Biography of Professor Ke Hsin Kuo

Kehsin Kuo was born on August 23, 1923 in Beijing, China. His father was trained a civil engineer in Tongji University in Shanghai, a small German university. The university had only two departments, which later became two big famous universities in China. This was a family of engineers. Under his father's influence, Kehsin, the fourth child, and his four brothers all majored in engineering: metallurgy, civil engineering, mechanical engineering, chemical engineering, and ship building.

Kehsin went to a primary school in Harbin when his father was then building a railway to transport soy beans, the most important export goods produced there, from Heilongjiang Province to the seaport Dalian. After Japan occupied Harbin and the whole Manchuria in 1931, the family moved to Chongching, but Kehsin and his three elder brothers went to boarding schools in Beijing and Tianjin because of the good reputation the middle schools there. Kehsin went to the famous Nankai Middle School in Tianjin, known not only for its high education standard but also for sports and various cultural activities. Former Chinese Premier Zhou Enlai went to the same school earlier. Back then he was known not only for his revolutionary activities but also for the actress role he acted in various modern plays. However, this quiet school life did not last long when Japan invaded the rest of China again on July 7, 1937 and occupied Tianjin on July 28. Kehsin and his elder brothers fled for the second time from the Japanese occupation to Chongqing, the war capital of China, and he resumed his middle school life in the Chongqing Nankai Middle School. Though Chongqing was far from the battlefront and lies behind the high mountains like the Three Gorges of the Yangtze River, there still was no peace in Chongqing and half of the downtown was burnt down in a great fire caused by a 48 hours nonstop bombing of Japanese planes during May 3-4, 1939. This was followed by numerous night-raids during the whole summer (heavy fogs prevail in autumn and winter) and Kehsin and his schoolmates had to sleep in the open air if they did not like to go into the man-made caves in the neighboring hills. However, teaching and studying never stopped. Nevertheless, even Nankai Middle School, located in the suburb, was not exempted from such air raids. In an August night more than a dozen of bombs fell on the campus and one of the bombs exploded only about 30 meters from where Kehsin lied. Though he was fortunately survived from this accident, a permanent scar of the size of a five-cent coin was left on his back owing to the burning caused by the red-heat soil fell there. Because of the constant air raids, a special regulation was formulated. If the air raid came after one half of the examination period, this test would be accepted, otherwise a new one were to be arranged. In summer 1941, Kehsin completed his secondary school study amid constant and fierce Japanese air raids.

Kehsin liked very much chemistry and decided to study chemical engineering in Chekiang University. During the Sino-Japan War, this university moved from Hangzhou, a beautiful sightseeing place known as "a paradise on the Earth" to the countryside of Zunyi, a small city in the mountainous hinterland in the southwestern part of China. There was no electricity supply but the best Chinese liquor, Maotai. It was not uncommon that a professor drank Maotai together with his students after a lecture under a willow tree along the bank of the curling May River. No wonder Dr. Joseph Needham, when he visited it in 1943, was very much charmed with this and called this university "Cambridge in the East". Kehsin enjoyed the free learning in this university and read comprehensively, from the 19^{th} century Western novels to current advances in technical journals. But in December 1944, Kehsin's fourth year in college, a few thousand Japanese cavalries invaded Guizhou Province from the south. This was the third time Kehsin faced a Japanese invasion. But this time, unlike the previous two, he joined, together with about two hundred fellow students, the Youth Army with the intention to fight the Japanese. After the collapse of the Nazis in the spring of 1945, thousands of American officers came to China to train and arm the Chinese Army and an equal number of interpreters were badly needed. Kehsin voluntarily joined the Interpreter Pool in June 1945, but soon the Japanese surrendered. Kehsin went back to Chekiang University to resume his last year study and graduated in June 1946 at an age of 23. Obviously, Kehsin spent his youth in a very humiliating and frustrating environment and this fostered a strong patriotic sentiment in him. He longed for to be a capable engineer and to contribute something in converting China to an industrialized country.

With such an intention Kehsin attended a nationwide competitive examination in September 1946 and won a government scholarship to study metallurgy in Sweden, known for the manufacturing of high quality alloy steels. After a one-month long sea journey Kehsin embarked at Naples in Italy and finally arrived at Stockholm in September 1947. In Sweden there was only one Department of Metallurgy, located in the Royal Institute of Technology in Stockholm. Professor Axel Hultgren, head of the Laboratory of Metallography, was known for his study of the macroscopic structure of segregation and gas holes in ingots as well as the study of the isothermal transformation of austenite in alloy steels. Thanks to these works, he was elected an Honorable Member of the American Society of Metals, a rather coveted honor limited then to only a handful of metallurgists. Kehsin joined his study of the effect of alloy elements on the isothermal transformation of austenite and learnt the orthodox metallography from Professor Hultgren, who in turn learnt it from Professor Hannemann in the Technical University of Berlin. Kehsin's main interest was gradually focused, on the one hand, on the partition of alloy elements between cementite and ferrite during this transformation [3,4], and on the other hand, on the formation of alloy carbides in high alloy steels [2, 8-10]. For this purpose, Kehsin studied X-ray crystallography first by himself and in 1950 he moved completely to the X-ray Crystallography Laboratory in the Institute of Inorganic Chemistry, Uppsala University.

Professor Gunnar Hägg was the inventor of the Hägg's Rule of the interstitial compounds and was a great crystallographer. He was elected the Vice President of the International Union of Crystallography in 1952. He established a rather liberal research environment, which draw a number of excellent scientists in his laboratory. Moreover, Uppsala is a university town with a long academic tradition. Kehsin enjoyed very much his stay there during 1950-1952 and produced several interesting papers. (1) Kehsin solved for the first time a crystal structure by X-ray diffraction, though it was rather simple with only 8 atoms in a unit cell. When he finally succeeded in obtaining the corrected crystal structure after a long working night, he was so excited that he could not fall asleep in the following day. Professor Hägg said to Kehsin: "This is only a small piece of work and does not merit to write a full paper. We might just submit it to *Nature* as a Letter to the Editor". Thus, "A new molybdenum carbide" was published in *Nature* in 1952 [1] and it was Kehsin's first publication in his research career. (2) Kehsin studied systematically "Carbides in chromium, molybdenum and tungsten steels" [8] and this paper was published in 1953. It has been cited no less than 20 times during 1991-2000, *i.e.*, about 40 years after its publication. This paper was almost completely reproduced in E. Houdremont's *Handbuch der Sonderstahlkunde*. Based on this study, Kehsin showed that the carbide precipitated that caused the secondary hardening in high-speed steels was the hexagonal W_2C, but not the generally accepted "high-speed steel carbide" Fe_3W_3C [2,9]. (3) Kehsin published 3 paper/letters in 1953 in the newly found *Acta Metallurgica*. Two of them concerned the η-A_3B_3C and η-A_4B_2C carbides [6,7], in which A is Nb, Ta, Mo, as well as W and B is Cr, Mn, Fe, Co, as well as Ni. It is of interest to note that the A atoms are generally located at the center of icosahedron, such as in $(Ta,Ti)_4Ni_2C$ [7]. This might be considered the precursor of the Ti_2Ni icosahedral quasicrystal [47] Kehsin *et al*. found 32 years later. The third paper concerned "Ternary Laves and sigma phases of transition metals" [8] originated from a study of these phases in heat-resistant alloys, later called superalloys. These two phases are, respectively, the pentagonal and hexagonal Frank-Kasper or tetrahedrally close-packed phases consisting of pentagonal and hexagonal antiprisms, respectively. Now they are known, respectively, as the crystalline approximants of the icosahedral quasicrystal. In the meantime Kehsin found a new constituent with the structure of consisting of tetragonal antiprisms in a burnt tungsten steel [17]. Later the tetragonal β-Mn was found to be the crystalline approximant of the octagonal quasicrystal. These studies helped Kehsin greatly in his later search of quasicrystals.

Kehsin returned to Stockholm in 1953 to resume the study of "Metallography of delta-ferrite" [11-15]. In the meantime he investigated "Alloy carbide precipitated during the fourth stage of tempering" [16] using an RCA electron microscope. He used the extraction replica to study the VC and Mo_2C carbide particles of nanometer size in tempered steels and proved that the precipitation of these fine carbide particles was responsible for the secondary hardening of V and Mo steels. This was an earlier use of electron microscopy to clarify the ultra-fine structures in alloys, which opened a new front for Kehsin in his later research work.

In November 1955 Kehsin went to Holland to work with Professor W.G. Burgers in the Department of Physical Chemistry, Royal Institute of Technology in Delft, on the transformation of white tin to gray tin by the Laue method [18]. One day in the end of March 1956, Kehsin read a recent speech of Premier Zhou Enlai on "Marching toward Science". He decided immediately to return to China to take part in this great movement. In July 1956 he joined the Institute of Metal Research, Chinese Academy of Sciences, in Shenyang.

Kehsin started with training graduate students using C.S. Barrett's "Structure of Metals". However, this endeavor was forced to stop when the Anti-Rightists Movement started in spring 1957, followed by the Great Leap Forward Movement in 1958-1961. Research resumed in 1962 and Kehsin's group began to study the short-range order in solid solutions, stacking faults in crystals, thermal diffuse scattering, *etc*. Nor did this last long enough to produce any noticeable progress since the precursor of the Great Cultural Revolution started already in 1965. This turned the country to a terrible disaster for all cultural activities in China; schools closed, research stopped, only a handful of "revolutionary" films and plays were on the show, *etc*. This nightmare came to an end only in October 1976, but it took another 3 or 4 years to convert chaos to order. When Kehsin visited Stockholm in 1980, his Swedish colleagues asked him: "Do you regret of your decision to return to China in 1956 when you were on the height of a flourish research career and since then nothing of importance has been made in the past 25 years?" Kehsin replied resolutely: "No, I have suffered together with my people and my country. A loss of 25 years is something terrible for an individual, but it is not much for a country with a long history of five thousands years as long as we can learn a lesson from it and find the right course to build a modern China."

After being away from the research scene for a quarter of a century owing to the successive political movements, Kehsin started to do research in 1983 at an age of 60. First he and his coworkers and students used an electron microscope to probe various frontiers of materials science, ranging from metals and alloys [29-32,39-48,54-60], amorphous materials [36,49], semiconductors [51,52], oxides [33,37,38], catalysts [35,61,69], ceramics [28], minerals [53,118], to organic compounds [81]. After the finding of a fivefold electron diffraction pattern in pentagonal Frank-Kasper phases [39-42] and shortly after the Ti_2Ni icosahedral quasicrystal [47], Kehsin's research gradually focused on quasicrystals. In the following years, he and his coworkers and students found successively the first octagonal quasicrystal [73,87,106], the first stable decagonal quasicrystal [108,109,130], the first cubic quasicrystal [147] and the first one-dimensional quasicrystal [93,135].

During Kehsin's sojourn in Europe during 1947-1956, he acquired enough knowledge in alloy chemistry, crystallography, and electron microscopy to become an independent researcher in materials science. Moreover, his knowledge of the β-Mn, $(Ta,Ti)_4Ni_2C$, Laves and sigma phases, as described above, was of vital importance in his study of quasicrystals. However, circumstance was also important. There was a jet-engine plant located quite close to the Institute of Metal Research and collaboration between them has a long history. In order to increase the high temperature strength of superalloys, Ti, Mo, and sometimes Nb have to be added and they invariably promote the formation of Sigma, Laves and related phases, which are notorious in causing embrittlement of these alloys. The icosahedral column or pentagonal antiprism serves as channels for incident electrons and therefore appears as a bright image point in the HREM image. By examining such images, domains of a few nanometers in size and of $n\times72^{o}$ rotations were observed [39-41]. Accompanying with these pentagonal domains, a fivefold distribution of electron diffraction spots always exists. In order to understand this, the Fourier transform of a single icosahedron was calculated and it turned out that this Fourier transform looked exactly analogous to the fivefold electron diffraction pattern. Fivefold rotation is incompatible with periodic translation and hence fivefold symmetry is generally called non-crystallographic symmetry or even forbidden symmetry in classical crystallography. A paper entitled "Fivefold symmetry in real and reciprocal spaces" [42] was published in *Ultramicroscopy*, in which a parallel arrangement of icosahedra in the micro domains of various Frank-Kasper phases was attributed to be the origin of this.

In order to probe this abnormal phenomenon in great depth, trials were made with the intention to obtain alloys consisting solely of individual icosahedra by very rapid solidification. Ti_2Ni and ZrNi were selected for this study because it was known that normal crystallization in them could be suppressed by very rapid solidification. Both gave fivefold electron diffraction patterns, but their high-resolution electron microscopy (HREM) images looked quite different. In the case of ZrNi, the image points formed 5 patches of two-dimensional periodic lattices whose orientations differed by n×72°. This was no doubt a group of five/ten differently oriented crystals or fivefold/tenfold twins. On the other hand, the image points in Ti_2Ni showed a quasiperiodic arrangement in good agreement with the celebrated Penrose pattern. It was an icosahedral quasicrystal analogous to the new Al-Mn phase discovered somewhat earlier by Shechtman *et al.* Thus, Kehsin and his coworkers knew right in the beginning that quasicrystals were not fivefold twins as Linus Pauling suggested. In 1985 two Letters appeared side by side in *Philosophical Magazine A* with the titles "A new icosahedral phase with m35 symmetry" [48] and "Tenfold twins in a rapidly quenched ZrNi alloy" [49]. The title of an invited lecture given by Kehsin at the International Congress of Electron Microscopy held in Kyoto (1986) was "Quasicrystals or multiple twins?" [68].

In March 1986, Kehsin attended the first International Conference on Quasicrystals in Les Houches, France, and the title of his talk was "From Frank-Kasper phases to the icosahedral quasicrystal" [64]. Based on this reasoning, Kehsin *et al*. found the icosahedral quasicrystal with the composition of Mn_3Ni_2Si, which would crystallize to a Laves phase (a pentagonal Frank-Kasper phase) on slow solidification [66]. A European scientist said to Kehsin: "From your systematic study of the pentagonal Frank-Kasper phases, it was no surprise that you will sooner or later encounter the icosahedral quasicrystal".

Once the fallacy that a crystal has to be periodic was proven wrong, quasicrystals with other symmetry than the three-dimensional icosahedral symmetry were to be found. In fact, the two-dimensional decagonal quasicrystal with a periodic tenfold rotational axis normal to a quasiperiodic plane and the two-dimensional dodecagonal quasicrystal with a periodic twelvefold rotational axis normal to a quasiperiodic plane were both found in 1985. Similarly, Kehsin *et al*. found in 1987 the first two-dimensional octagonal quasicrystal with a periodic eightfold rotational axis normal to a quasiperiodic plane [73,99]. In the same year, Kehsin *et al*. found a three-dimensional modulated structure with cubic symmetry [75], which was in fact a quasicrystal of cubic symmetry [147]. Thus it was experimentally proven that a quasicrystal could have either conventional or non-conventional symmetry. In other words, the essence of a quasicrystal is not its symmetry but its quasiperiodicity. Like in crystals, atoms in quasicrystals also have translation order (fixed positions); unlike in crystals, the atomic arrangements are not periodic.

The co-existence of an octagonal quasicrystal with a crystalline phase of the β-Mn structure [73,87,106,126,127], both consisting of the same tetragonal antiprisms, shows, like the pentagonal antiprisms in icosahedral quasicrystal and the pentagonal Frank-Kasper phases, once more the structural relation between a quasicrystal and its crystalline approximant. They have similar structural subunits, thus also similar composition, but these subunits are differently arranged, periodic in crystals and quasiperiodic in quasicrystals. This concept was enlarged in an invited talk on "Quasicrystalline and related crystalline structures" [76] by Kehsin in the International Conference of Crystallography in Perth (Australia) in 1987. In the same year Kehsin presented a paper entitled "Some new icosahedral and decagonal quasicrystals"[86] in the Second International Conference of Quasicrystal held in Beijing.

Several stable icosahedral quasicrystals existed, but no stable decagonal quasicrystal was known until Kehsin *et al.* found one in a slowly solidified $Al_{65}Cu_{20}Co_{15}$ alloy in 1988

[108,109]. Needle-like single crystals of a few mm in length have been obtained [130], thus it became possible to determine its crystal structure by X-ray diffraction and to measure its transport property of this decagonal quasicrystal. Thus, Dr. W. Steurer and Kehsin made the first five-dimensional structural analysis of a stable decagonal quasicrystal [143,144] and Kehsin and his students found anisotropy in electric and thermal conductivity, increasing in the periodic tenfold direction and decreasing in a quasiperiodic direction with increasing temperature [137,138,148]. Thanks to collaboration between experts in these two fields, the scope of quasicrystal research has been broadened.

In 1988 Kehsin and his students found the first one-dimensional quasicrystal with a quasiperiodic stacking of two-dimensional periodic planes [93] and this was the missing link between a two-dimensional quasicrystal and a crystal. The phase transformation of a decagonal quasicrystal into a one-dimensional quasicrystal [135] and further into a crystalline phase [136] has been studied by introducing increasing number of phasons, tiling mistakes causing a phase change of the material wave, into a decagonal quasicrystal. Phasons in an octagonal [188] and a decagonal [182] quasicrystal have been measured quantitatively for the first time by means of HREM. Kehsin was invited to give a Plenary Lecture at the 13th International Conference of Crystallography held in Beijing in1993 and the title was "decagonal quasicrystal and crystalline approximants" [180].

Kehsin and his coworkers have published 257 papers in international journals of which 153 deal with quasicrystals and crystalline approximants. ISI (Institute for Scientific Information) selected 57 papers published by researchers in China during 1981-1998 as High Impact Papers in 1999 and Kehsin has contributed three to this list. Over the years, Kehsin has trained 124 graduate students, many of them now hold academic positions in China or in the West.