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The Nilsson Model and Sven Gösta Nilsson

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It was certainly a very good idea our Swedish colleagues had to collect this community working on finite Fermi systems in order to mark the 50th anniversary of Sven Gösta Nilsson's wonderful paper on 'Binding States of Individual Nucleons in Strongly Deformed Nuclei' [1]. I want also to thank the organizers for giving me the privilege of providing a short reminiscence of the person Sven Gösta and the scientific state of nuclear physics that provided the context in which this seminal paper was written.

There had been for many years fruitful interaction and exchange between the physicists in Lund and in Copenhagen based on the personal friendship between Torsten Gustafson in Lund and Niels Bohr in Copenhagen. It was in the framework of this continuing interaction between the two institutes that Sven Gösta, who already had attracted the attention of his teachers, came to Copenhagen in 1952, as a fellow in the CERN theoretical group, that was temporarily located in Copenhagen while the permanent facilities were being built in Geneva.

Figure 1. Sven Gösta Nilsson (1926–1979). This picture of Sven Gösta is, I think, a wonderful document reminding us of his presence, his enthusiasm for life, and the twinkle in his eyes betraying his acknowledgement of the humerous ambiguity of the human condition.

Sven Gösta did not work on particle states in heavy nuclei duriing his first year in Copenhgen. Rather, he was captured by Tommy Lauritsen. Tommy, an experimentalist from California Institute of Technology, was on sabbatical leave in Copenhagen and was doing an experiment involving the scattering of deuterons on helium. He was by far the most colourful personality in the whole Institute in Copenhagen. He captured Sven Gösta and got him to describe the angular distributions that were being measured in this resonance scattering process.

This led to the determination of the spin and parity of the first excited state in ^{6}Li which turned out to be 3^+ which is an important confirmation of the coupling scheme expected for a system in which there is a strong spin–orbit interaction, tending to make the direction of the spin parallel to that of the orbit. Tommy was tremendously impressed by Sven Gösta's contribution to this work, and it looked as if this was the beginning of a career involving the light nuclei that everybody at Caltec was working on. But that was not to be. There was simply too much happening in the discoveries and understanding of much heavier nuclei. For example, in 1953 for the first time sequences of rotational states were observed obeying quantitatively the $I(I+1)$ energy dependence of a rotating quantal rigid body. In the same year the experimentalists Torben Huus and Crtomir Zupancic in Copenhagen discovered that the Coulomb excitation reaction could be used as a powerful new tool for exciting nuclei into rotational states [2].

The perspective opened by these developments led Sven Gösta to turn away from the study of the light nuclei, and to take up the fundamental problem of the analysis of single-particle motion in non-spherical symmetry. That problem involved diagonalizing the particle motion in a potential that deviates significantly from spherical symmetry.

The potential that Sven Gösta introduced,

$$V = \tfrac{1}{2}M\left[\omega_\perp^2(x^2+y^2)+\omega_z^2 z^2\right] + C\vec{l}\cdot\vec{s} + D(l^2 - \langle l^2\rangle_N)$$

involved an axially symmetric deformed harmonic oscillator, plus a spin–orbit term and the fourth term, proportional to D, that can be adjusted to correct the radial dependence of the potential for spherical nuclei. The magnitude of the deformation is controlled by the difference of the two oscillator frequencies, $\omega_\perp$ and ω_z.

This last term was quite important since it made it possible for Sven Gösta to incorporate the growing amount of experimental evidence that was becoming available concerning the sequence of single particle orbits in spherical nuclei. Indeed, I believe that it was this term that provided the crucial difference between Sven Gösta's work and that of the several other competitors in the scientific community who were at the same time calculating the spectrum of single particle levels in deformed potentials. When it came to explaining the rapidly expanding body of data on deformed nuclei, Sven Gösta's spectra were alone in providing the guiding light in this new spectroscopy, because only his potential started out from the correct sequence in spherical nuclei.

The numerical diagonalization of the matrices involved (up to dimensions 7×7) required that Sven Gösta travel to Stockholm in order to exploit the power of the BESK computer (at that time the largest available for scientific computation in Sweden). The work was carried out and the famous paper [1] shown below was published. In particular, the fold-out diagram of eigenvalues as functions of deformation marked a turning point in thinking about nuclear spectra.

To describe the period after the appearance of this paper, I think it captures very much the spirit of this time to remember Victor Weisskopf's summary talk at the Kingston conference 1960. He says:

'Another impressive indication of the validity of the independent particle model is the immense success of the Nilsson scheme. We all know the famous level scheme and the popularity of his paper—I am sure this is the one paper which one finds on the desk of every nuclear physicist.'

That was really true. That was the one paper that this very large community was using to interpret the rapidly expanding amount of experimental data that was being discovered. Now I would like to briefly run through the physics that was coming out of this marvellous paper. An appreciable part of all nuclear structure physics for the next 15 years was concerned with the exploration of the rich variety of physical phenomena that could be addressed by exploiting the solutions that Sven Gösta had found.

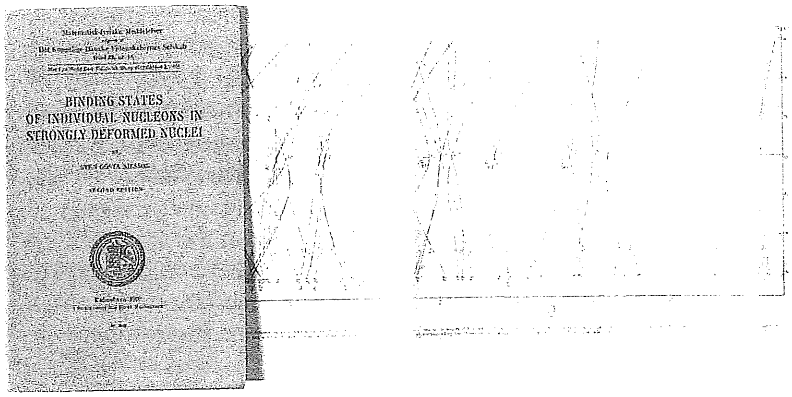

Figure 2. Nilsson's famous paper from 1955 [1] with the single-particle diagram as a fold-out. The second edition from 1960 is shown.

The application of the Nilsson Model 1955–1970 can be summarized as:

- Classification of ground states and low-lying excitations
- Selection rules for low-lying transitions
- Nilsson eigenvalues determine equilibrium shape
- Identification of polarization effects (effective moments)
- One-particle transfer measures the coefficients in the Nilsson wave functions
- Asymptotic quantum number can be seen as a generalization of Elliott's SU(3)
- Cranking model with Nilsson and pairing determine the rotational moment of inertia

It began with the classification of ground states and low-lying excitations. Actually Sven Gösta and I had published a paper [3] that came out just before his paper [1] where we applied this scheme for the first time to experimental data. It was published in a memorial issue of *Zeitschrift für Physik*, dedicated to the atomic spectroscopist Hans Kopfermann. It was applied to the nucleus ^{169}Tm, which has the spin $\frac{1}{2}$ in the ground state, and the experimental data defined the rotational band built on that configuration. The Nilsson scheme described in detail the decoupling factor, the magnetic moment, the magnetic transitions, and the electric transitions within this rotational band, brilliantly showing the relevance and the power of Sven Gösta's calculations. Then, for the next four years, Sven and I worked closely together extending that single example, first to classification of the ground states of the rare-earth nuclei [4], and subsequently to the low energy single particle spectra in all the different regions of deformed nuclei in the periodic system. In all regions where there occurred deformations, it was found that this scheme presented a unique and decisive interpretation of the available spectra. Selection rules for low-lying transitions and the use of eigenvalues, the energies of the different states, could be used to determine the equilibrium shape of the nucleus by carrying out a minimization of the sum of single particle energies. The detailed calculations of transitions revealed the existence of polarization effects; that the single-particle pulls and pushes the rest of the nucleus a little bit and thereby induces electric and magnetic moments that are different from the moments of a nucleon moving in free space. The effective polarization; because the Nilsson wave-functions were so precise and detailed that these effects could be measured and the effective moments of the single particles could be determined.

The one-particle transfer reactions measure expansion coefficients of the Nilsson wave functions. They are Nilsson fingerprints for the excited states of the many low-energy spectra of deformed nuclei. The period in the middle of the 1960s provided the determination of these fingerprints, especially for the rare-earth region, directly from experimental data.

There were also contacts with the general many-body nature of rotational motion, first through the asymptotic quantum numbers which provided a generalisation of the SU(3) scheme. One of the most interesting demonstrations of the pair correlations in nuclei, in fact the only clear evidence for the correlations involved, comes from the calculations of the moment of inertia of rotating nuclei [6]. The Fermi surface is smoothed out by any interaction, but only a pair interaction induces the correlations that are necessary to reduce the moment of inertia systematically below the rigid-body value. In a work in 1961 by Sven Gösta together with Prior these features were quantitatively worked out [7].

That was the era in which this marvellous new breakthrough in the understanding of independent particle motion in nuclei was experimentally and theoretically developed.

I want also to say a little about what came after this. In 1963 Sven Gösta took up a professorship at the Technical University in Lund. He immediately attracted a large group of students and colleagues, whom he inspired and led in a way that very much reflected that personality we saw in the picture. He concerned himself about his students, also with personal problems. He brought this community into his home and they experienced the warmth of his personal contacts and also his enormous enthusiasm for the physics which had been discovered and the excitement of being apart of this international community working to understand the properties of nuclei. The members of this group are one of the great legacies we have in the whole physics community that continues even today.

I want to say a few words about the issues that were especially discussed by this group:

- Independent particle motion for very large deformation illuminating the fission process and the fission isomers,

the remarkable states in the heavy element region that have fission life-times that are factors of 10^{20} shorter than the spontaneous fission lifetimes of the ground state of the same nucleus. The next problem attacked was

- The island of stability expected beyond the heaviest known nuclei—so-called super-heavy nuclei,

a quest that is still continuing and making progress and gradually exploring further and further along the peninsula of particle stability. Finally, during the last years of his career

- The yrast spectra up to the highest angular momentum allowed by the fission instability

became a problem that captured his interest.

Looking at that list, it is interesting to notice the issues that were being discussed, but not included in Sven Gösta's major interests:

- The reason for the validity of independent particle motion
- The origin of shell structure in periodic orbits
- Why the overwhelming dominance of prolate over oblate deformation?

These matters, I think, were less important to Sven Gösta. There is an interesting issue involved. All these problems invite speculations about how nuclei look if they become arbitrary large, if you let mass number $A \to \infty$. It is the condition for being able to discuss the questions that are involved here. That kind of speculations seemed to be on the edge of Sven Gösta's interest. His interests reflected a more down to earth point of view.

It was as if each particular nucleus was a God-given gift, which we must learn to understand in terms of its properties, and comparison of those properties with the other nuclei that can be experimentally studied. The rational extension of that area to include super-heavy nuclei, rapidly rotating nuclei, or drip line nuclei were appropriate extensions—because all these other nuclei could also be measured. But going to infinity was just a kind of speculation, a type of hypothetical nuclei that attracted his interest less. I think that we should not make too much of that, because it is very hard to know what a person is not thinking of. On the other hand there may be a message to us as we consider the nature of Sven Gösta's wonderful wide ranging contributions to nuclear physics.

His contribution has inspired us all and it is marvellous to be here together.

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EDITORIAL

International Conference on Finite Fermionic Systems: Nilsson Model 50 Years

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In 1955 Sven Gösta Nilsson published the paper 'Binding States of Individual Nucleons in Strongly Deformed Nuclei'. This eminent work has been crucial for the understanding of the structure of deformed atomic nuclei. Moreover, the so-called Nilsson model has been widely used for the description of other types of finite systems of fermions such as quantum dots and cold fermionic atoms. During one week in June 2005 we celebrated in Lund the 50th anniversary of the Nilsson model with the *International Conference on Finite Fermionic Systems—Nilsson Model 50 Years*. With the historical view in mind, the conference focused on present and future problems in nuclear structure physics as well as on the physics of other types of finite Fermi systems. As a background to the recent developments Nobel Laureate Ben Mottelson presented a recollection of early applications and achievements of the Nilsson model in the first talk of the conference, including a personal view of Sven Gösta Nilsson. We are particularly pleased that this contribution could be included in these proceedings. The scientific programme was structured according to the following subjects:

- Shell structure and deformations
- The heaviest elements and beyond
- Nuclei far from stability
- Pairing correlations
- Nuclear spectroscopy: large deformations
- Nuclear spectroscopy: rotational states
- Order and chaos
- Cold fermionic atoms
- Quantum dots

Many new and interesting results were presented in the 15 invited talks, 30 oral contributions, and in the 33 papers of the poster sessions. The present volume of *Physica Scripta* contains most of the talks, as well as the short contributions of the posters.

We thank the speakers and all participants who actively contributed to give this memorable conference a very high scientific level in the presented contributions, as well as in numerous discussions inside and outside the sessions. We also thank the international advisory committee for their invaluable work in helping us setting up a high standing scientific programme. Finally, we thank the Royal Swedish Academy of Sciences through its Nobel Committee for Physics, the Royal Physiographical Society in Lund, the Technical Faculty (LTH) at Lund University, and the Swedish Research Council (VR) for financial support.