Chapter 3
Music and Science: Tribute to Rolf Hagedorn

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Abstract I present here Rolf Hagedorn as a man, and present his achievements as a physicist. He has made several very important contributions: to particle and nuclear fields of research: The Hagedorn Temperature and the Statistical Bootstrap Model are concepts that are here to stay, and which have stimulated much further research. But Rolf Hagedorn is also a wonderful person and, saying that, does not require a specialist.

3.1 Personal Remarks

Visit to India

I first met Rolf Hagedorn (Fig. 3.1) in Madras in the fall of 1963. I had only seen him briefly earlier, and knew of him as a member of the CERN theory group. Madras, where we spent three full months together, is the place where I really got to know him. We had independently responded to the call of Alladi Ramakrishnan and were each giving a one-term lecture course at Matscience. Hagedorn was teaching relativistic mechanics based on his CERN lectures and a book which he had recently written on the subject.

We spent plenty of time together, sharing this fantastic Indian experience, and I greatly appreciated the friendship which he extended to me despite our difference in age. I strongly felt the sensitivity with which he was reacting to everything. I was impressed by his thoughtful kindness and his benevolent understanding in front of

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Fig. 3.1 Maurice Jacob (in right of center *back part of picture*) flanked by Ms Jenny (Léon) Van Hove on his *left*, and by Ms Mary (John) Bell on his *right*, observes Hagedorn's reaction to his 75th birthday gift, photo taken shortly before this address; *CREDIT: CERN Photo 1994-06-067-018*

many features of Indian life which were bringing a complicated mixture of great admiration and some of the times feelings of revulsion to our western eyes. His long war years had shaped up his compassion for humankind.

Rolf was a magnificent traveling companion and the great pleasure which he had in discovering these gorgeous temples of southern India was communicative. I remember him summarizing his visits saying, "Now I have seen something beautiful. I am happy". He was a zealous photographer and he collected a magnificent series of photographs which I admired later. He had clever ways to take close-up pictures of people without embarrassing them. I admired his skills.

I never saw Rolf lose his temper. His only strong reaction which I can recall was during a night which we spent in a guest house in an Indian wildlife reserve at Bandipur. This was during a wonderful 4-day trip which Lise and I shared with him through the magnificent Mysore area. During the middle of the night the guest house, where we had been alone in the evening, was invaded by a very noisy group of visitors who stormed it past midnight as if it was their own. I still remember Rolf shouting, "Since it is a guest house you should have realized that there could be guests inside".

Art and Music

I recall his appreciation for the magnificent Indian music which we heard in Madras. We listened together to "monuments" such as M.S. Subulakshmi and Ravi Shankar. The carnatic music of Subulakshmi is very different from our classical western music but Rolf would say, "Music can take many forms but one can always recognize and fully appreciate great music".

If I may at this point venture a hypothesis, I would say that music may have even played a role in Rolf joining the CERN Theory group. Rolf Hagedorn had come in 1954 to CERN to be at first an accelerator physicist, working with Schorr on accelerator theory. But his office was next to that of Jacques Prentki and Bernard D'Espagnat.

Jacques and Rolf could share their love for music during many discussions and also talk physics. Jacques told me that he remembers Rolf talking in a seminar about "an ensemble of accelerators". We notice here the influence of thermodynamical concepts! But, back to music: I was told that they were surprised to discover a common appreciation for Heinrich Schütz.

A student of Monteverdi, Schütz is considered by the experts as the initiator of Baroque music. He may not compare to the many giants who followed him and in particular to Bach but Rolf would say, "Bach is like the Alps when Schütz is rather like the Jura, and ... I like the Jura". This we know he does, living in the countryside where the slope of the Jura starts to rise sharply, and sharing with his wife this pleasant and quite country life with cats, horses and lots of music.

3.2 Contribution to Research

Torleif Ericson, for many years his neighbor in the TH Division, has told us about Rolf Hagedorn's place at CERN. I will turn now to the difficult task of trying to summarize in a few phrases Hagedorn's contributions to our field of research.

First with generalities, one may say that it is in the line with the brilliant Germanic tradition in statistical thermodynamics and Rolf may find well-deserved pride in having his name associated with a temperature. It is also in line with the phenomenological approach whereby one tries to understand and predict according to models. It is finally in line with the desire of any theorist to achieve a powerful synthetic view, providing a rationale for the observed phenomena. The Statistical Bootstrap Model, which is Hagedorn's brain child, fits perfectly the latter point.

Thermal Particle Production

Particle production processes are now so well known that they are taken for granted. Nevertheless the fact that very high energy collisions generally result in the production of many secondaries first came as a surprise to many. Having admitted that this is the case, the idea to try to apply the wide body of knowledge of statistical thermodynamics to such production processes may naturally come to mind.

However, difficulties quickly speak for themselves. Great minds like Fermi and Landau indeed made clever attempts but with unsatisfactory results. Particle physics and statistical physics were long separated. This is no longer the case! In particular, we now know of the great successes that were later met at the interface of statistical physics and field theory.

The contribution of Rolf Hagedorn concerns the application of statistical physics to the phenomenology of hadronic interactions, a field of research in which at CERN Léon Van Hove was also much interested, and which he described as follows: "A meeting ground between particle and statistical physics, a dialog between theory and experiment".

Rolf Hagedorn's work started long before I came to CERN. My understanding is that Bruno Ferretti, who was head of the Theory Division when Hagedorn joined it, asked him to try to predict particle yields in the accelerator high energy collisions of the time. This he started with Frans Cerulus. There were few clues to begin with, but they made the best of the fireball concept which was then supported by cosmic ray studies and used it to make predictions about particle yields and therefore the secondary beams to be expected from the machine beam directed at a target.

Many key ingredients brought soon afterward by experiment helped refine the approach. Among them one should quote the limited transverse momentum with which the overwhelming majority of the secondary particles happen to be produced. They show an exponential drop with respect to the transverse mass. One should also quote the exponential drop of elastic scattering at wide angle as a function of incident energy. Such exponential behaviors strongly suggest a thermal distribution for whatever eventually comes out of the reaction and it is to Rolf's great credit to have clung to this thermal interpretation and to have used it to build production models which turned out to be remarkably accurate at predicting yields for the many different types of secondaries which originate from high energy collisions.

Limiting Temperature

What could actually be "thermalized" in the collisions? Many objections were raised at the time. Applying straightforward statistical mechanics to the produced pions was indeed giving the wrong results. But, even if there was a thermalized system at all, why was the temperature apparently constant? Shouldn't one have expected it to rise with incident energy or with the mass of the excited fireball?

It was Rolf's great merit to interpret the apparently limiting temperature which could be associated with the transverse mass distribution of the secondaries as resulting from an exponential mass spectrum for the many resonant states in which hadrons can be excited into before these resonance would fragment into less massive ones to eventually give, at the end of the line, the observed secondary particles.

The rise of the temperature is associated with the population of higher and higher energy levels by the elements of a system. If there is an exponentially increasing number of level offering themselves to be filled, the temperature saturates. It is the entropy which eventually increases with the collision energy but the temperature gets then stuck to a limiting value. This is the Hagedorn temperature. It is of the order of 150 MeV, close to the pion mass.

The impressive number of states which have now to be considered at the same time leads to a new writing of equations based on statistical physics. The factorial n factor, which was plaguing statistical calculation focusing on pions only and which was introduced to rightfully avoid multiple counting in phase space integrals, now had to be dropped, since each one of the many states was unlikely to have a population exceeding one. Agreement between experiment and statistical calculations prevailed at long last.

In his popular book, “The Quark and the Jaguar”, Murray Gell Mann explains how progress in physics often results from the dropping of a condition which was long considered as mandatory and which had not been properly challenged. This applies very well to this $1/n!$ factor which as Rolf concluded for the hadronic system effectively had not to be there after all.

Statistical Bootstrap Model

Despite the great success of the Hagedorn approach at predicting particle yields, we may still have reservations at speaking about a temperature in collisions among elementary particles but, as we shall see later, this applies to heavy ion collisions which are attracting an increasing interest and attention. But now comes Rolf’s great achievement in pioneering the development of the Statistical Bootstrap Model. Rolf has beautifully described its genesis in *The Long Way to the Statistical Bootstrap Model* see Chap. 17 in this volume.

To put it in a nutshell, one may say that each of the many resonant states in which hadrons can be excited through a collision is itself a constituent of a still heavier one while being also composed of lighter ones. What Hagedorn showed is that when one puts logic and hard work into the idea one cannot escape an exponential spectrum of resonant states. The temperature of such a system is then limited from above.

This limit is the Hagedorn temperature. If one takes a more global view, talking about “fireballs” (in the old language) or “clusters” (in the more modern vernacular) rather than of resonances, the conclusion is that the temperature of such objects is independent of their mass. One can then also understand why the limiting temperature is of the same order as the mass of the smallest mass state, the pion.

The concept of an exponential spectrum is now part of our understanding of hadron phenomena. It has been reached through different approaches such as that offered by dual models. It fits beautifully the hadronic level counting which can now be followed up to over 4,000 cataloged resonances Rolf was first at pinning it down through his Statistical Bootstrap Model. The Statistical Bootstrap Model has been at the origin of many further works which have refined it. Rolf was thus at the origin of an important and very fruitful line of research.

Can one go beyond the limiting temperature set by Hagedorn? The answer is yes, but one has to consider a phase transition whereby one leaves the hadronic phase to reach a new phase where the hadron constituents, the quarks and the gluons, are no longer confined. The limiting temperature becomes a phase transition temperature which can be calculated by means of lattice gauge theory method.

The ongoing experimental and theoretical work bears witness to all the fascinating activities which now go on applying statistical and thermodynamical concepts to heavy ion collisions. Rolf Hagedorn can take fully justified pride in having pioneered and followed this line of approach for a long time and this despite the many stumbling blocks which he had to overcome. We can rejoice with him that many of his views have been vindicated by recent and promising developments.

3.3 Active Retirement

We can also rejoice with him that his "pro forma" retirement in 1984, which has kept him close to CERN and we enjoy his frequent visits. We are happy to see him following closely and participating in present research. His talk at this conference bears magnificent witness to that.

In connection with Rolf "pro forma" retirement, I should conclude by saying that I was thrilled to have Rolf as a test case when pushing through the Management Board, together with Adolf Minten and Allan Wetherell, a special status for "retired scientists willing to continue research".

Rolf Hagedorn was the first person at CERN to be granted the new status. Great was my joy when I could leave with him the letter from the CERN director general Erwin Schopper written to that effect which had followed by a mere few days the approval of the new scheme.

Let me try to summarize Hagedorn's research through a modest limerick (Fig. 3.2):

There are many hadrons with strong interaction
Which behave thermally in their curious motion
Rolf Hagedorn showed long ago
How S-B-M can make it go
Exponential spectrum is the explanation.

Fig. 3.2 Maurice Jacob (*center*) follows Rolf Hagedorn accompanied by Ms Mary (John) Bell. *CREDIT: CERN Photo 1994-06-065-026*