condensed matter

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Editorial

Alex's Vision in Functional Quantum Matter

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1. Introduction

In Memoriam, Karl Alex Müller

My 'In Memoriam' contribution is very personal, as it includes many human and professional insights that I received from Alex Müller himself. It places his views and convictions into the context of emerging scientific discoveries of our era. Alex was a very intuitive person, with strong personal preferences. For example, he enjoyed in-depth studies of versatile $SrTiO_3$ material and discussing the broad range of remarkable properties of oxides. He was an outstanding scientist and a wise manager who knew how to choose the best people and address key challenges. Alex was not just the co-discoverer of high-T_c superconductors, which is already remarkable; he was a visionary in how to obtain the desired functionality in complex quantum matter. Even today, several laboratories are exploring some of Alex's striking visions, not the least of which is superconductivity at ambient temperatures.

For me, it is difficult to calmly summarize the remarkable life and career of a towering personality like Karl Alex Müller, yet the reader can benefit from his own view in his Nobel prize summary [1] and from a special interview and a summary [2,3] by his close friends [2–7]. Here, I give some personal experiences and encourage the reader to study other fine contributions by distinguished colleagues in this and related *In Memoriam* publications [2–5].

In 1970, when I began my undergraduate studies in physics, Alex was already a very successful research director of the Physics Department at IBM in Zürich. At that time, condensed matter physicists were learning how to prepare new functional materials and master electron correlations [2–5]. Well-characterized single crystals were prominent in the field, and owing to the success of semiconductors, thin-film methods and technologies were exploding. By 1982, when Alex began his exploration in superconductivity [1–5], I was already a post-doc and lecturer in CNRS (Grenoble) exploring quantum phenomena in disordered and quasicrystalline materials. In collaboration with Joël Chevrier and Françoise Cyrot-Lackmann and other colleagues, we enhanced T_c in rapidly quenched Al-Si, and Guy Deutscher was an external examiner in Joël's thesis jury. With Guy, we discussed possibilities to enhance T_c even further. In passing I should note that, at that time, the idea of bipolaron pairing [1] was already 'alive' in IBM laboratories [1], so in CNRS in Grenoble, I was encouraged (mainly by Benoy Chakraverty and Julius Ranninger) to try to prepare a novel, hopefully biopolaronic superconductor. As my experience with oxides was negligible, I rather focused on superconductivity in Al-based systems, eventually also on quasicrystals. Little did we know (in 1982–1985) that in the IBM Zürich Laboratory, Alex had some very powerful insights with his in-depth experience with oxides and that he had convinced Georg Bednorz to systematically research (super)conducting oxides! The rest is, as they say, history [1–6].

2. High-T_c (R-) Evolution

By 1986, when high-T_c superconductivity revolution had begun, I was already in the Physics Department of the EPFL in Lausanne. The moment I received the news (on the phone by Michel Cyrot in Grenoble) about the striking Bednorz–Müller discovery [1–3]

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(at that time not yet confirmed by magnetic susceptibility measurements), I immediately jumped on the challenge. We quickly developed thin cuprate films, and I convinced my superiors to fund a bold project on superconductivity in oxides. Since that time, and especially following 'The Woodstock of Physics' research explosion, my path with Alex closely overlapped. Although I was never formally introduced to him, we often met in various Swiss colloquia (in Zürich); Swiss superconductivity meetings (often in Les Diableres); or relevant, stimulating conferences organized by Annette Bussmann-Holder and/or Antonio Bianconi et al. [2–6], and we *spontaneously* exchanged some scientific comments and/or insights. Many more conference series emerged, among others, memorable regular symposia in Erice, initially in 1992 organized by Alex Müller [4,5] and subsequently by Giorgio Benedek [4,5], Antonio Bianconi [4–6] et al. In all these meetings, we often continued our discussions over coffee and/or were puzzled how even some very distinguished colleagues had little understanding of oxides or easily ignored the essence of short-coherence-length superconductors [2–10]; the role of inhomogeneities; various degrees of disorder; and profound implications for electronic functionality [10] in oxides and emerging phenomena in complex matter [4–12]. Indeed, by 1987, Alex and Guy published an important paper [7] to emphasize that the very short coherence length in high-T_c cuprates required a different approach [7] to the phenomenon of superconductivity [1–10] compared with that used in 'pure' metals and alloys.

In these conferences on high-T_c superconductivity I often emphasized how crucial it is to have *full control of 'in-house-made' samples* (from the atomic and nanoscale to the 'perfect' bulk crystal) and not just publish the results of 'dry measurements'! Sometimes, the full history of the treatment of oxide samples (and many other metastable materials) is vital. Alex agreed (Figure 1) that even the most reputable laboratories were conducting advanced physics research on incompletely characterized samples that were often received from an external source, and we gradually became closer. Moreover, at the Erice workshop [6] on Symmetry and Heterogeneity [6] (2006), tired of many rather long talks by some colleagues, Alex imposed the rule that each speaker may present only three slides! And he publicly appointed me as the 'slides controller': Whoever used more than three transparencies had to pay for a bottle of wine at dinner, for *every extra slide!* Needless to say, presentations became more focused, and we all enjoyed our 'extra dinner wine', as many colleagues were still rather relaxed in 'overshooting' their number of slides!

The Unique Properties of Superconductivity in Cuprates

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Copper oxides are the only materials that have transition temperatures, T_c, well above the boiling point of liquid nitrogen, with a maximum T_c^m of 162K under pressure. Their structure is layered, with one to several CuO_2 planes, and upon hole doping, their transition temperature follows a dome-shaped curve with a maximum of T_c^m. In the underdoped regime, i.e., below T_c^m a pseudogap $\Delta^* \propto T^*$ is found, with T^* always being larger than T_c, a property unique to the copper oxides. In the superconducting state, Cooper pairs (two holes with antiparallel spins) are formed that exhibit coherence lengths on the order of a lattice distance in the CuO_2 plane and one order of magnitude less perpendicular to it. Their macroscopic wave function is parallel to the CuO_2 plane near 100% d at their surface, but only 75% d and 25% s in the bulk, and near 100% s perpendicular to the plane in yttrium barium copper oxide (YBCO). There are two gaps with the same T_c. As function of doping, the oxygen isotope effect is novel and can be quantitatively accounted for by a vibronic theory or by the presence of bipolarons. These cuprates are intrinsically heterogeneous in a dynamic way. In terms of quasiparticles, bipolarons are present at low doping and aggregate upon cooling, so that probably ramified clusters and/or stripes are formed, leading over to a more Fermi liquid-type behavior at large carrier concentrations.

Figure 1. One of the abstracts where Alex summarizes his views on high-Tc superconductivity in cuprates.

3. Friendship and Our Science in Action

Ever since the discovery of high-T_c superconductivity in cuprates, I was teaching an introductory course on superconductivity and quantum fluids at the EPFL; had many notes and 'in vivo' experience with students by 1992; and with Michel Cyrot (Grenoble), we wrote a textbook [8] entitled *Introduction to Superconductivity and High-T_c Materials*. We sent a copy to Alex, and he was delighted as we did respect some of his core ideas that were also discussed at length in a subsequent, rather timely, NATO workshop in Cargese, Corsica [9].

Moreover, encouraged by many fruitful discussions with Alex, as well as Pierre-Gilles de Gennes, with financial support from the EPFL and the Swiss National Science Foundation, I was awarded the mandate to build a new, special thin-film facility in the Wisconsin synchrotron and later also in Villingen and at the EPFL in Lausanne. The scientific experimental challenge was to measure the in situ electronic structure of oxide superconductings films, initially YBCO [11]. This implied a 'perfect' control of the film's growth and required addressing the numerous challenges involved in growth characterization measurements. It was a very difficult project [11], and I often discussed it with Alex; he was genuinely interested and very supportive.

In parallel, by 2000, Annette et al. invited me to give a talk at the Klosters symposium on superconductivity [2,3] to discuss a highly controversial topic (at that time) regarding the role of pseudogap in high-T_c oxides. After an in-depth introduction, I showed that our latest ARPES measurements supported Alex's views on pseudogap in cuprates and Guy Deutscher's latest published letter [10]. Both were delighted. The next day, Alex and I, both passionate expert skiers, had a great time skiing together in the sun on beautiful Klosters' ski slopes . . . during lunch, Alex ordered a bottle of champagne to celebrate my wife's birthday! After that, we became ever closer, and he accepted the invitation to our very first pluridisciplinary conference in Dubrovnik [12] to give the very first plenary talk (Figure 2). Alex loved the place, enjoyed numerous discussions, was delighted by the music of my jazz band 'Tsha-Coo', and even paid for our dinner on the ferryboat (Figure 3) . . . upon our return, he drove me in his Jaguar (Figure 4) part of the way to Trieste.

Eventually, Alex also came to visit our Physics Institute at the EPFL, as he was part of the jury of my PhD student Mike Abrecht [11]. He said it has to be a *short manuscript*, as he will not read more than 80 pages, and we agreed. Alex complimented the aforementioned research effort that enabled us to develop thin cuprate films within the Wisconsin synchrotron and perform the in situ measurement of their electronic structure [11]. Currently, such an approach (originally proposed by Ivan Bozovic [11]) is used in leading synchrotrons, like the Swiss Light Source, or in the Oasis facility in Brookhaven National Laboratory. A few years later, Alex revisited the EPFL, this time to hold a special colloquium in physics. His strict condition was to focus on 'science only' and stay away from any local dignitaries and/or various authorities so that we could freely discuss our science and the core challenges in our ongoing research. However, every morning, Alex would go swimming in Lake Leman, so only later, over lunch, did we enjoy discussions of emerging physics in quantum matter.

There were many other high-T_c superconductivity meetings closely related to Alex's interests—with Dragan Mihailovic et al. in Bled (Slovenia); with Boris Kochelaev et al. in Kazan (Russia); with Alex Shengelaya et al. in Tbilisi (Giorgia); with Hiroyuki Oyanagi et al. in Tsukuba (Japan); and with Ali Gencer et al. at ICSM in Istanbul, in 2012, where we also critically discussed some of the high-pressure research results and much more . . . My apology to many friends and colleagues as I surely forgot to mention some events or some names, but one can easily find them in numerous publications about Alex: His legacy lives! Several laboratories are exploring some of his visions, not the least of which is high-T_c superconductivity at ambient temperatures (Figure 5).

From Solid State To BioPhysics

Friday, June 14 :

8:25 Introductory remarks and official welcome

Challenges in Solid State: High-Tc Superconductivity,
Chair: Stuart Wolf (Washington D.C.)

8:30 Karl Alex Müller (Zürich): On the Analogy of Cuprate Superconductors and Atomic Nuclei

9:00 Dragan Mihailovic (Ljubljana): Pairing in short coherence length superconductors as an inhomogeneous state of matter

9:30 Christos Panagopoulos (Cambridge): A novel quantum transition in high temperature superconductors

10:00 Robert J. Soulen, Jr. (Washington D.C.) : New insight into enhanced superconductivity near the metal-insulator transition

10:30 - 11:00 Coffee break

Toward Oxide Nanoscience and Nanotechnology,
Chair: Julien Bok (Paris)

11:00 Andras Janossy (Budapest): Electron spin resonance in superconductors

11:30 Ivan Bozovic (Palo Alto): Atomically smooth high-Tc films: what can they teach us

12:00 Stuart Wolf (Washington D.C.): Spintronics - The Next Electronic Frontier

Figure 2. In 2002, Alex was our very *first plenary speaker* in a pioneering pluridisciplinary conference [12]. With László Forró (EPFL) and other colleagues, we examined the vision that many principles in condensed matter physics can often be successfully extended (with appropriate approximations) to soft matter and even to living organisms. The conference is still active and delivering striking insights [12].

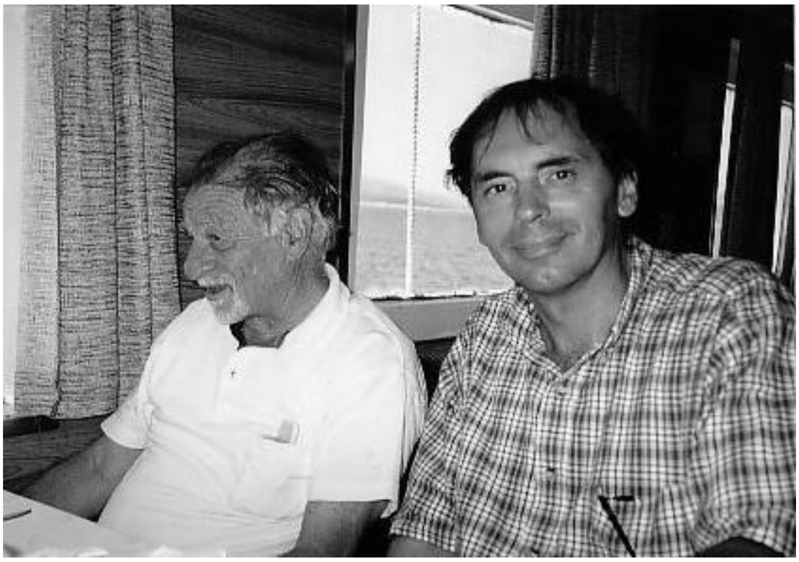

Figure 3. In June 2002, we were traveling from Switzerland to Dubrovnik [12], partly by boat from Ancona. On the ferry boat, Alex invited me and my jazz band 'Tsha-Coo' to dinner.

Figure 4. On our way back from the very first Cavtat conference [12], Alex drove me in his beloved Jaguar, and again we had very lively, friendly discussions and a lot of fun together.

Figure 5. Cheering at Alex's birthday party (on 20 April 2006) in Los Alamos, home of the Conradson family. From right to left: Hugo Keller, Ivan and Natasa Bozovic, Alex, Steve Conradson with his son and wife, Takeshi Egami, and myself.

We were privileged to share many events, brilliant discussions, and always a special ambiance by an active presence of a highly original visionary spirit and profoundly human, warm personality of a truly great scientist, Karl Alex Müller (Figure 6).

Figure 6. Alex passionately describing the functionality–structure correlation in layered quasi-two-dimensional quantum materials.

Conflicts of Interest: The author declares no conflict of interest.

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