinning effects for different temperatures were found to be valid in samples with high critical current densities ($J_c(77K) > 10^6$ A/cm^2), while in the low J_c thin films more scattered results were observed. The pinning mechanism of flux line shearing which was found in the Nb-based superconductors[12] has been conjectured to be responsible for the pinning in the high quality Tl-based superconducting thin films. To use the irreversible field H*'s which were measured from the field-cooled and zero-field-cooled critical current densities as the normalization parameters resulted in good scaling behavior in the sample E, which indicated that the granularity may play an important role in this sample.

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The Proceedings of the First Symposium on Trends in Particle and Medium Energy Physics November 14-15, 1991, Taipei, Taiwan, R.O.C.

Preface

The idea of organizing a series of relatively small and compact symposia on trends in particle and medium energy physics occurred to us and our colleagues about two years ago. It is obvious that a small cross section of speakers, most of them active local and oversea Chinese physicists, can never be considered as a balanced sample for giving talks (or lectures) on the trends in particle and medium energy physics. Nevertheless, a forum that would provide local researchers some ideas concerning what has been going on in the field should be organized from time to time. It was in this spirit that we kicked off the First Symposium on Trends in Particle and Medium Energy Physics, and, of course, we hope that this would only be the first in the series and that in the future the horizon of speakers would indeed extend to cover a fair cross section of the entire community.

With the limitations just stated, we nevertheless feel that our first such symposium has been a great success, judging from the unusual high level of participation from the local community. Indeed, we have had the opportunity of listening to many pedagogical and illuminating (and some perhaps unusual) talks, most of which have been rewritten by the authors for publication in Chinese Journal of Physics.

Among people who had helped to run the scientific program smoothly, we wish to acknowledge specifically our colleagues and graduate students at National Taiwan University as well as Miss Shu-Hwa Wang (Symposium Secretary) for their indispensible helps on administrative matters. We are also grateful to invited speakers for undertaking their tasks seriously and to session chairmen for running the programs smoothly. **This** symposium was supported financially by the Ministry of Education of R.O.C., the National Science Council of R.O.C., National Taiwan University, China Foundation for the Promotion of Education and Culture, the Republic of China Committee for Scientific and Scholarly Coorperation with the United States (Academia Sinica), and Physics Research Promotion Center (Natural Sciences Division, National Science Council of R.O.C.). Co-sponsorship from the Physical Society of R.O.C. is also acknowledged.

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