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Historical Article

Professor Shin Sato, a Physical Chemist and Teacher for 50 Years

Yona Siderer

Edelstein Center for the History and Philosophy of Science, Technology and Medicine, The Hebrew University of Jerusalem, Israel
E-mail: sideryon@netvision.net.il

Abstract. This article presents a portrait of the scientific work of the Japanese physical chemist Shin Sato[1] (1928-2022) at Tokyo Institute of Technology from the mid-1950s until 2019. His work included studies in both photochemistry and radiation chemistry with a special emphasis on small molecules, attention given to analogies with the behavior of small molecules under atmospheric condition. Noteworthy is his contribution to a new intuitive semi-empirical method of drawing the Potential Energy Surface of the collisions between an atom and a diatomic molecule, now known as the LEPS Method. He published more on the following: photosensitization reactions of mercury, cadmium, zinc and benzene; insertion of NH radical into the C-H bond of carboxylic acid to form amino acids; the isotope effects of deuterium on the reaction of the hydrogen atom with the hydrogen molecule; ESR studies and calculations of tunneling in bimolecular reactions; developing temperature dependent rate formula for the reactions at temperatures lower than 10 K, lower than the Arrhenius equation that is applicable to temperatures higher than room temperature. Sato published a textbook on quantum chemistry, co-authored a book on photochemistry and radiation chemistry and translated from English two chemistry books. As a teacher he supervised about one hundred students in his laboratories. By his research and teaching he became a bridge between the Eastern and Western scientific and cultural worlds. He had a major impact on intercultural dialogue.

Keywords: Shin Sato, physical chemistry, LEPS method, photochemistry, radiation chemistry, Tokyo Institute of Technology.

INTRODUCTION

During 1972-1973 the author, a recent graduate from the chemistry department, The Hebrew University of Jerusalem, held a UNESCO and Japanese government fellowship in chemistry and chemical engineering course. I arrived at the Tokyo Institute of Technology (T.I.T.) in Tokyo with twelve other UNESCO fellows. Following introductory conversations with several professors, Shin Sato was chosen to be the mentor for my research in his laboratory. This article is based upon our many years of correspondence, meetings during visits to Japan and T.I.T., and his assistance with my recent research about the history of chemistry in Japan. There are contributions from George C. Schatz, Toshiyuki Takayanagi, and Kazutaka Nakamura all of whom collaborated with Sato. The main aim here is to describe the physical chemistry research of Shin Sato, and the recognition which he received.

The paper consists of two sections:

The first section covers "Shin Sato's Biography and Scientific Career."

The second section is somewhat personal in that it discusses how "Sato Followed my Career, and my Literary Writing, and Mentored my Japanese Studies." Sato followed my progress in other scientific directions. I returned to the T.I.T. Japan (2008) and to the International Research Center for Japanese Studies in Kyoto (2009-2010), in order to study the history of chemistry, and Sato graciously helped me in research, the language, and the culture and history of Japan. I emphasize the importance and extracurricular benefits of students' exchange programs, and research grants to visit foreign countries.

1. SHIN SATO'S BIOGRAPHY AND SCIENTIFIC CAREER

Sato's Biography

Shin Sato was born in Yokohama in 1928 (his birth year is 辰 *tatsu*, dragon in the Japanese calendar). He was the second son of four siblings: an elder brother, a younger brother, and a younger sister. In 1954 he married a childhood friend who was a pianist. He had two daughters. His elder daughter became a musician and his younger daughter studied physics and worked for an electronics company.[2]

Sato's Professional Curriculum Vitae

Shin Sato's academic career was mainly at the Tokyo Institute of Technology in Tokyo: He graduated in 1951; was Assistant professor, Department of Chemistry, 1956 -1960. He was appointed Doctor of Engineering (D.Sc.) in 1960; Associate professor, Department of Chemistry, 1961-1963; Associate professor, Department of Applied Physics, 1964-1981; Professor, Research Laboratory Nuclear Reactors, 1981-1988.

In according with the regulations of the governing body of academic institutes, at age 60 years, in April 1989 he retired from T.I.T. to become professor emeritus at T.I.T. He then became a professor at the College of Arts and Science, Chiba University 1988-1993. He then taught chemistry at a private university.

Figure 1. Shin Sato's photo taken by M. Kaji, at K. Shibuya's house, 2008.

Sato spent two periods out of Japan: as a postdoc fellow, 1956 Sep.-1958 Dec., and as a visiting scientist, 1965-1966., both at the National Research Council (NRC), in Ottawa, Canada.

In 1975, he received the Teshima Award, which was given to an instructor at T.I.T.

He served as President, of the Japan Society of Radiation Chemistry during 1987-1989.[3]

What was the scientific context in which Shin Sato developed his chemistry knowledge, worked at the T.I.T. and who was his teacher? Before presenting Sato's research, a short paragraph on Tokyo Institute of Technology is called for.

Tokyo Institute of Technology

Tokyo Institute of Technology (東京工業大学), *Tōkyō Kōgyō Daigaku* (now Tokyo Tech) is a national research university located in the Greater Tokyo Area. Tokyo Tech is an institute for higher education in Japan dedicated to science and technology, one of the first five Designated National University Corporation started in 2017: (Tokyo University of Tokyo (founded 1887); Kyoto University (1892); Tohoku University (1907); Nagoya University (1939) designated in 2018); Tokyo Institute of Technology (designated in 2018). It is one of the most prestigious universities in Japan. Since 1924, Tokyo Tech's main campus has been located at Ōokayama, on the boundary of Meguro and Ota, with its main entrance facing the Ōokayama railway station. Its history goes back to 1881 when the government of Japan founded a Vocational School, 13 years after the Meiji Restoration (1868). During the years it went through several changes of name and size; its name was changed to Tokyo Technical School in 1890, Tokyo Higher Technical School in 1901, and Tokyo Institute of Technology around 1946. Currently it has two other campuses.[4] The alumni of T.I.T. share a kindred brotherhood, especially when they happen to meet, even if they did not know each other before.

Physical Chemistry and Sato

Progress in Japanese chemistry and physical chemistry was outlined by Furukawa (2017) and Kikuchi and Siderer (2021). In the case of Shin Sato, he followed in the footsteps of "Professor Shōji Shida (1912-2001), who graduated from Kyoto University, and arrived at the Laboratory of Physical Chemistry, Tokyo Institute of Technology in 1952. Shin Sato was one of Shida's students. They published several articles and a book together."[5] (Kikuchi and Siderer (2021)).

Sato's Main Fields of Research

In a letter by Sato to the author on 16 July 2017 he wrote:

> I am still alive, writing the history of my research work over 65 years.
> LEPS method, Reaction of oxygen atoms with olefins, Benzene photosensitized reaction, Theoretical calculation of G-values, Radiation chemical reactions in liquid carbon dioxide and in liquid nitrogen, Empirical rate formula for low temperature reactions and ion-molecule reactions, and so on.

The following is Sato's summary, an adapted translation into English by Kazutaka Nakamura, his former student. It includes the relevant article numbers from Sato's list of publications (Appen.1.), including some of his, and others' comments on his articles.

> Sato: "If we divide the world of physical chemistry into three fields: structure, physical properties, and reaction, the field I have been involved in belongs to the reaction category."

After becoming a special research student, Sato participated in research on "recombination reactions of hydrogen atoms on metal surfaces," which is the basis of solid catalytic reactions. Therefore, his study was exclusively on reaction kinetics. He read books such as "The Theory of Rate Processes" by H. Eyring. Sato wrote:

> At that time, I proposed a new method for drawing potential energy surface, now known as the LEPS (London-Eyring-Polanyi-Sato) method. It was widely used in the kinetics and dynamics of chemical reactions and still often appears in papers. In the 38 years since then, there are more than 200 articles including books and commentaries, but not one paper has been cited by overseas researchers to the same extent as this letter.[6]

Sato published his first letter to the editor of the International *Journal of Chemical Physics* "On a New Method of Drawing the Potential Energy Surface" in March 1955 (received December 1954). He extended that letter into "A New Method of Drawing the Potential Energy Surface" in the *Bulletin of the Chemical Society of Japan*, in Sept. 1955. His third letter on this topic was published in the *Journal of Chemical Physics* in December of the same year.

In those letters he addressed the Energy Potential curve that was started by Morse, writing a semi-empirical equation for the anti-bonding energy for a reaction of molecule-atom collision, for which, he wrote, there was not an approximation function. "For the potential energy of the system of three atoms London derived an equation which has been used by Eyring *et al.*" Sato made some slightly different assumptions and derived a new equation for energy. He calculated and showed a figure of the Potential Energy Surface of H_3. The result obtained differs essentially from Eyring's one which has two saddle points and one basin; Sato's result coincided with that of a nonempirical calculation. (Glasstone et al. (1941) and Ref. 3 therein: Hirschfelder, (1937)).

In the introduction to the second letter Sato explained the need for an approximate function for the anti-bonding states of two atoms:

> When two atoms approach each other, there appear two energy states generally: the one is bonding and the other anti-bonding. The potential energy for the bonding state can be obtained experimentally as a function of the distance between two atoms. As is well known, the curves for many diatomic molecules are conveniently approximated by the Morse function (P.M. Morse, (1929)). For the anti-bonding state, however the curve cannot be obtained experimentally and the function is not yet proposed. The present author researched the function and found that the equation [of a modified Morse equation] is in good agree-

> ment with results previously calculated by other authors (Appen.1. no. 4 (1955), Refs. 3 and 4 therein: H.M. James (1937) and J. O. Hirschfelder (1950)) The applicability of that function for the anti-bonding states of other diatomic molecules cannot be ascertained because of no existing data…." (Appen.1. no. 4 (1955)).

The third letter on this topic that dealt with "Potential Energy Surface of the System of Three Atom." Different reagents were used, e.g., H+HX→H_2+X, whereas X=H, Cl, Br, I, and F+H_2 →HF+H). Sato showed the validity of his semi-empirical equation in these cases (Appen.1. no. 5 (1955), Table 1).

Early Scientific Recognition of "A New Method of Drawing the Potential Energy Surface (1955) LEPS Method"

Sato's work on Potential Energy Surface of the System of Three Atoms (1955), led to the modified LEP term into LEPS (London-Eyring-Polanyi-Sato Method), (H. S. Johnston (1966)).

H. S. Johnston wrote:

> This equation is based purely on intuition… Thus Sato's potential-energy surface for H_3 is a complete potential-energy surface that appears to be qualitatively correct…
> …This Semiempirical method does not predict activation energy. Its evaluation of other properties of the saddle point will be compared with other methods in a later section, where it will be referred to as the LEPS (London-Polanyi-Eyring-Sato) method (Johnston (1966) p. 179).

The LEPS method and Modified LEPS method calculations were further studied and published by Sato's group in 1988 and 1990.[7]

Recollections of Shin Sato by George C. Schatz[8]

Schatz recalls:

> I was a graduate student at Caltech in the early 1970s, at a time when it first became possible to describe the dynamics of the simplest possible chemical reactions using computational methods to solve the Schrödinger equation for the motion of the nuclei. To do these studies it was necessary to have a potential energy surface (PES) that describes the forces between the nuclei while the reaction occurs. Potential surfaces were extremely difficult to determine in those days, but one way to do it was to solve the electronic Schrodinger equation using semiempirical theory, in which the complex parts of this equation were replaced by approximate functions that were based on a combination of physical intuition and guessing. It turns out that for reactions involving an atom colliding with a diatomic molecule, this was first done in the late 1920s and 1930s by the famous scientists London, Eyring and Polanyi, leading to a function called the LEP potential. However it was subsequently demonstrated that this function had unphysical features, so it wasn't useful for studying reactions. However in 1955, Shin Sato published a paper (J. Chem. Phys. 23, 592 (1955)) that modified the LEP expression in a way that fixed the most serious problems with LEP, leading to what was known as the LEPS potential surface. I used this function in some of my studies in the 1970s, and as a result I was aware of Shin Sato, but I never thought I would meet him.

Sato's Experience in Canada

In September 1956, Sato went to Canada to study at the National Research Council of Canada in Ottawa. At that time, his mentor was Prof. R. J. Cvetanović, who was forming oxygen atoms by photochemical methods and studying their reactions with olefins. Cvetanović was one of the leaders in photochemistry at that time and Sato was attracted to his line of work. Under his supervision, Sato photolysed NO_2 with ultraviolet light (high-pressure mercury lamp) to form oxygen atoms and investigated their reactions with various olefins.[9]

> Sato: "This was around the time that photochemical smog began to become a problem. Cvetanović's work on the reaction of oxygen atoms with hydrocarbons has now become a classic, but it is very famous in this field. Since that time, I had wanted to work on reactions involving nitrogen atoms."

Sato joined Cvetanović laboratory for a second time (1965-1966), when he worked on "Intersystem Crossing of the Electronically Excited Dideuteroethylene Molecules Formed in Benzene Photosensitization." This was collaboration between the research carried out at T.I.T. by Terumi Terao and Shun-ichi Hirokami of Sato's group, and the work he carried out in NRC Ottawa. (Appen.1. no. 29 (1966). In the introduction the authors explain:

> Electronically excited states of olefins are formed when olefin molecules absorb ultraviolet light either directly or from photosensitizers. The chemical behavior of the excited states depends both on the amount of energy transferred and on the nature of the sensitizer employed. With ethylene the following reactions are observed: (i) *cis-trans* isomerization (in the reaction of *cis-* and *trans*-1,2-dideuteroethylene), (ii) internal H-atom scrambling (formation of 1,1- from 1,2-dideterroethylene), (iii) molecular decomposition into H_2 and acetylene, and (iv) decomposition into H-atoms and vinyl radicals.
> Studies of these chemicals processes present an interesting opportunity to gain insight into the nature and behavior of the excited states involved.

A previous article by Cvetanović is referred to (Cvetanović 1964).They present the results of the benzene-photosensitized isomerization of dideuteroethylene at room temperature.

They showed experimental evidence for a rapidly occurring intersystem crossing of the electronically excited dideuteroethylene molecules initially formed in the benzene-photosensitized reaction at 2537 Å and 25°C to another excited state which is responsible for the internal H-atom scrambling. They concluded that the mechanism is entirely analogous to that previously postulated for the photoexcited states sensitized by $Hg(^3P_1)$ atoms but the rate constants for intersystem crossing and molecular decomposition are drastically decreased as a result of the smaller amount of energy available for the excitation (Appen.1 no. 29 (1966)).

Back In Japan

After returning to Japan in December 1959, Sato found that radiation chemistry had become the main research subject in Shida's laboratory at T.I.T. He participated in radiation chemistry research, starting with "Radiolysis of Cyclohexane." His Doctoral Dissertation (D.Sc.) was "Research on the reaction between oxygen atoms and olefins" Tokyo Institute of Technology Academic Bulletin, (1960) first issue; 酸素原子とオレフィンの反応の研究、東京工業大学学報、１９６０年　第一号。博士論文.

Sato summarized the effect of the change in Shida's lab to radiation chemistry and later observed: "Thus, after becoming an associate professor in January 1961 and running an independent laboratory, I was engaged in research in both the fields of photochemistry and radiation chemistry. My subsequent papers have been almost equally divided between photochemistry and radiation chemistry."

Photochemistry Research

Photosensitization reactions

In a series of articles Sato's groups studied the mechanism of photosensitization by mercury, cadmium, zinc and benzene, and the combination of the photoexcited state with molecules like water, alcohols, ethers, cyclohexane and others. This method allowed them to better understand the mechanism of energy charge transfer, life time of excited state of the intermediate that was formed between the photoexcited reactant and the molecule it collided with, the emission of light from the combined intermediate excited species and/or their dissociation.

A useful introduction to this area of work can be read in Calvert and Pitts *Photochemistry* (1966), on Sensitized Fluorescence.[10] Calvert and Pitts further explained and showed relevant results and suggested mechanisms for those results.[11]

In the following, examples from Sato's laboratory of photosensitization reactions and their mechanisms are summarized.

Mercury Photosensitized in Sato's laboratory

Photosensitization by mercury in Sato's laboratory was carried out between 1960 and 1978, starting with "Mercury Photosensitized Decomposition of Cyclohexane at High Temperatures".[12]

In the mercury photosensitization experiments in 1978, in addition to demonstration of charge transfer another phenomenon of the complex emission was studied in "Phase-Shift Studies of Mercury-Photosensitized Luminescence of Ammonia" (Appen. 1. no. 103 (1978)). For an introduction to phase-shift see Note 13. This article is summarized here:

In the introduction to a 1978 article by Sato and coauthors, they surveyed seven articles in this field dating 1970-1977 (Refs. there). The introduction is followed by a detailed experimental section on the instruments and measuring methods, as well as materials purity and their sources. Two emission lines were detected at 282 nm and 350 nm, attributed to two intermediate excited complexes of the excited mercury with ammonia, labeled $HgNH_3$† and $HgNH_3{}^*$, an unstabilized and a stabilized intermediate respectively. The phase-shift between the photosensitized luminescence of each of these spectral lines and the light emitted from the excited mercury atom were measured. Fig. 2 of the article presented phase difference between the 253.7 nm fluorescence from the excited complex at 282 nm and 350 nm as a function of the ammonia pressure. Solid lines show the values calculated according to equations (9) and (10) of the proposed reaction mechanism.

Cadmium Photosensitization

The reactions of Cd photosensitization, measuring the emission from the complex between the photoexcited triplet Cd with ammonia, amines, water, ethane, and ethylene, was studied. (Appen.1 no. 81 (1975))

This research was mainly conducted with Shigeru Tsunashima (later to become professor of the Department of Applied Physics, T.I.T.), and was completed around 1980 with about 20 papers published.[14]

Two examples follow:

1. Cadmium Photosensitization of Aliphatic Amines

In Shunzo Yamamoto and Sato's article, "The Quenching of the Cadmium Resonance Radiation at 326.1 nm by some Aliphatic Amines and the Cadmium-sensitized Luminescence of These Amines." (Appen. 1. no. 78 (1975)), they described their experiments and findings as outlined in the following:

> From the pressure dependence of the intensity of the 326.1 nm resonance line, [Table 1 there], the efficiencies of the quenching of the resonance line by methylamine, ethylamine, n-propylamine, n-butylamine, *sec*-butylamine, *tert*-butylamine, diethylamine and trimethylamine were estimated to be 14.2, 36.0, 58.6, 71.2, 116.7, 434.5, 69.6, and 66.0 respectively, the efficiency of ammonia being assumed to be unity [Fig. 3 there]. The relative values of rate constants for the formation of the excited complexes between the excited cadmium atoms and the amines, and the wavelengths at the peaks of the emission bands from the complexes, were measured [Tables 2 and 4 there]. The quantum yields of luminescence were also measured by comparing the integrated intensities of the emission bands with the decrease of the intensities of the resonance line at 326.1 nm upon the addition of amines. From the relationship between these values and the structure of the amines, it is concluded that the complexes are of the charge-transfer type.

In their discussion they present a reaction mechanism similar to the mechanism they showed before that explains their findings and interpretation. (Appen. 1. no. 77 (1975)). The mechanism involves cadmium excitation by light, its collision with argon or amines to give products, and in addition, the excited cadmium atom and amines collisions that form two excited intermediates, an unstabilized and a stabilized complex between the triplet cadmium and the amines. The evolving luminescence is emitted from the stabilized complex whereas the unstabilized complex does not fluoresce.

2. Cd Photosensitized Reactions of Water, Alcohols and Ethers

In a following article in the same year: "The Cadmium-photosensitized Reaction of Water, Alcohols and Ethers – The Quenching of the Resonance Radiation at 326.1 nm and the Photosensitized Luminescence" (Appen.1 no. 81 (1975)), after summarizing their previous two related articles, Sato and his co-authors stated:

> It now seems valuable to observe the similar luminescence in the cadmium-photosensitized reactions of water, alcohols and ether, to measure the rates of the quenching of the resonance radiation and of the formation of the complex, and to determine the effects of the structure of the alcohols and ethers on the quantum yields of the luminescence and the position of the emission band, in order to gain a further understanding of the cadmium-photosensitized luminescence.

They showed the emission band contours for H_2O, methanol and ethanol in Fig. 1, including NH_3 emission graph from their 1973 article (Appen.1. no. 68 (1973)). In Table 1 they present the wavelengths at the peak of the emission band and quantum yield of the luminescence. Table 4 shows the rate constants of the quenching of the resonance radiation and of the formation of the complex for Primary-, Secondary-, and Tertiary Amines. A mechanism similar to that described in previous papers (Appen. 1. no. 77 (1975) and Appen.1. no. 78 (1975)) is presented, followed by discussion of the rate constants of the various steps in the mechanism suggested. In a final statement they mention a factor that affects some of the results which is still an open question for them.

Benzene Photosensitization[15]

For benzene photosensitization article an example is given above in the section about Sato second visit to Canada.

Zinc Photosensitization[16]

The article on "The intramultiplet mixing of $Zn(4^3P_J)$ by collision with ^4He and ^3He" employed pulsed laser techniques. Several cross sections of the collisions between the zinc triplet and the helium isotopes were assumed and calculated (Appen. 1. no. 179 (1990)).

Photochemical Reactions Research Continued

Amines Formation[17]

In a series of articles by Sato's group including Shigeru Tsunashima, they showed the insertion of the NH radical into the C-H bond of olefins and C-H bond of carboxylic acids. NH radical was formed by the photolysis of hydrogen azide HN_3, and the insertion of the NH radical to the C-H bond of olefins producing amines: ethylamine from the ethane solution, propyl amine and isopropylamine from the propane solution, and isobutyl- and t-butylamine from the isobutane solution (Appen.1. no. 108 (1979), Appen.1. no.117, (1980)).

Amino Acid Formation

In a further study they conjectured that if the singlet NH inserts into the C-H bonds of hydrocarbons, the singlet NH will insert into the C-H of carboxylic acids to form amino acids. It was considered that the formation of amino acids on the primitive earth is an interesting problem in the study of prebiotic molecular evolution. Thus, they could further show by the photolysis of hydrogen azide, NH_3, in the relevant solutions, the insertions of NH radical into C-H bonds of carboxylic acids that produced amino acids: glycine was formed from acetic acid, α- and β-alanine formed in the case of propionic acid (Appen. 1. no. 120 (1981)) and isobutyric acid, α-and β-aminoisobutyric acids are formed, which correspond to the two types of the C-H bonds involved in the carboxylic acid. They suggested the chemical mechanism for these reactions, and showed that the quantum yield of amino acids increased with an increase in the number of C-H bonds in the reactant acid. They concluded that their study suggests a new possibility of the prebiotic synthesis of amino acids on the primordial earth (Appen. 1. No. 125 (1981)).

Discussion of the Photochemistry Reactions

In *Photochemistry* by Jack G. Calvert and James N. Pitt's textbook they explained and summarized the works in photochemistry since books dated more than twenty years earlier and emphasized: "During this period the primary literature of photochemistry has progressed at a phenomenal rate." (Calvert (1966) Preface, p. vii).

Describing the content of the book, its authors wrote: "In chapter 2 the reactions of the electronically excited atoms, conceptually the simplest of the photochemical systems, are studied. In chapter 3 the photochemistry of simple molecules and in Chapters 4 and 5 the photochemistry of more complexed molecules are covered." They cited several of S. Sato articles in chapters 2 and 3.[18-20] (Calvert (1966)).

Specific discussion in a photosensitized article was presented in 1971, in an article on "Photosensitization by Cd($^3P_1$) atoms. II. Gas Phase Decomposition of Cyclohexane" by B. L. Kalra and A. R. Knight, in which they discussed Sato's group articles on mercury and cadmium photosensitization. (Appen. 1. no. 16, and Appen.1, no. 35) (B. L. Kalra and A. R. Knight, (1972)).

Radiation Chemistry Research

The Cobalt-60 source for γ-rays radiation that was used in the chemical experiments stood in the basement of the radiation laboratory building. Sato's office, the vacuum systems laboratory and measuring instruments were on the second floor.

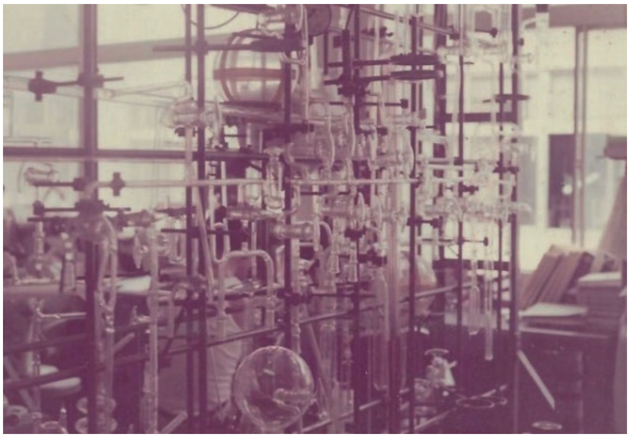

Figure 2. The vacuum system in Sato's radiation chemistry laboratory: Used by the author in 1972-73.

In the study of radiation chemistry, efforts were made to clarify the initial process of radiation chemical reactions, focusing on the γ-ray decomposition of cyclohexane.[21] Among these experiments, the study of the formation mechanism of N_2 by adding N_2O to cyclohexane and showing that electrons play a role in the initial process attracted considerable attention. Sato commented: "It is not surprising in hindsight, but in the late 1960s it was not believed that electrons could be observed as a manifest [of] chemical reaction in the radiolysis of hydrocarbons." In July 1974 Sato went to Seattle, to attend the 5th International Congress of Radiation Research and presented a paper on the reaction of CO_2.

Theoretical Calculation Method of G-values[22]

In the field of radiation chemistry Sato developed the "theoretical calculation method of G-values" with Dr. Shinichi Ohno of JAERI (Japan Atomic Energy Research Institute) and Dr. Kiyoshi Okazaki (Appen. 1. no. 73 (1974)). The study of the G-value of other reactions were further studied[23] which attracted attention from abroad. For this research Sato received The Seiichi Teshima Memorial Research Award that is designed to encourage research at the National University Corporation's Tokyo Institute of Technology, and is awarded to individuals who have achieved particularly outstanding research and writing.

This work continued, by comparing theoretical and experimental results. Sato later added: "The theoretical calculations were done by Mr. Okazaki's calculation of the G-value, and Mr. Takayanagi's trajectory calculation and my long-standing thought have come to fruition."

Sato observed in retrospect: "The next 10 years [1970s] will be the most productive time for me. The lab was poor, but the ideas were plentiful." Another frank, revealing statement that he wrote: "Experimentation is creation every day. I strengthened my imagination so as not to lose to the creativity of the students." [24]

In the 1970s, Sato's laboratory began to receive research grants and modernized its measuring instruments. The first of these is the Febetron 706 electron accelerator (pulse width: 3 nanoseconds, current: 6000A), which, in combination with a vacuum ultraviolet spectrometer, makes it possible to measure "elementary reactions involving atoms" in real time. As a result, they were able to study the reaction of hydrogen atoms, the isotope effects of H and D, the reaction of oxygen atoms, and the reaction of nitrogen atoms. Sato added: "I had been thinking about [those] for a long time. Nitrogen atoms are difficult to generate photo chemically and have not yet been fully investigated.

Around this time, Dr. Tsunashima and Dr. Hironobu Umemoto (a research associate in the Department of Applied Physics at that time) developed a method to apply the phase-shift method to photochemical reactions, making it possible to directly measure rate constants in photochemical reactions.[25]

Electron Spin Resonance (ESR) Research

Still in the 1970s, Sato was able to receive another Grant-in-Aid for Scientific Research, which enabled him to purchase an Electron Spin Resonance (ESR) absorption spectrometer and at the same time to set up research facilities at low temperatures such as liquid helium. Several works using ESR were published.[26] Thus, they were able to measure the tunneling effect that appears in the reaction of hydrogen atoms, which Sato wrote that he had dreamed of 30 years earlier, and that the tunneling effect is far greater than usually believed.

ESR Studies Discussed by K. Nakamura[27]

> In Sato's lab, both the photochemistry and radiation chemistry were studied at low temperatures using ESR. The structure of cation radicals, which are produced by radiolysis with Cobalt-60 γ-rays radiation in Freons and SF_6 matrices, has been studied at 77 K (Appen.1. no. 135 (1983), no. 142 (1985), no. 145 (1985), and no. 146 (1986)). In photochemistry, bimolecular reaction of H-atom with simple molecule such as SiH_4 has been studied in a rare-gas matrix at very low temperatures between 4.2 and 100 K. Structures of SiH_5 were found to be an intermediate with two conformers during the hydrogen abstraction reaction ($H+SiH_4 \rightarrow H_2 + SiH_3$). (Appen.1. no. 144 (1985)).[27]

G.C. Schatz's letter of 22.12.2023 continues:

> In 1985, I spent two months in Japan as a result of being granted a travel award from the Japan Society for Promotion of Science (JSPS). By then I was at Northwestern University, and my primary reason for visiting was to interact with a former office mate of mine (when I was a postdoc at MIT), Kazuo Kitahara. As a result I spent some time at Tokyo Institute of Technology, where Sato was located his entire career. It was during this time that I met Sato, who was actively involved in radiolysis studies in which radiation was used to produce deuterium atoms in matrices of solid H_2 at temperatures of 2-5K. This leads to the reaction $D + H_2 \rightarrow HD + H$, which is slightly downhill in energy due to the difference in zero point energy between H_2 and HD, and therefore has a measurable rate using electron paramagnetic resonance spectroscopy. Sato's research group had measured this rate, and was trying to interpret the results using transition state theory. By then my research had led to the determination of highly accurate rate coefficients (better than transition state theory) for $D + H_2$ and other reactions, including results at the very low temperatures that Sato was interested in, so I was able to help Sato to improve his modeling, leading to an accurate comparison of Sato's experimental results with first principles theory. The good agreement obtained suggested that even though the Sato experiments were done in a low temperature matrix, one could understand the rate based on assuming the rate was governed by a collision between D and H_2 without interacting with anything else. Moreover we were able to show that the resulting rate coefficient was largely governed by the "Wigner threshold law" of quantum mechanics, which refers to collisions that take place in the very low temperature limit (Appen. 1. no. 156 (1987)).

Quantum mechanical tunneling for the $H + H_2 \rightarrow H_2 + H$ reaction and its isotopic analogues in solid hydrogen.

Toshiyuki Takayanagi's memories follow: [28]

> My research career with Sato started in 1985. Sato was an experimentalist in physical chemistry field, but he was very familiar with theoretical chemistry. When I joined his research group, he was very interested in the experimental study performed by Prof. Tetsuo Miyazaki at Nagoya University, who found that the $D + H_2 \rightarrow HD + H$ reaction occurred in solid hydrogen at timescale from several minutes to hours at very low temperatures around $T = 4$ K. Notice that this reaction is an isotopic analogue of the $H + H_2 \rightarrow H_2 + H$ hydrogen exchange reaction, which is also

> the simplest chemical reaction consisting of only three atoms. Accurate ab initio molecular orbital calculations have already shown that the reaction barrier of this reaction was around 10 kcal/mol. This suggests that quantum mechanical tunneling should be playing an important role in order to explain the experimental result in solid hydrogen performed by Miyazaki's group. This is a primary hypothesis made by Sato. So the next project is to calculate the thermal rate coefficients for the $H + H_2 \rightarrow H_2 + H$ and its isotopic analogs at very low temperatures as accurate as possible and then to compare to the solid state experimental results performed by Prof . Miyazaki. These theoretical calculations were a part of my PhD thesis.
>
> Accurate calculations of thermal rate coefficients for the $H + H_2 \rightarrow H_2 + H$ and its isotopic analogs in the gas phase have long been very important subjects in the theoretical chemistry field. Fortunately, very accurate ab initio electronic structure calculations of the full-dimensional potential energy surfaces have been already done. Using the developed potential energy surface, quantum reactive scattering theory has been applied to calculate accurate reactive cross sections as well as thermal rate coefficients. George C Schatz and Aron Kuppermann have developed a sophisticated theory to perform accurate multi-dimensional quantum reactive scattering calculations for the first time. In 1987, Prof. Schatz was temporarily staying at Tokyo Tech for three months and Schatz and Sato have started a collaboration work on the calculations of rate coefficients for the $H + H_2 \rightarrow H_2 + H$ and its isotopic analogs at very low temperatures.
>
> Needless to say, it is a very daring conjecture that the gas phase chemical reaction rate theory is applied to the solid state reaction. However, Sato believed that the gas phase theory could be approximately applied since the molecular density is not so large in solid hydrogen. In an early stage of the computational work, a simple transition state theory including sophisticated multi-dimensional tunneling correction was used to calculate the rate coefficients at low temperatures. Later, multi-dimensional quantum reactive scattering theory was applied. Through a series of those theoretical projects, we succeeded in explaining the experimental findings by Prof. Miyazaki; i. e., it was definitely established that quantum mechanical tunneling was playing an important role for the $H + H_2 \rightarrow H_2 + H$ and its isotopic analogs at very low temperatures (Appen.1. no. 170 (1989), Appen.1. no. 173 (1989), Appen.1. no. 176 (1990)).

On 27 January 1987 Sato wrote to the author: A week ago, I was very busy because I organized a small seminar for the reaction kinetics. Nearly 50 people (all Japanese) joined the meeting and discussed for three days. I believe that the meeting was fruitful.

It is interesting that, apparently, he appears not to have discussed the relations between photochemistry and radiation chemistry despite his research on small molecules in both cases.

Sato Theoretical Work

During his last twenty year, Sato has been working on theoretical calculations. He wrote: "I would like to continue my research mainly on theoretical calculations in the future."

After his retirement during the years 2004-2019, he published six articles as a sole author (Appen.1. no. 181, (2004)[29] and Appen. 1. no. 182 (2005)). Then followed the articles (Appen. 1. no. 183, Appen.1. no. (2011), Appen.1 no. 184 (2016), Appen.1. no. 185 (2017)[30] and Appen.1. no. 186 (2019)).

In a short paper in the journal Radiation Chemistry放射線 化学 issue 80 p. 6 (2005) that Sato titled: 雀百まで (What is learned in the cradle is carried to the tomb), he discussed his two recent articles: on "Cumulative Reaction Probability N(E) as Estimated from Empirical Bimolecular Rate Constant k(T)" (Appen.1. no. 181 (2004)) and on "Tunneling in Bimolecular Reactions" (Appen.1. no. 182 (2005)).

Those two articles were written after Sato's retirement. Sato used to visit the library of Tokyo Tech to study in the morning. At lunch time, he came to visit Professor Kazuhiko Shibuya in his office at the Department of Chemistry with a lunch box that he bought in the cafeteria. He knew that Shibuya ate lunch in his office. Over lunch, they talked about a lot of things, research, friends in the academia, foreign countries, etc. They became good friends.[31] Sato mentioned discussion with Kazuhiko Shibuya[32] and acknowledged him and Dr. Mitsuhiko Takasawa in (Appen.1. no. 182 (2005)). Shibuya married Yumiko Sato (not Shin Sato's daughter) who is my good friend since she was the coordinator of the UNESCO Chemistry and Chemical Engineering Course at T.I.T. in 1972-73 (Figs, 3, 4. and 6).

In a letter to the author (9.4.2020), Sato wrote:

> I have been working for last few years to make temperature dependent rate formula for the reactions at low temperatures which are lower than room temperature reaching 10K. As you know, Arrhenius equation is applicable to the reactions at temperatures higher than room temperature. For the reaction rates at the temperatures lower than room temperature, Arrhenius equation has been modified without little success. Three papers for this problem have been published in the Journal, Chemical Physics 49 469-470 (2016); 45 487 (2017); 525 110358 (2019). If you find out interest in them, please read these papers which are written with poor English containing many mistakes in the numbers so on (Appen.1. no. 184, (2016), no. 185 (2017), no. 186 (2019)).

In those last articles he presents the equations which he developed or improved, and shows graphs containing data from his laboratory or quoting others' data, checking the agreement between the theory and the experimental results.

In 2019, in the conclusion to his last article Sato wrote:

> Conclusion
> Proposed empirical rate formula (4) was found to be able to express all experimental data of ion-molecule reactions and low-temperature-high-speed reactions taken up in this paper. Since the existence of Wigner's limits was ascertained, the rate constants could be expressed from very low temperature such as ~10 K to high temperatures ~1000 K. As a result, several comments could be revealed. (Appen.1. no. 186 (2019)).

Books Authored by Shin Sato are in Japanese[3]

In addition to the research articles listed in appendix 1, Sato published and translated several books. Their details, original Japanese titles and titles in English are listed in appendix 2. They include:

1. Text books *Photochemistry and Radiation Chemistry* (**1966**, co-author Shōji Shida, Appen. 2, no. 1).
2. *Quantum Chemistry* (**1974**, Appen.2, no.2,). In this book he included a short explanation to the LEPS method. Each of the 13 chapters is followed by questions; selected answers are given at the end of the book.
3. Co-authored *Introduction to Modern Chemistry* (**1992**, Appen.2, no.3).
4. Translated into Japanese: *"Chemical Kinetics and Dynamics"* (**1995**, Appen.2 no. 4).
5. Co-authored translation of "*Reactions in Quantum Chemistry* (**1998**, Appen. 2. no. 5), see below, Schatz telling about the effect of the translation of his book into Japanese.

Other publications, not listed in Sato's Lists of Publication and books (Appendix 1 and Appendix 2), including review article, commentary, translation, shared writing, etc. are listed in Supplementary Material of Prof. Shin Sato.

Laboratory Life: Shin Sato's Attitude to Students and Colleagues

I have counted 100 names of students and colleagues who were co-authors of Sato's articles during 1954-1991. The impact of all those former students in Japanese academy, industry and commerce, government and prefectural offices, teaching in colleges and high schools should be appreciated. Among them, co-authors that I knew in 1972-1973: I. Yasumori, S. Tsunashima, Y. Hatano, K. Hosoya, K. Okazaki, T. Toyono, K. Yamamoto, Y. Ishikawa, and laboratory assistant Ms. R. Yugeta. I met Y. Hatano a few years ago and learnt about his successful career.[33] Yo-ichi Ishikawa and his wife Sachiko who live in Kyoto are good friends of mine.

Sato had a sensitive human approach to his students and colleagues. Concerning a colleague who had just left the room after my arrival, Sato said: "He came to discuss his scientific and personal problems." Sato attended Okazaki's wedding and possibly weddings of other students.

Saturday afternoons in the radiation laboratory were dedicated to the Mahajan game.

We went for a short vacation to the beach in Ibaraki prefecture, in the Kantō region of the main island, Honshu (27-30 July 1973): Sato, his students and his daughters. We all lived in a local family house who also cooked meals for us. We walked along the beautiful vacant beach and avoided a nearby crowded one. Local fishermen treated us with food from shells that they had just gathered.

During the year I was Sato's student I was invited to Sato family's house in Yokohama three times. On 10th December 1972 Prof. Sato, his younger daughter and I traveled by train to Kamakura, where we met his student K. Yamamoto who lived there. After a day visiting the temples, the large Buddha statue, and the lovely gardens, we visited Yamamoto's parents' house. Yamamoto's mother humbly greeted her son's professor visiting their house by kneeling at the entrance door. We continued early evening by Yamamoto's car to Sato's house in Yokohama. In the house, the eldest daughter played the piano. We ate a good supper, listened to records of Israeli songs, and watched a TV movie telling of samurai war eight hundred years ago. On 7th January 1973 Professor Sato invited his present and past students to his house. Together we all went to a Chinese restaurant and returned to the house to play Mahajan. In September 1973 Sato invited his students to his house before the start of the school year and my departure. I do not know whether other professors treat their students with hospitality at home, but I appreciate very much his invitations to me and others.

In 2017 Sato advised me that Tsunashima passed away after a heart attack. Tsunashima became professor of the Applied Physics department after Sato moved to the Department Research of Nuclear Reactors. After the department's change they continued their collaboration and worked together for more than fifty years.

In the 1970s Prof. Sato had two more foreign students: L. Wojnarovits, IAEA fellow 1975-1976, originally from Institute of Isotopes of the Hungarian Academy of Sciences, Budapest, and Kim Eung-Ryul_, 1977, later Professor in Hanyang University, South Korea. Going through Sato's List of Publication there are names of four non-Japanese co-authors: Y. Siderer (Appen. 1. no. 83 (1975)). L. Wojnarovits (Appen.1. no. 92 (1976)), E. R. Kim (Appen.1. no. 95 (1977)), and G.C. Schatz (Appen.1. no. 156 (1987)), coming from four overseas countries, that is, Israel, Hungary, South Korea and the United States respectively, which seems like a nice spread of guests from around the globe. Those are in addition to his articles from Cvetanović lab in Canada.

G.C. Schatz Recollection of Sato's Translation of his Book and his Attitude to Students and Colleagues:

> I got together with Sato and his research group several times during my visit, and I recall Sato as being a gentle person, who was truly dedicated to his scientific work, and helped his students to become better scientists. He was also very kind to me, which was endearing. I was acutely aware that Sato had been a teenager during WWII and probably had a very difficult time surviving, let alone become a scientist who would make important contributions to the science that I found fascinating at that time. My research interests changed after 1985, so I did not meet Sato after that visit (occasionally we exchanged letters), however two other events brought us together from a distance. One is that Sato translated a book that I wrote with my colleague Mark Ratner, "Quantum Mechanics in Chemistry", published in 1991, into Japanese. He sent me a copy, and it sits prominently on my bookshelf. Several younger Japanese scientists that I have met since then have told me that this book was influential in their careers. The other is that the lead student on our joint paper, Toshiyuki Takayanagi, was a visitor for one year in my research group in the 1995-96. We wrote several papers together, and I have kept in touch with him since then in his position on the faculty at Saitama University. Also, I have followed the field of reaction kinetics in low temperature matrices as others have continued to study this topic. Our joint paper in 1987 now has 64 citations including several in the last 5 years, so my collaboration with Shin Sato has had lasting value to the scientific community, and I am delighted that I had the chance to meet and work with him (Appen. 2. no. 5).

Shin Sato, More on His Life

From his early history Sato told me that after the war, in 1945, there was a great scarcity of food and hunger. He went with his uncle to his mother's old family village near Matsushima, Miyagi Prefecture, north-east of Tokyo. They brought back home a sack of rice, the Japanese staple food.

He regularly took a train from Yokohama to the station near the institute, Midorigaoka station, and walked to the building in which the radiation chemistry laboratory was located. Students came to study and working with him. In the afternoon he went to the South Building in which the photochemistry laboratory was located. In the late afternoon he played Japanese table games like Go and Shogi, that is, Japanese chess, with other partners from the applied physics department. Early evening he returned to the radiation laboratory. He continued supervising students in the laboratory, in which there were glass vacuum systems and measuring instruments. Early in the evening he changed his campus brown shoes to his black commuting shoes which he left in the morning near his desk, took his thin leather bag loaded with papers to be read later, and returned to the train station to Yokohama.

Sato continued his research in the Department of Applied Physics of T.I.T. In 1983 he moved as a professor to the Research Laboratory for Nuclear Reactors.

From 1974 until 2019, Sato wrote in his letters to me about his daughters growing up, then the birth of his granddaughter and great-granddaughter. He passed away in April 2022.

2. SATO FOLLOWS MY RESEARCH CAREER, LITERARY WRITING, AND MENTORS MY JAPANESE STUDIES

UNESCO group of twelve fellows from Afghanistan (2), Bulgaria, Egypt (2), India (2), Israel, Pakistan, Poland and South Korea (2) attended several cultural events and lectures and occasionally travelled out of

Figure 3. Shin Sato teaches Yona Siderer how to play Japanese Chess. Ms. Yumiko Sato (unrelated to S. Sato), UNESCO course coordinator, is watching, 1973.

Figure 4. UNESCO Course participants visit a nuclear reactor station and a nearby park, 1973.

Tokyo. In one of those travels, we were accompanied by the UNESCO office staff and Sato, standing at the end of the right hand row (Fig. 4). On another tour in May, 1973, the UNESCO fellows went to Kyoto, Kobe, Hiroshima, Nagasaki, Kumamoto, Beppu and Nara, exposing us to the beauty, geography and history of Japan.

During my Ph.D. studies at the Weizmann Institute of Science in Rehovot, Israel (1974-1979), I studied the mechanism of oxygen evolution in plant photosynthesis by observing light induced room temperature changes of manganese ESR signals in chloroplasts. In a letter on 30th September 1974 Sato reflected: "…Now, I am very glad to hear that you could start to work at the Weizmann Institute. Photosynthesis is one of the most exciting fields. I sincerely hope that you make a great progress there and grow up as an excellent researcher. I know you have a great ability for this." Sato congratulated me for receiving an EMBO fellowship to London for three months, adding in an aerogram in 1977: "Please write to me your impression of England." When I wrote to Sato that I was offered a post-doc position at Princeton University he answered on 7 December 1978: "If I were you, I won't miss the chance for a next big jump."

Between 1984 and 1994 I sent Sato my poetry book that includes my painting. He reflected on those occasions in the followings letters: On 30th January 1984: "Unfortunately my English is not good enough to appreciate the nuance of your poems, but I understand the situations and feelings which you are intending to tell us." On 29th April 1993 he observed: "Two weeks ago, I received your package which contained two Hebrew books with [the famous poet Shuntaro] Tanigawa translations of your poems. I can recognise our portrait on the cover of your book. You have done nice work." On 25th February 1994 he wrote: "Since I received your books of poems and translation and a pamphlet for your paintings and poems, I was surprised by your talent. One of the paintings entitled "interior" makes me recall Matisse." On 7th March 1973, I presented Sato with the book "The Little Prince" in Hebrew for his birthday. The book is still kept among his belongings in his house in Yokohama, together with other five books including my Ph.D. Dissertation, my poems and paintings, Natsume Sōseki's book *Kusa Makura* translation that I sent him. I saw the books in his house during a visit on 13 July 2023.

Figure 5. Prof. Shin Sato and Dr. Yona Siderer in front of the Main Building, Tokyo Institute of Technology, 1984. Taken when I was a summer visiting scientist in Y. Inoue laboratory at Riken, the Physical and Chemical Research Institute in Saitama.

Sato Follows Siderer Research and Teaching the History of Chemistry in Japan

Early in July 2008 I arrived again at T.I.T., as a recipient of a Japan Foundation Fellowship to study "the history of chemistry in Japan" in Professor Masanori Kaji's laboratory. Masanori Kaji and Kazuhiko Shibuya encouraged me to teach a course on this topic to Master's students of chemistry at T.I.T. I taught an eight meetings course during October to December 2008. Preparing the eight session course assisted my further research.[34] Kaji was first an organic chemist, eventually a very capable historian of chemistry, who studied in Russia, and made many overseas colleagues-friends. He passed away in 2016, at the age of sixty years. (Siderer, 2016).

Sato attended my lecture on "Chaim Weizmann, a Chemist and a Statesman" which I presented at the Annual Meeting of the Japanese Society for the History of Chemistry at T.I.T. in 2008, since then, I have been a member of this society. Sato reflected on Weizmann's career, appreciating his Japanese patent.[35] The *Kagakushi*

Figure 6. In front of the Centennial Hall, Tokyo Tech 2015. From Left: Kazuhiko Shibuya, Shin Sato, Yona Siderer, and Yumiko Shibuya.[36]

Jitten that was prepared by members of that society includes my contribution on Chaim Weizmann, introducing the successful chemist and the first president of the State of Israel to the Japanese readers (Encyclopedic Dictionary 2017).

After six months at T.I.T. (2008), I went to the International Research Center for Japanese Studies (Abbreviated in Japanese: Nichibunken) in Kyoto for one year (2009-2010), holding their Visiting Scholar Fellowship. Professor Frederik Cryns was my host at Nichibunken, we continue our correspondence and discussion concerning writing and publishing my research results.

Sato meticulously and patiently answered my various naive questions, adding to my knowledge of Japanese culture and history when I studied the history of chemistry in Japan. Starting with the research of the Japanese physician and scholar Udagawa Youan (1798-1846), I needed further Japanese explanation and clarification for several topics that I encountered. Those topics included names of people, names of places, e.g. hot springs, the Japanese traditional calendars, and counting the age of Japanese people. Certain kanji characters that were changed, modified or deleted during time, Japanese chemistry nomenclature, Galvani pile, Utamaro's *Book of Insects*, Japanese 1873-74 translation of H. E. Roscoe's 1872 (Science Primer Chemistry) book, Kuroda Chika a pioneering woman chemistry career, etc. (Siderer 2017, Siderer 2021a. Siderer 2021b, Kikuchi and Siderer 2021), Siderer 2023a, Siderer 23b).

While participating in several of the annual meetings of the Japanese Society for the History of Chemistry I had the opportunities to meet T.I.T. friends and others (Fig. 6).

Sato appreciated the support from Israel after the March 2011 Tsunami-earthquake-Fukushima reactors disaster: On 30.3.2011 he wrote: "Dear Yona, Israeli medical team has opened their office at Minami-sanriku-chou in Miyagi prefecture. Their activity was reported on TV. The town was completely destroyed by the tsunami. Half of the residents have been found dead or are still missing, Shin."

CONCLUSIONS

In the foregoing I have summarized the research work of Professor Shin Sato, a physical chemist who spent his career at Tokyo Institute of Technology in Japan. Very early, in 1954-1955, he added to the already known equation of London-Eyring-Polanyi for the drawing of the Potential Energy Surface (PES) for the collision of two small molecules (LEP), and developed his intuitive semi-empirical improvement of their equation that was later called LEPS Method (S after Sato), and later highly cited. His interest in photochemistry deepened during the two periods he spent in the laboratory of R. J. Cvetanović in NRC, Ottawa, Canada (1956-1958 and in 1965-1966). On returning to Japan, and finding that the laboratory he had left had moved over to radiation chemistry, he entered into this new field. After receiving his Doctor of Engineering degree he directed two laboratories, in photochemistry and in radiation chemistry. He attracted around a hundred students to his laboratories, taught chemistry, and continued to work on understanding the dynamics of small molecules, excited states of light induced or γ-rays hit of olefins and other small molecules, reaction of photosensitization by mercury, cadmium, zinc and benzene, and the reactions of nitrogen. Through these investigations he improved the calculation of reactions rate in low temperatures that could not be calculated by the Arrhenius equations.

The year I spent in Tokyo in Sato's laboratory as a UNESCO fellowship fellow influenced the rest of my life: It gave me the opportunity to appreciate the Japanese scientific culture. I enjoyed the friendly atmosphere in the laboratory. I was taken by Japanese art and literature, and fascinated by the kanji, the Chinese-Japanese characters that deepened my research on the history of chemistry in Japan, for which so much inspiration and help was given to me by Shin Sato.

POST-SCRIPT

I invited Sato's younger daughter, and her husband to attend my lecture on Prof. Sato (*Professor Shin Sato, Physical Chemist and my Teacher for 50 Years*, (Siderer

2023b)) at the Annual Meeting of the Japanese Society for the History of Chemistry held at Hitotsubashi University in Tokyo on 8th July 2023. After my lecture we sat together with my friends Kazuhiko Shibuya and his wife Yumiko, and friends of Sato, and discussed his life. On 13th July Sato's younger daughter's husband accompanied me and a friend from Tokyo to Sato's grave in a cemetery in the outskirts of Yokohama. We put flowers and a small plant near the grayish tombstone. We continued and visited his house in Yokohama. Walking upstairs from the street to the house, we entered the living room that had somewhat changed during his illness. But the wonderful spirit, with the many books, the magazines, and the musical notes was still there. Sato's younger daughter later wrote to me, thanked me for having visited her father's grave and told me some stories about him during her childhood.

NOTES

1. Japanese names are written with the family name follows the first name, as they appear in publications titles in English, contrary to the traditional Japanese order of family name first.
2. Information contributed by Sato's family, 28 December 2023.
3. Correspondence with K. Nakamura during 2023.
4. T.I.T. website 17.1.2024, and Wikipedia, 17.1.2024.
5. Shida. (Appendix, hence Appen. 1. no. 7 (1955), Appen. 1. no. 8 (1955), Appen. 1. no. 38, (1968), Appen. 1. no. 39 (1968), Appen. 1. no. 40 (1968)) (Kikuchi and Siderer (2021)) (Appen. 2. no. 1. Shōji Shida and Shin Sato (1966)).
6. Sato LEPS Method (Appen. 1. no. 3 (1954), Appen. 1. no. 4 (1955), Appen.1. no. 5 (1955), Appen 1. no. 10 (1956)).
7. LEPS Method and Modified LEPS method (Appen. 1. no. 161 (1988)), Appen.1. no. 176 (1990), Appen.1. no. 178 (1990)).
8. George C. Schatz to Siderer on 22nd December 2023: Morrison Professor of Chemistry at Northwestern University. He specializes in theoretical and computational chemistry, and has worked in many subdisciplines over the years (nanoscience, materials modeling, light-matter interactions, electronic structure, rate processes). Early in his career (1971-2000) he studied processes important in chemical reaction dynamics that overlapped with Shin Sato.
9. NO_2 Photolysis (Appen.1. no. 11 (1958), Appen. 1. no. 12 (1958), Appen. 1. no. 13 (1958), Appen. 1. no. 14 (1959), Appen. 1. no. 15 (1959)). Articles nos. 11 and 13 in appendix 1 were cited in a leading photochemistry book by Calvert and Pitts, (1966).
10. Sensitized Fluorescence. "Franck predicted in 1922 that a transfer of electronic energy could occur between excited atoms and atoms of a different species in their ground states (Ref. 60). He further stated that the efficiency of the transfer should increase for various systems as the difference in electronic energy levels of the excited donor atom D* approached the difference in energy levels of the non-excited atom A (i.e., approached resonance). This prediction was soon verified by Cario and Franck, who irradiated mixtures of mercury and thallium vapors with the Hg 2537 Å line, to which the thallium was transparent. The observed sensitized fluorescence from the excited states of thallium which lie near or below the 4.86 ev of $^3P_1$ mercury (Ref. 61)." Calvert, chapter 2-9D p. 84.
11. Calvert, (1966), pp. 83-105.
12. Mercury Photosensitization. (Appen. 1. no. 17 (1960), Appen. 1, no. 23 (1964), Appen. 1, no. 35 (also Cd) (1968), Appen. 1. No. 55 also Cd and benzene (1970), Appen. 1. no. 82 (1975), Appen. 1. no. 97 (1978), and Appen. 1. no. 103, (1978)).
13. Phase-shift method for emission lifetime determination. Fluorescence may be excited with light of intensity modulated at a high frequency (5-12 Mc/sec). Because of the finite lifetime of the excited state of an absorbing molecule, there is a delay before the emission of fluorescence by the excited molecule; this results in a difference in the phase of the modulated fluorescence emission and the modulated exciting light. The difference in the phase angle ϕ can be measured experimentally, and the mean fluorescence lifetime can be calculated from its relation to ϕ: $\tan \phi = r2\pi\nu$ (7-31), where ν is the frequency of the modulation of the light. (*Photochemistry* (1966) on phase shift. p. 806; After Lord and Rees (Ref. 120 there).
14. Cd Photosensitization. (Appen.1. no. 33 (1967), Appen.1. no. 34 (1968), Appen.1. no. 35 also Hg(1968), Appen.1. no. 37 also Hg(1968), Appen.1. no. 42 (1968), Appen.1. no. 44 (1969), Appen.1. no. 48 (1969), Appen.1. no. 53(1970), Appen.1. no. 68 (1973), Appen.1. no. 69 (1973), Appen.1. no. 70 (1974), Appen.1. no. 75 (1975), Appen.1. no. 77 (1975), Appen.1. no. 78 (1975), Appen.1. no. 81 (1975), Appen.1. no. 90 (1976), Appen.1. no. 96 (1977), Appen.1. no. 100 (1978), phase-shift), Appen.1. no. 105 (1979), Appen.1. no. 109, (1979) phase shift, Appen.1. no. 112 (1980), Appen.1. no. 113 (1980), Appen.1. no. 119 (1980)).

15. Benzene Photosensitization. (Appen.1. no. 22 (1963), Appen.1. no. 26 (1965), Appen.1. no. 28 (1966), Appen.1. no. 29 (1966) Appen. 1. no. 46 (1969) in Japanese), Appen.1. no. 63 (1972), Appen.1. no. 64 (1972)).
16. Zinc Photosensitization. (Appen. 1. no. 41 (1968), Appen. 1. no. 172 (1989), Appen. 1. no. 179 (1990)).
17. Amine formation. (Appen. 1. no. (108 (1979), no. 115 (1980), no. 117 (1980), no. 120 (1981), no. 125 (1981), no. 128 (1982), no. 129 (1982), no. 132 (1983), no. 134 (1983), no. 136 (1984), no. 139 (1984), no. 148 (1986 Phase-shift), no.149 (1986 phase shift), no. 163 (1988), no. 165 (1988), no. 167 (1988)).
18. Calvert p. 102. In chapter 2 on "The Interaction of Light with Atoms", they cite the article by Arai, Sato and Shida, in *Nippon Kagaku Zassi*, **81**, 1790, (1960), ref. 110, p. 102) (Appen.1. no. 6, in Japanese). On cycloalkanes, "in Studies of Hg($^3P_1$)-cyclohexane mixtures over the range of 60-400°C, they found that below 200°C the major products are hydrogen, bicyclohexyl, and cyclohexene, in accord with Gunning et al.(ref. 107 therein) Above 300°C the ring ruptures, and products include propylene, methane, ethylene, ethane, butadiene, propane and butane, presumably arising from the decomposition of the cyclohexyl radical formed in the primary act. The quenching cross section of cyclohexane was estimated to 1.9 Å^2. (Calvert and Pitts, *Photochemistry* (1966) p. 102).
19. Calvert p. 218. In chapter 3, "The Interaction of Light with simple molecules" section 3-3B-2 "The Oxides of Sulfur and Nitrogen: SO_2, SO_3, N_2O, NO, and NO_2" the following article is cited. "Sato and Cvetanović, however, in studying the Photooxidation of 1-butene by nitrogen dioxide, found that the same addition products, α-butene oxide and butanal, were formed at several ultraviolet wavelengths, including 4047A. Furthermore, the ratio of their yields was the same at all these wavelengths. They found no reaction at 4358 Å. They point out that this would be difficult to understand if free oxygen atoms were not involved at all wavelengths used, including 4047 A but not 4358 Å." (Calvert 1966. p. 218. Ref. 168 (p. 237)).
20. Calvert p. 221. Chapter 3 section 3-3B-2 "The Oxides of Sulfur and Nitrogen: SO_2, SO_3, N_2O, NO, and $NO_{2,}$ as the previous section … "Sato and Cvetanović (ref. 173: (Appen.1. no.13 (1958))) have found a change in the electronic state of oxygen on photolysis at the shorter wavelengths. 1-butene was photooxidized, using NO_2 photolysis at 3261, 2537, and 2288 Å. Between 2537, and 2288 Å a change in the mechanism of oxygen atom attack occurred, and it is likely that the primary reaction for these conditions is NO_2+hv > NO (X^2II) + O(^1D). As in all cases discussed in this book we have restricted our attention to those directly concerned with the nature of the primary photochemical processes." (Calvert (1966)).
21. Cyclohexane. (Appen.1. no. 16 (1960), Appen.1. no. 17 (1960), Appen. 1. no. 19 (1962), Appen. 1. no. 20 (1962), Appen. 1. no. 21 (1963), Appen. 1. no. 24 (1964), Appen. 1. no. 30 (1967), Appen. 1. no. 31 (1967), Appen. 1. no. 36 (1968), Appen. 1. no. 43 (1968), Appen. 1. no. 58 (1971), Appen. 1. no. 59 (1971), Appen. 1. no. 92 (1976), Appen. 1. no. 104 (1979)).
22. G-Values. (Appen. 1. no. 67 (1973), Appen. 1. no. 72 (1974), Appen. 1. no. 79 (1975)).
23. G-Values. (Appen. 1. no. 80 (1975), Appen. 1. no. 82 (1975), Appen. 1. no. 86 (1975), Appen. 1. no. 87 (1976), Appen. 1. no. 89 (1976), Appen. 1. no. 91 (1976), Appen. 1. no. 94 (1977), Appen. 1. no. 102 (1978)).
24. Citation of the original sentence in Japanese: 『どの論文にも夢があった。実験とは毎日毎日が創造である。学生の創造に負けないように想像力を逞しくした』。
25. Phase Shift Method. (Appen.1. no. 97 (1978), Appen.1. no. 100 (1978), Appen.1. no. 103 (1978), Appen.1. no. 113 (1980), Appen.1. no. 149 (1986)).
26. ESR experiments. (Appen.1. no. 135 (1983), Appen.1. no. 140 (1984), Appen.1. no. 144 (1985), Appen.1. no. 145 (1985), Appen.1. no. 146 (1986), Appen.1. no. 150 (1986), Appen.1. no. 153 (1987), Appen.1. no. 155 (1987), Appen.1. no. 164 (1988), Appen.1. no. 171 (1989), Appen.1. no. 175 (1989)).
27. Kazutaka Nakamura is an Associate Professor at Tokyo Institute of Technology. He was a student in Sato's lab officially in 1984-1986. Nakamura recalled ESR experiments in which he was involved. (Email, 12.2023).
28. A short introduction: Toshiyuki Takayanagi was a student of Sato since 1985; he is now a professor at Saitama University, Department of Chemistry. Takayanagi wrote his reflection about their scientific research in the 1980s, his acquaintance with Schatz in Sato's lab and his work at Schatz's laboratory as a result of that acquaintance and a co-authored article: T. Takayanagi, N. Masaki, K. Nakamura, M. Okamoto, S. Sato and G. T. Schatz (Appen. 1. No. 156 (1987)).
29. Abstract of Sato's 2004 article. Approximate cumulative reaction probabilities have been calculat-

ed from two empirical rate equations: one is the 3-parameter rate equation, $AT^n \exp(-E/k_BT)$, and the other is the modified Arrhenius equation proposed in Chem. Phys. Lett. 160 (1989) 295, for expressing the rate constants at low temperatures. Numerical calculations were made for the $D + H_2 \rightarrow DH + H$ reaction. It is shown that this reaction occurs mainly through tunneling at 200 K, and that the 3-parameter rate equation involves the tunneling effect along with the correction at high temperatures (Apenn.1. no. 181 (2004)).

30. Abstract of Sato's 2017 article. On "Empirical rate formula for ion-dipolar molecule reactions": New empirical rate formula for the low temperature reactions is proposed. The formula proposed previously has been simplified by using incomplete gamma function. A few examples of temperature dependence of rate constants for the reactions of ions with dipolar molecules and that for the reaction $F+H_2 \rightarrow HF +H$ are demonstrated by using new rate formula (Appen. 1. no. 185 (2017)).
31. Mrs. Y. Shibuya conversation with the author on 1 August 2023.
32. K. Shibuya, discussion, in the above mentioned journal Radiation Chemistry 放射線 化学 issue 80 p. 6 (2005).
33. I met Y. Hatano with his friend T. Yamaguchi and their friend in a restaurant near Tokyo Station in 2016.
34. History of Chemistry in Japan: From Cotton Dyeing to Nobel Laureates. Monthly reports I sent to Japan Foundation in Tokyo, 2008.
35. Chaim Charles Weizmann Letter patent no. 33502, English translation 1924 001. A copy of Chaim (Charles) Weizmann patent: "Improvement of relating to the carrying out of bacteriological process", in Japanese Patent Bureau, in 1918 (Taisho 7), and reregistered in 1924 (Taisho 13). A copy is kept at the Weizmann Archive at the Weizmann Institute of Science, Rehovot.
36. On 8 November 2015 Sato congratulated me for becoming a member of the Directorate of the Israeli Association for Japanese studies (IAJS). S. Sato, Tatsumasa Dōke and Mrs. Yumiko Shibuya attended my seminar at T.I.T. in July 2018. I keep twenty five New Year greeting cards that he had annually sent; the last one is for 2022 showing snow on top of Mount Fuji, flowers and flying cranes, one of Japanese symbols of longevity.

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APPENDIX 1. SHIN SATO LIST OF PUBLICATION IN JOURNALS

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APPENDIX 2. BOOKS AUTHORED, CO-AUTHORED, TRANSLATED AND CO-TRANSLATES BY SHIN SATO

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SUPPLEMENTARY MATERIAL OF PROF. SHIN SATO

Other publications, not listed in Sato's List of Publication (Appendix 1), including review articles, commentaries, translations, shared writings, etc.

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