Chapter 9

100 Years Molecular Beam Method Reproduction of Otto Stern's Atomic Beam Velocity Measurement

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Abstract The history of Otto Stern's pioneering measurement of the Maxwell-Boltzmann velocity distribution of a Silver atomic beam performed 1919 in Frankfurt is described. It is shown how Albert Einstein influenced Stern in his research. This experimental apparatus is not any more existing; therefore it was reconstructed in the workshops of the Physics faculty of the Goethe University in Frankfurt. The experimental verification of Stern's results was finally achieved by a team of Frankfurt high school students (Gymnasium Riedberg) under the supervision of their teachers Axel Gruppe and Simon Cerny. By fighting against a number of difficulties, they succeeded to get the reconstructed apparatus started and were able to reproduce the results from the early experiments of Stern.

1 Otto Stern's Historic Atomic Beam Velocity Measurement

Otto Stern was originally educated as a theoretical physical chemist. That he finally turned into one of the most genius experimenters in modern quantum physics is indeed astonishing. In 1912 he completed his dissertation with the title "Zur kinetischen Theorie des osmotischen Druckes konzentrierter Lösungen und über die Gültigkeit des Henryschen Gesetzes für konzentrierte Lösungen von Kohlendioxyd

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Fig. 1 Otto Stern and his brother Kurt as soldiers [3]

in organischen Lösungsmitteln bei tiefen Temperaturen” [1], which was partly experimental and partly theoretical. Thereafter he began his career in theoretical physics working with A. Einstein in Prague.

In the same year he followed Einstein to Zürich. In 1914 Einstein was appointed professor in Berlin. Stern accepted the offer by Max von Laue to become Laue’s “Privatdozent” in Theoretical Physics at the newly founded University in Frankfurt. From 1914 until the end of 1918 Stern was soldier in World War One serving as weather observer (Fig. 1). In the second half of the year 1918 Stern was delegated to the Institute of Walter Nernst in Berlin, where, together with Max Volmer (Fig. 2), he performed several experimental investigations [2] in which Stern already demonstrated his ingenious skill of designing sophisticated physical experiments.

It therefore was not a surprise, that, after his return to Frankfurt in February 1919, Stern, the initially theoretically trained physical chemist continued performing experiments in physics. The Frankfurt Institute of Theoretical Physics (see faculty members in Fig. 3), directed by Max Born, owned a workshop with the young Adolf Schmidt as the only precision mechanic.

The first experiment that Otto Stern performed in 1919 in Frankfurt was the measurement of the Maxwell-Boltzmann-velocity distribution [5] of Ag atoms evaporated from a solid at the temperature of the melting point ($T_m = 962\text{ }^{\circ}\text{C}$) [6]. He explained that he was interested in this experiment because, due to the influence of the “zero-point energy”, he expected deviations from Maxwell’s law at very low beam velocities. Together with Einstein he had published a theoretical paper on this issue in 1913 [7].

Fig. 2 Max Volmer and his wife Liselotte nee Pusch [4]

Fig. 3 Members of the Frankfurt Physics faculty in 1920. From right: sitting Otto Stern, unknown, Max Born, Hedi Born and Richard Wachsmuth, standing: 3rd from right Alfred Landé, 4th Walther Gerlach, and next to Gerlach probably Elizabeth Bormann [3]

This pioneering experiment was the corner stone for Stern's famous molecular beam method MBM, which enabled the first ultra-high precision measurements of momenta of moving atoms or molecules in vacuum. With this experiment Stern established a method allowing the observation of inner atomic or even inner-nuclear ground state properties with unprecedented resolution, which, at least in 1919, was not achievable by energy spectroscopy (see Stern-Gerlach-Experiment SGE in 1922 [8]).

At a first glance, the measurement of the Maxwell-Boltzmann velocity distribution [6] looks simple. However, the authors of this paper, in their attempt to repeat this experiment, had to learn how difficult it really was, in particular, if one considers the very poor economic conditions in the year 1919 when the seminal experiment was performed.

The priming condition for the development of the MBM was the revolutionary progress in vacuum technology. Diffusion pumps became available creating vacuum in the low 10^{-5} torr regime. In such vacuum the free-path-length of moving atoms reaches several meters before they undergo a second collision. Stern benefited from his friendship with Max Volmer, who had developed a glass-made mercury diffusion pump, patented in 1918, Figs. 4 and 5. The Volmer mercury diffusion pump was fabricated in Berlin by Hanff and Buest. The rough vacuum was created by a rotating mercury pump invented by Wolfgang Max Paul Gaede (1878–1945) [9].

Otto Stern's experiment was inspired by the atomic beam experiment of L. Dunoyer in 1911 [10]. Dunoyer observed in his experiment that the beam particles move in vacuum like photons on straight lines. This is expected as long as the particles are not deflected by an external force or scattered by a gas molecules in the vacuum chamber. Vice versa one can use the transverse deflection in x and y direction (z is the direction of the velocity vector) by an external electro-magnetic force and thus determine electric or magnetic properties of the moving particle.

To perform deflection measurements and to obtain quantitative information on inner atomic properties one must measure the absolute value of the transverse momentum change. Therefore one has to know very precisely the direction of motion as well as the mass and the absolute velocity of the particle. In order to achieve this, one has to carefully prepare the atomic or molecular beam by a well aligned system of accurately manufactured slits. The principle of the transverse beam collimation is shown in Fig. 6.

The direction of motion is known from the geometry of the slit system. The velocity distribution of the atoms in the beam, generated by evaporating the atoms from a source at a defined temperature T was in 1919 only theoretically predicted but experimentally never measured. Thus, in order to later use the MBM for absolute momentum measurements, Stern had to verify Maxwell's theory [5] by measuring the Maxwell-Boltzmann velocity distribution of atoms, evaporated in a sufficiently good vacuum.

To perform these measurements Stern invented a kind of "streak camera" which is an ingeniously simple apparatus but which is very difficult to set into operation [6]. It is therefore astonishing and highly meritorious that the experiment had been accomplished, in particular when one considers the short period of one year from

Fig. 4 The Volmer diffusion pump

beginning until getting a final result. One certainly has to anticipate that the help of the 26-year-old mechanic Adolf Schmidt was crucial for making the experiment a success.

In Fig. 7 Stern's "streak camera" is shown. The glass recipient had an inner diameter of 24 cm and was 30 cm high. With the help of the Gaede rotating mercury pump and the Volmer one-stage mercury diffusion pump the recipient could be evacuated to a pressure below 10^{-4} torr. The quality of the vacuum was measured by Geissler tubes. The pumping speed of both pumps was rather low (a few liters per second). The glass recipient was mounted vacuum-sealed on a $40 \cdot 40 \text{ cm}^2$ iron plate. The stationary frame (D) inside the recipient was fixed by screws on the iron plate. The streak camera (R) was adjusted inside D and could be rotated by a small motor (not seen on Fig. 7) with frequencies between 25 and 45 Hz. The axis of the motor was connected to the lower end of the main axis (A) of the apparatus by a short piece of vacuum hose. The other end of the motor axis was connected to a revolution counter by a flexible shaft. In the center of R a platinum wire (L) was mounted, the surface of

Fig. 5 Historic pumps used in the original SGE. Left the Volmer mercury diffusion pump, right the Gaede diffusion rough pump [photo HSB]

Fig. 6 Principle of the transverse beam collimation

which was covered by a thin layer (about $20\text{ }\mu\text{m}$ thick) of Ag. It could be heated by an electric current up to the melting temperature of Ag, emitting Ag vapor from the surface. It was very important that the wire remained stretched during heating. Two geometrically very thin beams were created by collimation by slits (S_2), mounted symmetrically on both sides of the wire. These beams condensed on two polished

Fig. 7 Stern's "streak camera" apparatus. G = Glass recipient, R = "rotating streak camera" (within the red dashed line), D = stationary frame, in which the "camera" is rotating, L = Platinum wire, from where the silver atoms evaporate, S₁ and S₂ = slits, P = detection plate. The pumps connected to the glass tubes and the motor are not shown [6]

brass plates (P) in 6 cm distance from the wire. The slits (S₂) were halfway between L and P. A further set of two slits (S₁) (8 mm distance from the wire) was mounted to ensure that the well-defined position of the Ag beam source did not change during the time of the measurement.

In order to measure the atom velocity, the streak camera (R) had to be rotated around the axis A (see Fig. 7, lower part, where the clockwise rotation is indicated by the arrows). In case of no rotation the slits and the wire were aligned on one straight line leading to a small streak in the middle of P. In case of rotation the streak on the detector plate is shifted in opposite direction of the rotation by about 0.4 mm (at a rotation frequency of 25 Hz). The reason is that, depending on their velocity, the atoms need some time to fly from the slit to the detector P while the detector has rotated forward. To obtain a better separation the system was rotated in both directions yielding about 0.8 mm separation.

Although the working scheme of the apparatus is rather simple, it required a number of skills in different experimental fields to make it run successfully: precision engineering, pumping and sealing to obtain a good vacuum, frequency and temperature measurement etc. One may anticipate that the help of the young mechanic Adolf Schmidt was essential for Otto Stern to make the apparatus run. In order to get a good velocity resolution the whole segment R had to rotate with a constant frequency. According to Stern, the required balance of the rotating part and the necessary vacuum sealing at the feedthrough of the rotating axis were the most difficult problems. For sealing the axis they used oil-soaked asbestos rope (see (St) in Fig. 7). Since this sealing was too leaky, they additionally had to evacuate the space M1/M2 where the axis A rotates in a tight-fitting but not touching brass tube (see Fig. 7). Because of frequent heating and cooling the Platinum wire got stretched and had to be adjusted frequently, in order to avoid bending when glowing.

On both detector plates (P) Stern observed two clearly separated lines one for rotating the system clockwise and the other for rotating counterclockwise (see Fig. 8). From the measured separation, the geometry of the streak camera and the rotation frequency he deduced a mean velocity of the beam of about 600 m/sec. Maxwell's theory, however, predicted only 534 m/sec for a temperature of the Ag melting point at 962 °C. Stern assigned this difference to a possible deviation between the measured and the real temperature at the wire.

However, Einstein in Berlin recognized that Stern had made a mistake in his analysis. He had overseen that the transmission flux of the beam through a slit depends on the third power of the atom velocity but not on the square. Walter Grotrian, who reported on Stern's experiment in a seminar in Berlin, where Einstein, Planck, Laue and Nernst [12] were in the audience, wrote in a letter to Stern (on July 30, 1920) and informed him about the discussion in this seminar in Berlin [12]:

Dear Stern!

... Your experiment appeared to all, who listened, also Franck and Reiche astounding and convincingly. After long discussions we were convinced, that also in case of sublimation of a solid, e.g. coal, the mean kinetic energy of the emitted atoms or molecules is $3/2$ kT. Thus the issue was settled.

Then followed the discussion, which I will present in detail. It began with Nernst. His remark was related to experimental details. First he mentioned the rotating electric contact into the vacuum ("Öhse") and named it a master piece. After some insignificant remarks Laue asked, whether the evaporating molecules do really have the mean energy $3/2$ kT. I tried first following your letter to turn the concerns down which were related to the evaporation

Fig. 8 Detector image (see text). Left and right detector plate [11]

energy. Then Einstein stood up and went to the blackboard. He explained now, that one had to distinguish between velocity distribution per volume and the velocity distribution of these molecules which impact on or are emitted from a surface. The latter ones would be shifted to higher velocities.

From what he said and his later discussion with Planck it was not clear whether he was objecting your results or not.

We discussed yesterday again this issue in detail and came to the conclusion: ... The question is: Is the mean square of the velocity distribution of a molecular beam penetrating in one direction per 1 cm^2 through a slit equal to the mean square of the velocity distribution per 1 cm^3 volume?...

We hope that you can inform us soon what is the answer to this question. It would be the best if you could visit us in Berlin.

Yours Walter Grottrian.

Einstein's concerns were proved to be true. On October 20 1920 Stern submitted an addendum to *Z. Physik* with a new analysis of his data based on Einstein's arguments [13]:

In the recent published communication [6] I have reported on experiments where the velocity of Ag atoms evaporated from a melting Ag surface into vacuum was measured with 600 m/sec. This value is within the error bars in agreement with the mean value calculated from the kinetic gas theory at the temperature of the melting point. This result seems to verify the assumption that the Ag atoms, which are emitted from the surface have the same velocity like the atoms of melting silver. But several people have now criticized this assumption, where the objection of Mr. Einstein is justified. The issue is the following: 1. We have a recipient filled with gas at a given temperature in equilibrium state. We now look at

atoms that escape through a tiny hole into the vacuum. These atoms do not have the Maxwell velocity distribution of the equilibrium state inside the recipient in contrast to the analog case of black body radiation. The fast atoms have a higher probability to escape. Following known gas theoretical considerations the number $dn \cdot c$ of the molecules with velocity c escaping through the hole per time unit is equal to the number of atoms per volume unit dn multiplied with the volume of a cylinder of length c . Therefore is $dn \cdot c$ not proportional to dn but cdn .

With this experiment Otto Stern for the first time confirmed that the Maxwell-Boltzmann theory on the velocity distribution of gases at temperature T agrees well with experimental results. By measuring the temperature T of the evaporating gas, Stern, with the help of Maxwell's theory, could deduce the velocity and thus the momentum of the moving atom or molecule. This experiment was the foundation of Stern's molecular beam method (MBM) enabling high-resolution momentum measurements. In the following decades even up to today numerous milestone experiments of quantum mechanics have been performed basing on this method.

In all his publications until his retirement in 1945, Stern never mentioned that his new method provided a high-resolution momentum spectrometer yielding a resolution never achieved before. He presented his data always as function of deflection angles. Therefor the extremely high momentum resolution was not obvious to the readers of his publications. It is important to note that the line width measured by Stern already in this first experiment corresponds to a transverse momentum width of sub-atomic size. This excellent momentum resolution can be estimated from Fig. 9 as follows: Let the velocity of the Ag atoms be 540 m/sec, corresponding to a momentum of about $p = 50$ au. The two lines in Fig. 9 are separated by 0.8 mm (on the detector plate) in 60 mm distance from the wire. Transformed into momentum space this distance corresponds to a momentum difference of $\Delta p = (0.8/60) \cdot 50 \text{ au} = 0.67 \text{ au}$ (see Fig. 9). The width of the left line is then less than 0.2 au, demonstrating the excellent momentum resolution achieved in this experiment. Reducing the slit width, the momentum resolution could even be improved.

In the conclusion of his paper [6] Stern revealed the motivation for measuring the Maxwell velocity distribution:

Fig. 9 Line splitting as function of transverse momentum

A very precise examination of Maxwell's velocity distribution law would be of particular interest. According to the Quantum theory, small deviations occur in gases with a small molecular weight at high pressures and low temperatures, which are estimated to be about 1 percent for hydrogen at the boiling point under atmospheric pressure. Unfortunately, it is not possible to give more precise information about the type and amount of these expected deviations - except, for example, that assuming zero-point energy, the low velocities will occur more rarely than according to Maxwell - because the Quantum theory of translational motion encounters previously insurmountable difficulties. The experimental investigation of these deviations would be thus even more important, and it was precisely this problem that gave me the reason for the present investigation. Unfortunately, the conditions here are also very unfavorable for the experiment, but perhaps gravity will provide sufficient dispersion for the analysis of the low speeds.

Finally, it should be noted that the above method allows for the first time to produce molecules of uniform speed, and e.g. to investigate whether condensation only takes place above or below a certain speed.

The first application of Stern's atomic beam method was performed by Max Born and Elisabeth Bormann [14]. They successfully used an Ag beam in 1920 in Frankfurt to determine the free path length λ of the Ag atoms in air. The Ag beam was collimated by a cascade of round copper screens, in each of which a centric hole was drilled for passing the beam through. When the air pressure in the recipient was gradually increased, more and more Ag atoms were scattered by the air molecule and were deposited on the copper diaphragms, which had been mounted in well-defined distances. The amounts of depositions were carefully measured and it was then possible to use a theoretical scattering model according to Jeans [15] to determine the "free path length" λ of the Ag atoms for the given pressure.

Stern himself used the atomic beam method for the first time in the famous Stern-Gerlach experiment SGE [8], which was carried out in Frankfurt from 1920 to 1922. The SGE demonstrated in an impressive manner what the MBM can achieve as a means for momentum measuring.

In 1928, when he worked as fellow in Stern's laboratory in Hamburg and later as professor at Columbia University in New York and at the MIT in Boston Isidor Rabi developed a new extremely powerful scheme for the application of MBM by using first a SGE approach to prepare atomic beams in well-defined quantum states. In a second interaction region the prepared states could be excited by resonant photon absorption into another quantum state with different magnetic quantum numbers. These states, excited by resonance absorption, moved into a third interaction region on a different trajectory and could be detected separately. He and his group very successfully applied this method to use the very narrow line width of photon absorption for high precision measurements of transition energies, like e.g. the Nobel Laureates [16] Willis Lamb and Polykarp Kusch for measuring the so-called Lamb-shift, Norman Ramsay to develop the Cs atomic clock (with 10^{-9} precision), Felix Bloch and Henry Purcell for developing the Nuclear Resonance technique etc.

Since 2002, when in Frankfurt the 80th anniversary of the SGE was commemorated, one of the authors (HSB) looked for remainders of the historical experimental set ups used by Stern at the various working places of Stern and Gerlach. The only parts he found were the microscope bought by Stern in 1919 from the company of

Seibert in Wetzlar (found in Berkeley) and the Volmer diffusion pump (found in Frankfurt). Obviously the historic apparatus did no longer exist. Therefore, the idea was born to reconstruct both experimental apparatus of Stern: the set-up to measure the Maxwell-Boltzmann velocity distribution and the famous Stern-Gerlach experiment. While the Stern-Gerlach experiment is still waiting for its reconstruction, the first one was now reconstructed and was put into operation. In the following the reconstruction and the successful commissioning of the first apparatus is described.

2 Reproduction of Otto Stern's Atomic Beam Velocity Measurement

2.1 *Reconstruction of the Apparatus*

On the occasion of the 100th anniversary of Stern's appointment to Frankfurt, the initiative was taken to reconstruct the historic set up, which did no longer exist, and to reproduce Stern's famous measurement of the velocity of Ag atoms in an atomic beam. Based on the drawings and the detailed description in Stern's publication [6], and sponsored by Roentdek Handels GmbH, a number of identical copies were fabricated in the workshops of the Institute for Nuclear Physics in Frankfurt.

One of the copies was given to the Gymnasium Riedberg at Frankfurt with the requirement to repeat Otto Stern's measurements and, if possible, to verify his results. This task was adopted by a team of high school students from the 10th grade, who founded an "Otto-Stern-Arbeitsgemeinschaft" (OSAG) and, under the supervision of their physics teacher, Axel Gruppe, started to work on this project in summer of 2015. Their work was presented at the VDI Student Forum 2015 [17].

First, the students read Otto Stern's biography to get an impression of his scientific achievements. Then they began to examine the optically very appealing replica (Figs. 10 and 11) in view of its suitability in a real experiment, which Otto Stern described in great detail in his work from 1920 [6]. The following points were studied in detail: the trajectories of the silver atoms, the measurement of the rotation frequency, the mean free path of the silver atoms and the measurement of the temperature of the platinum wire.

2.2 *The Trajectories*

Anticipating the rotating frame to be at rest, it appears beyond question that the silver atoms, emitted from the Platinum wire, will fly through the slit diaphragms S1 and S2, which are aligned on a straight line with the emitting wire, and will impact on the collecting plate P exactly at the point, where the straight line hits P. But how does the trajectory change when the frame rotates?

Fig. 10 Plan for the restoration of Stern's "streak camera" system

To understand this, one has to convert the path of the silver atoms, which in the laboratory system corresponds to a rectilinear, uniform motion, into the rotating coordinate system of the frame of the camera (R), with which the diaphragms and the collecting plate are firmly connected.

In [6] Stern describes the trajectory of the atoms in the co-rotating system as to represent a "horizontal throwing parabola" ("... by neglecting the centrifugal acceleration and the change in the Coriolis acceleration.").

In order to get an impression of the parameters of this parabola, the students developed an EXCEL worksheet for the coordinate transformation of the rectilinear,

Fig. 11 Reconstructed apparatus to measure the Maxwell velocity distribution (without vacuum pumps and diagnostics)

uniform atomic motion into the rotating aperture system and thus studied the intricacies of Stern's experiment. In the upper part of Fig. 12 one can see the wire L in the coordinate origin of the rotating system X'/Y' as well as the slit diaphragms S1, S2 and the collecting plate P.

Starting from L with a velocity of 500 m/s, the Silver atoms have to be emitted at an angle $\alpha = -0.55^\circ$ relative to the X' -axis, to pass through slit diaphragm S2. It is evident that in this case the beam trajectory does not pass through S1 with the result that the silver atoms will not hit the detection plate P. To make the trajectory passing through S1 and S2, the location of the emission point must be shifted in the Y' direction (Fig. 12, lower part).

This is the reason why Otto Stern had rolled down the initially round wire (0.4 mm diameter) to a width of 0.6 mm in the Y' direction [6]. By this, he wanted to ensure that the locations of emission of the Silver atoms enable trajectories that run through both S1 and S2. With these calculations, the students also realized how small the expected shift really is. At a rotation frequency of 25 Hz, the displacement of the point of impact for silver atoms with $v = 500$ m/s is only about 0.5 mm in the Y' direction!

Fig. 12 Trajectories of the silver atoms in case of rotation ($f = 25 \text{ Hz}$). Upper picture: the atoms start at L on the straight line passing through apertures S_1 and S_2 . Since the trajectory has the shape of a parabola, no silver atom reaches the collecting plate P. Lower picture: The silver atoms must start from a point L shifted by dy' in the Y' direction from the center of rotation in order to reach the collecting plate P through the two apertures

2.3 Measurement of the Rotation Frequency

Since the slit diaphragms have a width of 0.2 mm, a 0.4 mm wide silver line is expected on the collecting plate. Under the most favorable conditions, the silver lines with the streak camera at rest and with the rotated camera would then be separated by just 0.15 mm. The students calculated that at a speed of 25 r/s a fluctuation of $\pm 2 \text{ r/s}$ would lead to a shift in the impact point of $\pm 0.1 \text{ mm}$. Therefore the fluctuation of the rotation speed must not exceed this value if one wants to be able to separate the two silver lines and the rotation speed had to be controlled with sufficient accuracy. To achieve this a digital speed counter was designed and built by the students [18]. In this design, signals from chopping a light barrier by a slotted disc, which was

attached to the axis of the built-in direct current motor, are read out and displayed as a frequency on a 4-digit 7-segment display by means of a tricky circuit.

2.4 Mean Free-Path and Quality of the Vacuum

Considering the dimensions of the original equipment, one may wonder, why it was not built larger, as the offset, and hence the effect would become larger, the longer the distance between source (L) and the screen (P) would be. At this point, the quality of the vacuum comes into play. The deposition lines of Silver will only sharply be imaged on the collecting plate (P) if the silver atoms do not undergo collisions with air molecules during their flight. Therefore the vacuum inside the apparatus must be good enough to avoid such collisions as far as possible. In order to estimate this influence, the students investigated the physics of the “mean free path” (MFP). MFP is the distance a molecule travels on average in a gas before it collides with another molecule. (According to the definition, the average number of molecules in an atomic beam, which have not yet collided with a residual gas atom, is only 1/3 after the beam has passed the length of MFP [19]). In addition to the temperature, MFP is essentially dependent on the gas pressure in the recipient.

For air at 20 °C the students found a value of $\text{MFP} = 6.8 \times 10^{-3} \text{ mbar cm/p}$ [19]. Otto Stern mentions 1/10,000 mm ($=1 \times 10^{-4}$, torr = 1.33×10^{-4} mbar) as the required vacuum. This corresponds to an MFP of approximately 50 cm in Stern’s apparatus. According to the nomenclature of vacuum technology, such a pressure is already termed “high vacuum”. This means that in Stern’s experiment only about 8% of the silver atoms collided with an air molecule on their 6 cm path to the screen.

2.5 Measurement of the Temperature of the Filament

Another difficulty was the measurement of the temperature of the silver-plated platinum wire. Stern writes in [6]: “Now the temperature of the evaporating silver was certainly higher than 962° because the molten silver contracts to form droplets and the parts of the platinum wire that have been freed from silver assume a higher temperature due to their higher resistance, which increases due to conduction to the Silver droplets. According to the brightness, the temperature should have been around 1200° ...”. The mention of the brightness of the wire by Stern suggests that he used a pyrometer to measure the temperature. Fortunately, a functional pyrometer from Hartmann and Braun (“Pyropto”, manufactured in 1951 [21]) was found in the collection of the physical internship of the Institute of Applied Physics, and was kindly donated to OSAG.

2.6 *The Improved Experimental Setup and the Decisive Measurement*

After the essentially theoretical and preparatory work accomplished by this first OSAG at the Gymnasium Riedberg, the work was transferred back to the Goethe University. In discussions with physicists and mechanics of the Institute for Nuclear Physics Research (IKF), it became clear that the available replica of the Stern apparatus had to be changed in several details in order to successfully start with the next step, i.e. to reproduce the measurements from 1920:

- The sealing surface of the base plate for the glass bell was reworked.
- The cross section of the pump opening in the base plate was enlarged.
- The feed-through of the axis in the base plate was reconstructed. It was additionally encapsulated as in Stern's original equipment [6] so that this area could be evacuated separately by the backing pump.
- The power supply to the platinum wire was redesigned in order to be able to supply the comparatively high currents (up to 8A) at rotation frequencies of up to 45 Hz without interruption.
- The clamping device for the platinum wire was modified to withstand the high temperatures (up to about 1200 °C) and to maintain the mechanical tension of the platinum wire during the heating-related extension.
- During assembly, the unbalance of the rotating system was minimized with great mechanical effort.

In the school year of 2018/19, a new OSAG at the Gymnasium Riedberg started to perform measurements with the improved equipment. In the first test runs, it became clear that the necessary constancy of the rotation frequency could only be achieved with the help of a speed control of the DC motor. Using an Arduino[®] microcontroller, the students first built a simple linear control loop, the control oscillations of which, unfortunately, were still too large. However, reprogramming the Arduino to a more sophisticated proportional-integral-derivative (PID) controller led to the desired success (Fig. 13).

With the successful establishment of the PID control, all preparations for repeating the Stern experiment were completed in summer 2019. The final experimental setup is shown in Figs. 14, 15, 16, 17, 18 and 19.

The decisive measurement took place on August 30, 2019. Initially, the members of OSAG recorded a weak but clearly visible Ag line at a rotation speed of 45 r/s. During a second irradiation with the camera at rest, the lower part of the detector plate was covered with a plastic film to facilitate detection of the separation of the two lines. Figure 20 shows a scan of the brass plate which has been processed to enhance contrast. The evaluation shows a distance of the line centers of 0.62 mm with an estimated accuracy of 10% to 15%. This result must be compared with the value that Otto Stern presented in his publication [13]: "For 2700 tours (i.e. rotations/minute),

Fig. 13 The proportional-integral-derivative (PID) control of the rotational speed. Above: the time course of the manipulated variable (pulse wave modulation). Below: the time course of the regulated rotation frequency. In this case the PID controller has settled after 20 s and keeps the rotation speed constant at 45 ± 0.5 r/s

the distance between the centers of the two lines created with right and left rotation was 1.26 mm". Otto Stern's value divided by 2 yields 0.63 mm, which is in excellent agreement with the value measured by OSAG (0.62 mm at 45 r/s = 2700 tours with all other experimental parameters kept identical as far as possible). After a few measurements, the platinum wire had to be readjusted regularly (Fig. 21).

The OSAG team was very much impressed by this excellent agreement 100 years after the original measurement by Otto Stern. The participants were very proud that they had managed to successfully complete this experiment, which was easy to understand but technically difficult to carry out.

From the teacher's point of view, this project was an ideal example of how to offer students deep insights into the interplay of theoretical and experimental physics with the help of an ambitious topic and authentic material.

Fig. 14 The final experimental setup of the Otto Stern experiment in 2019: In the center: glass recipient with pressure gauge on an iron plate. Inside, the fixed frame with the rotating slit system is visible. On the right: parts of the vacuum system with backing pump (red, in front) and turbo-molecular pump (rear). In the foreground in front of the glass bell stands the pyrometer (“Pyropto”, Hartmann & Braun®) for temperature measurement. Right front: PID controller for speed control on breadboard with an ARDUINO® controller. Rear right: controllable DC power supplies for the motor and the heating wire. Below is the vacuum measuring device with the vacuum display. The Pirani and Penning sensors (Balzers®) are positioned under the base plate and are not visible. On the left: Laptop for setting and logging the rotation speed during the measurement

Fig. 15 The view through the pyrometer. The bent pyrometer wire is adjusted to the same brightness as the vertical platinum wire (left: at room temperature, right: at 1050 °C)

Fig. 16 The Members of the Otto-Stern-AG during a measurement (from left to right: Leander Weimer, Nils Müller, Simon Cerny, Jakob Hoffmann)

Fig. 17 The glowing platinum wire in the center of the rotating slit system at a rotation speed of 45 r/s

Fig. 18 The slit system with the detector plate after the experiment. On the right is the platinum wire; on the left, next to it, is the first slit aperture, which is completely covered with silver. To the left of it is the second slit aperture on which one can clearly see the “shadow” of the first slit aperture. On the far left, the detector plate is to be seen, on which a faint, brownish Ag line is just visible

Fig. 19 According to legend, Otto Stern “developed” the faint traces of Ag on the brass plates by cigar smoke, as Leander Weimer and Nils Müller also tried after the experiment

Fig. 20 Contrast-enhanced scan of the collecting plate. The longer thin line on the left was recorded at a speed of 45 r/s. The shorter line on the right was taken with the camera at rest. The distance between the line centers is 0.62 mm

Fig. 21 The mechanic Stefan Engel balancing the equipment

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