In Memoriam Ludwig Waldmann

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Ludwig Waldmann, who died on February 9th, 1980, would have become ninety years old on June 8th, 2003. On this occassion, a list of his scientific publications is presented here. To honour Professor Waldmann and to point out his contributions to the progress of science, some comments are made on his publications, after a few brief remarks on his biography.

Ludwig Waldmann was born in Fürth (close to Nürnberg in Northern Bavaria) on June 8th, 1913. He attended high school ("Oberrealschule") in his home town. After graduation (Abitur 1932) he received a "Maximilianeum" scholarship in Munich and studied there and in Göttingen Mathematics und Physics. He passed the state exam which entitled him to become a teacher (Staatsexamen für das höhere Lehramt) and got his PhD (Dr. phil.) under the supervision of Arnold Sommerfeld in Munich. The title of his thesis was "Über die Verallgemeinerung der Boltzmannschen Abzählmethode auf das van der Waalssche Gas" (On the generalization of Boltzmann's counting method to the van der Waals gas). From 1937 – 39 he was assistant of Sommerfeld at the Institute of Theoretical Physics, from 1939 – 43 of Clusius at the Institute of Physical Chemistry in Munich. From 1943 – 54 he worked at the Kaiser-Wilhelm Institute and the Max-Planck Institut (MPI) for Chemistry, 1943 – 1944 in Berlin, 1944 – 49 in Tailfingen, and 1949 – 54 in Mainz. From 1954 – 63 he was a fellow (wissenschaftliches Mitglied) of the MPI in Mainz, afterwards he was an external fellow. In 1963 he accepted a chair of Theoretical Physics at the University Erlangen-Nürnberg. He spent the academic year 1964/65 as a visiting professor at the Department of Chemical Engineering at the University of Minnesota in Minneapolis, USA; in 1974 he worked in the Molecular Physics group of Jan Beenakker and Hein Knaap at the University of Leiden in Holland. For many years, Waldmann was the chairman of the section "Thermodynamics and Statistical Physics" of the German Physical Society and he served as a member in the corresponding IUPAP commission. Waldmann was a member of the Bavarian Academy of Science. Already strongly suffering from a serious disease, he retired from his active duties at the university in 1978. In February 1979, he received the degree of an honorary doctor from the University of Leiden for his important contributions to the kinetic theory of molecular gases and his essential role in a fruitful collaboration between experiment and theory. Ludwig Waldmann had six children, and as he liked to stress with his cunning smile, "one wife only". He died on February 9th, 1980.

The topics of Ludwig Waldmanns first publications [1 – 3] were strongly influenced by his teacher Sommerfeld. These were the electro-statics calculation of an electron lens, the derivation of an equation of state for a real gas and the analysis of the modification of the Boltzmann statistics by Quantum Mechanics. The theory of isotope seperation by means of the method of Clusius und Dickel, where the thermo-diffusion effect is enhanced by convection currents, is presented in the articles [4 – 6] and [13]. A careful comparison with experiments is made. Publications [7] and [10] are concerned with isotope seperation in flames and by exchange reactions. A few years later, the results of the latter paper were rediscovered by J. Bigeleisen and M. Goeppert Mayer (J. Chem. Phys. **15**, 261 (1947)). Several publications are devoted to a "disregarded gas kinetic effect", viz. the diffusio-thermal effect, which is reciprocal, in the sense of the Onsager relations, to the thermal-diffusion effect. These theoretical and in particular also experimental studies continued over many years, see the publications [8, 9, 11 – 19, 21, 22, 24]. A new stationary method for measuring thermal-diffusion and diffusion is introduced and applied in the articles [13] and [29]. Theoretical considerations on the consequences of Quantum Mechanics for the diffusion in para- and ortho-hydrogen mixtures are followed by pertinent experimental investigations, *cf.* [20] and [23]. The publications [26, 27] and [31] are reviews giving a survey of the activities of German scientists in the years 1938 to 1948 in the field of transport phenomena in gases and liquids. In connection with the determination of the masses of isotopes of many elements, performed at the Max-Planck Institute in Mainz under the supervision of J. Mattauch, *cf.* [33, 39, 41], Waldmann invented a device with a negative electric resistance intended to be used in analog computations for matrix inversions. Publications with A. Klemm on thermal-diffusion and heat conduction in hydrogen-isotope mixtures, *cf.* [49] and [50], show that Waldmann maintained a strong interest in experiments. At the same time, he was concerned with fundamental problems of theoretical physics. The articles [32, 34 – 36] are devoted to classical field theory calculations of the *g*-factor of the electron and to the quantum mechanics of the Lamb-shift of the "stiff electron" as conceived by H. Hönl (Ann. Physik **33**, 565 (1938)) and F. Bopp (Ann. Physik **38**, 345 (1940)). In [35] the existence of negative masses is considered, as discussed in a report by F. Winterberg (Z. Naturforsch. **58a**, 231 (2003)).

An outstanding article by Waldmann is his contribution "Transporterscheinungen in Gasen von mittlerem Druck" (Transport pheneomena in gases at moderate pressure, 220 pages) to Flügges "Handbuch der Physik" which appeared 1958, see publication [44]. This is still the best introduction to the Kinetic Theory of Gases and, at the same time, it provides a profound survey of the relevant experiments. This article, however, did not get the international attention it would have deserved because it was written in German, like most of Waldmanns papers till the mid sixties. The Handbuch article also contains a chapter devoted to the then new quantum mechanical version of the Boltzmann equation which later, in the literature, was referred to as "Waldmann-Snider equation". The original publications on this topic, viz. [42] and [43], carry the titles "Die Boltzmann-Gleichung für Gase mit rotierenden Molekülen" (The Boltzmann equation for rotating molecules) and "Die Boltzmann-Gleichung für Gase aus Spin-Teilchen" (the Boltzmann equation for particles with spin). The scattering amplitude or the T-matrix occur in the collision term of the new kinetic equation. For particles without rotational degrees of freedom it reduces to the collision term of the Boltzmann equation containing the scattering cross section. The new features of the kinetic equation are essential when, in addition to the standard transport processes, also orientational phenomena linked with the spin or the rotational angular momentum of the particles are treated. The same kinetic equation was derived somewhat later, but unaware of Waldmann's work, by the Canadian scientist R. F. Snider (J. Chem. Phys. **32**, 1051 (1960)), hence the name Waldmann-Snider equation. The first application of the new kinetic equation, *cf.* publications [46] and [47], was the study of the influence of multiple scattering processes and diffusion on the orientation of the spin of an electron. These processes are of importance in connection with investigations of the parity violation in β-decay, a hot topic in those days. Then followed the kinetic theory for gases of particles with exitable internal degrees of freedom, paper [53], and the analysis of the influence of a magnetic field on the diffusion of particles with spin. *cf.* [54]. In 1962, Jan Beenakker and coworkers at the University of Leiden in Holland (J. J. M. Bennakker, G. Scoles, H. F. P. Knaap, and R. M. Jonkman, Phys. Lett. **2**, 5 (1962)) demonstrated that the influence of a magnetic field on transport properties such as viscosity and heat conductivity exists for the diamagnetic gas N_2. Thus it is a phenomenon typical for gases of rotating molecules and not a pecularity of the few paramagnetic gases like O_2 and NO, as was believed since the early findings of H. Senftleben (Phys. Z. **31**, 822 and 961 (1930)). In the following years, the "Senftleben-Beenakker effect" was studied experimentally for many molecular gases, and numerous theoretical papers, based on the Waldmann-Snider equation were published by several international groups. Contributions by Waldmann and his coworkers on this topic are the articles [58, 60 – 64, 67 – 73, 78], and [80]. Two episodes deserve mentioning. Ludwig Waldmann believed in the existence of "transverse", i. e. Hall effect like contributions to the heat conductivity and the viscosity of electrically neutral gases in the presence of a magnetic field. These effects were calculated in a master thesis in 1964 by S. Hess, a student of Waldmann in Erlangen. In 1965, F. R. W. McCourt, a student of R. F. Snider in Vancouver, Canada, obtained similar results in his PhD-thesis. Both thesis advisers thought that this phenomenon does not deserve rapid publication since it cannot be measured. A short time later, however, the Dutch group in Leiden and a Russian group presented experimental results for transverse effects in the viscous behavior (J. Korving, H. Hulsman, H. F. P. Knaap, and J. J. M. Bennakker, Phys.Lett. **21**, 5 (1966)) and heat conduction (L. L. Gorelik, V. G.

Nikolaevskii, and V. V. Sinitsyn, JETP Lett. **4**, 307 (1966)). So when the link was seen between the alignment of the rotational angular momenta which is responsible for the Senfleben-Bennakker effect of the viscosity and the optical anisotropy leading to flow birefringence, calculations based on the Waldmann-Snider equation were published immediately (S. Hess, Phys. Lett. **30A**, 239 (1969)). The experimental verification of this effect which Waldmann had aniticipated, *cf.* [60], came soon afterwards (F. Baas, Phys. Lett. **36A**, 107 (1971)). A good account of the impact of Waldmann and his group is found in the book "Nonequilibrium phenomena in polyatomic gases" by F. R. W. McCourt, J. J. M. Bennakker, W. E. Köhler and I. Kuscer (Clarendon Press, Oxford 1990) and in a contribution by S. Hess in Bergmann-Schaefer, "Lehrbuch der Experimentalphysik", Vol. 5 (de Gruyter, Berlin 1992).

For more than two decades Ludwig Waldmann was interested in transport processes in rarefied gases. Topics in this field are the calculation and measurement of forces acting on solid particles (aerosols) suspended in gases, *cf.* the publications [45, 48, 51, 65] and [86], as well as flow phenomena and heat conduction in systems where the mean free path of the gas molecules is no longer very small in comparison with the distance between the walls confining the gas, *cf.* [52, 82], and [90 – 93]. An effect typical for rarefied molecular gases is the "thermo-magnetic twist" which was discovered accidentally in the magnetic field laboratory of General Motors in Detroit (G. G. Scott, H. W. Sturner, and R. W. Williamson, Phys. Rev. **158**, 117 (1967)). Waldmann presented the first theoretical explanation for this effect, see [67, 68], and [72]. The "strange twist" had a side effect. Due to the interaction between experimentalists and theoreticians, a daughter of Waldmann met her husband who was the son of the boss of G. G. Scott, the discoverer of the effect. An important contribution of Waldmann to the advancement of theoretical physics is the generalization of the equations of thermo-hydrodynamics for rarefied gases and the introduction of boundary conditions consistent with the enlarged set of equations. A method for the derivation of boundary conditions within the framework of irreversible thermodynamics was invented by Waldmann in 1967, *cf.* publication [66], for a generalization see [99]. Ten years later followed the derivation of boundary conditions for the Boltzmann equation and, of course, for the Waldmann-Snider equation, *cf.* [90, 98], and [100]. Various applications of the theory are presented in the articles [81 – 87, 89 – 93, 98 – 100]. Fundamental problems like the time-reversal behavior, reciprocity relations and a time-dependent variational principle were addressed in the publications [85, 86], and [94]. Even in the last two years of his life, when Ludwig Waldmann was seriously impeded by his illness, he worked with an enormous drive, with great enthusiasm and he was always delighted by new ideas and insight into physics.

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