WALTER GREINER
Memorial Volume

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Contents

The Early Work of Walter Greiner (1960–1968)

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The first decade of Walter's Greiner scientific career is analyzed. It is a timespan of outstanding achievements in various subjects of theoretical nuclear physics: nuclear collective motion, and theory of nuclear reactions.

1. Scientific Genealogy

Walter Albin Erhard Greiner steems from one of the most prodigious scientific lineages. According to the Mathematical Genealogy Project[1] his genealogic tree plounges its roots deep into the fertile soil of German culture and science. No doubt it can be compared with other German scientific dynasties such as the one starting with Gottfried Leibniz, continuing with Fr. Gauss and Felix Klein, which subsequently evolves in the modern physics branch (Sommerfeld – Pauli – Heisenberg – Bethe), continuum mechanics branch (Prandtl – Timoshenko – von Kármán), and mathematical physics branch (Hilbert – Courant – von Mises – Weyl). The genealogic tree of Walter Greiner, displayed in Fig. 1, starts with Friedrich Leibniz (the father of Gottfried Leibniz) and includes names that are forever engraved in the Pantheon of German culture (Georg Lichtenberg), mathematics (Karl Weiserstrass, Carl Runge), and modern physics (Max Born). The "grand-father", Siegfried Flügge (1912–1997), was also a remarkable theoretical physicist and teacher. He published in the thirties influential articles on the exploitation of nuclear energy and during the war, in collaboration with C. F. Weizsäcker, he worked on the theoretical basis of uranium reactors and extended the Bohr–Wheeler theory on nuclear fission to the transuranic elements.[2] The famous collection of problems in Quantum Mechanics was first issued in 1947 and as Walter Greiner recalled in 1983,[3] this book, known also as the "Flügge–Marschall", was an ubiquitous didactic material for the German post-war generations of theoretical physicists.

Scientific Genealogy of Walter Greiner
(according to the Mathematics Genealogy Project)

Friedrich Leibniz — Universität Leipzig (1622)
Jakob Thomasius — Universität Leipzig (1643)
Otto Mencke — Universität Leipzig (1665)
Johann Wichmannshausen — Universität Leipzig (1685)
Christian Hausen — Martin-Luther-Universität Halle-Wittenberg (1713)
Kästner Abraham — Universität Leipzig (1739)
Georg Lichtenberg — Georg-August-Universität Göttingen (1765)
Bernhard Thibaut — Georg-August-Universität Göttingen (1796)
Christoph Gudermann — Georg-August-Universität Göttingen (1823)
Karl Weierstraß — Westfälische Wilhelms-Universität Münster (1841)
Carl Runge — Universität Berlin (1880)
Max Born — Georg-August-Universität Göttingen (1906)
Siegfried Flügge — Georg-August-Universität Göttingen (1933)
Hans Marschall — Humboldt-Universität zu Berlin (1944)
Walter Greiner — Albert-Ludwigs-Universität Freiburg im Breisgau (1961)

Fig. 1. Scientific lineage of Walter Greiner. The succession from the top to the bottom of the list follows the order "adviser"–"student". For each member of the list the place where and year when the dissertation was defended is provided.

2. Doktorarbeit in Freiburg im Breisgau

In February 1960 Walter Greiner passed the Diplomphysiker-Hauptprüfung (Master of Science — Main Examination) at Technische Hochschulle (TH) Darmstadt with a thesis entitled "Plasmareaktoren", a work that to the date seems to be lost. His advisor was Otto Scherzer (1909–1982), an outstanding German physicist, student of Arnold Sommerfeld and pioneer of Electron Optics, who authored in collaboration with E. Brüche the first book (*Geometrische Elektronenoptik*, 1934) in this field, and fathered the so-called *Scherzer theorem* which, according to the Nobel Laureate Dennis Gabor, grounded the foundations of Holography.[4]

Stimulated by Hans Marschall (1913–1986), who was at the time a Diätendozent (sessional lecturer) at TH Darmstadt and Albert-Ludwigs Universität Freiburg, Greiner moves in May 1960 to Freiburg with a fellowship offered by the "Studienstiftung des Deutschen Volkes" (Foundation for Education of the German People). Three months later he married Bärbel Chun.

Starting several years before, Hans Marschall has been dedicating his efforts to the theory of muonic atoms, especially the description of μ-capture reactions $(pp)\mu$, $(dp)\mu$, $(dd)\mu$.[3] During the fifties he systematically worked on problems related to charge distributions in nuclei and how they are influenced by muons, excitation of nuclei induced by the capture process and during the atom excitation via Auger and radiative transitions.

2.1. *Nuclear polarization in muonic atoms. Role of nuclear structure*

In less than a year (April 1961) Walter Greiner succeeded to complete and submit his Dissertation entitled "Die Kernpolarisation in μ-Mesoatomen" (Nuclear Polarization in Muonic Atoms) for the "Erlangung der Doktorwürde" (Attainment of the Doctorate).

Muonic atoms consists essentially of a simple negative muon μ^- bound to a nucleus due to the electromagnetic force. In contrast to the ordinary atoms, in muonic atoms the nuclear degrees of freedom determine a series of interesting properties due to the large mass difference between muon and electron, as well because of the corresponding difference in scale of sizes and energies. One of the effects arising from the internal degrees of freedom of the nucleus is the nuclear polarization, which consists in energy shifts of the muon levels. In his first paper[5] Walter Greiner applied the formal theory of nuclear polarization to the muonic ^{208}Pb. This was previously developed by Cooper and Henley,[6] with the difference that Greiner is giving-up the single-particle feature of nuclei and instead adopts the macroscopic (hydrodynamical) approach of Steinwedel and Jensen.[7,a] In this picture the muon induces a relative motion between the neutron and proton fluids such that a modification of the potential produced by the nucleus takes place. This variation of the potential leads to the muon level energy shift. Numerical estimations, produced with the help of his younger collegue Amand Faessler, also student of Hans Marschall, show that the inclusion of proton fluid small-amplitude oscillations raise the bottom of the polarization potential by $\approx 5\%$ and by using the exact meson wave-functions instead of the hydrogen, one lowers drastically the sojourn probability of the muon inside the nucleus. For the 1s state in μ^{208}Pb atom he obtained a shift $\Delta E_{1s} \approx 1$ keV. At the end of the paper Greiner noted that extrapolating the conclusions drawn from a previous study on nuclear polarization in deuterium, the single-particle contribution in the studied case should not be expected to exceed 100 eV. It is also interesting to note that the Hydrodynamical Model used by him in calculating the nuclear polarization in muonic atoms played an important role in the model of giant resonances developed together with Danos a few years later.

In a subsequent paper with Hans Marschall he extended this framework in order to account for the quadrupole deformation of the nuclear surface induced by the muon.[9] They estimated that the energy shift of the 1p state in μ^{208}Pb due to the quadrupole distortion should be ≈ 4 keV. The contribution brought by Refs. 5 and 9 was recognized in reviews and textbooks on muonic atoms[10,11] especially concerning the step forward undergone by Greiner's framework that goes beyond the closure approximation of Cooper and Henley, by using matrix elements of the perturbation from nuclear wave-functions. In these early publications Walter Greiner proved

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[a] Actually it was Nuding who had first the idea to apply the concept of low and high proton tide effect on the muon orbit.[8] However he failed to couple the proton density fluctuations to the muon quantum dynamics in the wave equation.

that he was already on the route of becoming a real master in handling quantum problems involving strongly coupled modes.

Other contributions to this domain concern: (a) a study on the reconciliation between the experimental value for the Bi-Pb energy difference and the value calculated from electron scattering data by using the single-particle shell-model for the $(Z+1)$-th proton in the muonic atom ${}_{Z+1}X^{A'}$ and the Ford–Willis wave-functions for muon;[12] (2) the effect of nuclear collective motion (rotations, surface oscillations, giant resonances) in the X-ray spectrum of a muonic atom.[13] These two studies demonstrate the prevailance of rotational excitations on the muon state compared to β and γ vibrations. In Ref. 14 Greiner is for the first time concerned with the issue of vacuum polarization, and he provides an estimate of the vacuum polarization potential for sharp nuclear surfaces. In the following years and up to the end of his life he will devote continuous efforts to this subject.

3. The Rotation–Vibration (RV) Model

In 1962 together with Amand Faessler, Greiner published a landmark paper,[15] which gives a detailed quantum mechanical treatment of collective nuclear motion derived from the classical Hamiltonian of a symmetric rotator with a vibrating surface. More precisely, the Rotation–Vibration (RV) framework assumes quadrupole distortions of the nuclear shape with amplitude small compared to that of the equilibrium deformation. An essential assumption of this model, where rotations and vibrations are fully coupled, concerns the hydrodynamical nature of surface vibrations and of the inertia moments. The same problem was treated a few years earlier in the Soviet Union by Davydov and collaborators in the lowest-order adiabatic approximation and only in a few cases (see Ref. 16 and references therein). The merit of the Faessler–Greiner approach was the exact treatment of (β,γ) vibrations by splitting the total Hamiltonian in a purely rotational, a purely vibrational and a coupled term. In the uncoupled case (zeroth-order) the energy eigenvalue is expressed as the sum of vibrational and rotational energies, a fact that provides a convenient way to classify various rotational bands that can be built on the β and γ vibrations. The effect of the remaining terms, describing the coupling between rotations and vibrations, is estimated in the first-order perturbation theory. For larger spins ($J \gtrsim 4$), the ratio between the rotational and vibrational quantum energies ceases to be very small and an exact diagonalization of the total Hamiltonian is necessary, taking the wave-functions of the uncoupled Hamiltonian as basis states. In the mass range $156 \leq A \leq 184$ the diagonalization procedure applied by Faessler and Greiner resulted in a fitting error generally less than 0.4%! Of particular importance in the Faessler–Greiner model was the treatment of γ vibrations. They showed that for vibrations around $\gamma \neq 0$, the term $\hbar J_3^2/(2I_3)$ in the Hamiltonian for γ vibrations takes the form of a centrifugal potential, viz. $\sim 1/\gamma^2$, such that a qualitative distinction between $K=0$ and $K \neq 0$ states occurs. In other words, the centrifugal repulsion for the second class of states shifts the average value of γ^2 to non-vanishing values, thus making the gamma vibrational bands effectively more triaxial. The power of the Faessler–Greiner framework compared to the predictions of the Bohr–Mottelson model became transparent from their first paper (see Figs. 4 and 5 of Ref. 15). A similar comparative study was made a year and a half later[17] and demonstrated that the $E2$-transition probabilities from the states of the γ-band to the states of the ground state band are better described in the RV model than in the Davydov theory. A comprehensive summary of the RV model in deformed nuclei was given in Ref. 18. Here, the Hamiltonian is diagonalized up to $I = 20$ and the energies and wave-functions for various states in the ground state, β and γ bands are tabulated.

In a short time Refs. 15, 17–20 became standard references in the literature dedicated to nuclear collective motion, e.g. Refs. 16, 21–25, and the framework developed by Faessler and Greiner is sometimes evoked in the literature under the name of Bohr–Mottelson–Frankfurt model. Even in the rare occasions when criticism was raised against this model, mainly related to its hydrodynamical foundations, it was stressed the progress achieved in understanding the collective feature of the atomic nucleus.[23] As Walter Greiner remembered almost four decades later about the inovative role played by the RV model developed together with A. Faessler:[26] "It was the first dynamical solution of the Bohr–Hamiltonian and up to now also the only analytical solution (Bohr and Mottelson had never solved it; they only talked qualitatively about it)."[b]

Other outstanding contributions of Walter Greiner using the RV framework concern the magnetic properties of even nuclei, Coriolis anti-pairing and blocking effects, and the octupole vibrations of deformed nuclei. Thus, in Refs. 27–29 he established a remarkable relation between the lowering of the g_R-factors and the magnetic dipole transitions, using the idea that the proton moment of inertia is less than the neutron moment of inertia on account of unequal pairing forces. Therefore this disbalance should be reflected in energies and magnetic transitions. By 2016, Ref. 29 received 152 citations (see for example the discussion from Ref. 30). The ideas developed by Greiner and collaborators in these papers were instrumental in the elaboration of the two liquid drops model used to describe the M1 properties of the rotational bands.[31]

In a very simple picture consisting of a core and a j-shell on top of it, which contains sufficiently enough nucleons such that core deformations are engendered, Greiner calculated the collective potential energy up to the fourth order in the quadrupole moment using the quasi-spin formalism and showed that in order to describe nuclear deformations one needs to take into account anharmonic terms.[32] Analytical formulas for the strengths of the harmonic, cubic, and quartic potential terms are given in terms of the strengths of short-range (pairing) and long-range (quadrupole–quadrupole) residual interactions, the number of nucleons in the j-shell, the quasi-spin and the reduced matrix element of the quadrupole operator.

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[b] A thorough discussion on the question of the complete solution of the Bohr–Mottelson Hamiltonian is given in the monography.[25]

This study served for a later analysis (in collaboration with Faessler and Sheline) on the effects induced by Coriolis anti-pairing and blocking effects in the second-order rotational–vibrational Hamiltonian.[33] This paper is still cited in the literature today.[25]

In Ref. 34 he described octupole states as octupole phonons strongly coupled to a quadrupole deformed nucleus in a manner analogous to the Nilsson model. The Hamiltonian splits in rotational, quadrupole and octupole vibrational terms, and a quadrupole–octupole interaction term. Decades later the interest on octupole states was revived especially in connection with pear-shaped nuclei[35] and magnetic collective modes.[31] The $E1$ mechanism to the low-lying negative parity states suggested by Donner and Greiner for rare-earth nuclei was confirmed experimentally by Guhr *et al.* for light actinides.[36]

4. Washington D.C. and Collaboration with Michael Danos

In 1962 Walter Greiner crossed the Atlantic and begun one of the most fruitfull periods in his career, first as a postdoc and soon after as an assistant professor at the University of Maryland at College Park, a suburb of Washington D.C. The first published paper, while on American soil, concerns a theme on the electromagnetic radiation of nuclei, i.e. the braking radiation produced in proton–neutron scattering.[37] This work has two important results: (1) Greiner and Green pointed out that the model dependence of the bremmstrahlung at low energies ($E_{\rm lab} = 10$ MeV) should be small; (2) the Bloch–Nordsieck transformation was proved for the first time for wave-packets and stationary bound states. This paper provided a simple tool for the calculation of probability amplitudes of single-particle $E1$ transitions between continuum states. It is regrettably that this nice paper was overlooked for so long. The simple but efficient framework proposed by Greiner and Green can be readily applied to radiative capture reactions involving halo nuclei with a single valence neutron or proton that are relevant for modern studies of nuclear astrophysical reactions of the type ${}^{A}Z(n,\gamma)^{A+1}Z$, ${}^{A}Z(p,\gamma)^{A+1}Z+1$. This model could be also applied to the soft dipole mode in halo nuclei. However in 1962 the existence of a considerable dipole strength in neutron-rich nuclei was not yet known.

According to his recollections, published in 2001,[26] while at College Park, and following a seminar at the Physics Colloquia, Greiner made acquaintance to Michael (Mike) Danos who was at that time a member of the Photonuclear Data Center of the US National Bureau of Standards (present NIST).[c] This center of excellence was carrying out a project of significant importance that consisted in the systematic collection of bibliography and data regarding the interaction of photons with atomic nuclei. Danos, a former student of Hans Jensen in Heidelberg, had already acquired a worldwide recognition especially for his earlier contributions to the

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[c] According to Amand Faessler, Michael Danos visited previously Hans Marschall in Freiburg at the suggestion of Hans Jensen, and it was there he got to know Walter Greiner (communication to the author, May 26, 2017).

hydrodynamical model of dipole proton–neutron oscillations (Giant Dipole Resonance, GDR) where he extended the Steinwedel–Jensen model. In 1958 he established a remarkable relation between the ratio of the two components of the GDR in deformed nuclei and the ratio of the long and short axes lengths of the nuclear ellipsoid. The theoretical description of the GDR splitting in deformed nuclei is frequently referred to in the literature as the Danos–Okamoto model. Their meeting resulted not only in what became a life-lasting friendship but also in an outburst of publications "one better than the other" as Walter Greiner recalled long after.[26] Returning to Germany, Walter Greiner will send many of his students to NBS to work with Michael Danos: M. G. Huber, H. Arenhövel, D. Drechsel, B. Fink, and J. Rafelski.

4.1. *Dynamical theory of nuclear collective model*

The first pillar of the Greiner–Danos collaboration is the unification of the collective surface degrees of freedom, as encoded in the earlier developed rotation–vibration model, with giant resonance motion. For the first time in the literature it was revealed that the strong interaction between dipole or quadrupole density fluctuations and surface degrees of freedom leads to the experimentally observed substructures in the giant resonances. They laid down the foundations of the Dynamical Collective Model (DCM) theory in Refs. 38–40. In this framework the giant resonances are described within the hydrodynamical model, mentioned above,[7] which works reasonably well for medium and heavy nuclei. However the model developed by Steinwedel and Jensen has a serious limitation, which at that time was not considered to be important: though density fluctuations of separate proton and neutron fluids are allowed, the total density remains constant during the oscillation. Danos and Greiner admit themselves that "we neglect this nuclear property," i.e. nuclear compressibility, "and as a result lose the states corresponding to compression waves (ordinary waves)." From the modern perspective the assumption that the sound-wave state lies at a much higher energy than the dipole state on account of the incompressibility of nuclear matter is no longer acceptable. Presently (see the discussion and literature in Ref. 41) we are aware of the existence of an isoscalar dipole resonance where the nuclear compresibility plays a crucial role. Danos and Greiner considered in the DCM framework nuclei having large deformations and, assuming that rotational and vibrational motion is slow compared to giant resonance oscillations (adiabatic approximation), they showed that once quadrupole vibrations are included, the nuclear ellipsoid acquires a dynamic triaxiality and each of the two principal peaks is accompanied by a satellite carrying about 10% of its strength.

Once professor in Frankfurt, Greiner vastly extended the DCM framework. With Weber and Huber he published an exhaustive study in two parts dedicated to the application of the DCM to spherical nuclei and compared the result of calculations to experimental data showing thus that the structures in the gamma-absorbtion cross-section are surprisingly well described.[42,43] Together with Ligensa[44] he operated the dynamic coupling of the giant quadrupole oscillations with the RV modes and single-particle motions and obtained an excellent agreement to the experimental $E2$ absorbtion cross sections for ^{165}Ho and ^{159}Tb. They found that the giant electric quadrupole resonance has five components for these rare earth nuclei. The inclusion of both dipole and quadrupole giant resonances in DCM was published in the same year with another of his Frankfurt students (T. Urbas).[45] A formulation of the DCM in the particle–hole framework was operated in Refs. 46 and 47. While retaining from the original model the treatment of surface excitations, the dipole Hamiltonian and the dipole operator from the dipole–quadrupole Hamiltonians are replaced by corresponding operators in the one particle–one hole (1p–1h) subspace. The new interaction between the giant dipole resonance and the quadrupole oscillations leads to collective correlations.

Extensive tables of neutron and proton partial and total escape widths of various dipole states in several spherical nuclei were published in Ref. 48. They stressed the strong dependence of the widths on the angular momenta of the hole state of the nucleus and the emitted particle. A crucial assumption made in this paper was that the residual interaction determines the coupling of the single-particle continuum to the collective states of the DCM.

4.2. *Eigenchannel model of nuclear reactions*

In 1965 the main framework to calculate resonant nuclear states was the R-matrix method (for an early review see Ref. 49). As we have seen above, Greiner and Danos were focusing on the giant resonances and at that particular time they were looking to study the excitation of these modes based on shell-model techniques. Therefore they proposed a new treatment[50,51] of nuclear reactions, which shared some common features with the R-matrix theory such as the separation from the total Hamiltonian H of a shell-model Hamiltonian $H_{\rm shell} = \sum_i h_0(i)$, the division of the space into an internal (nuclear) region and an external (scattering) one, separated by the so-called surface channel of radius a_i in each channel i, as well as the diagonalization of H in a truncated set of eigenfunctions of $H_{\rm shell}$ with the exclusion of all configurations with more than one nucleon in continuum eigenstates (*i.e.* considering only 1p–1h excited states in the reacting nuclei). One should remind the reader that in the traditional R-matrix framework, the wave-function in the internal region is expanded into a set of solutions of $h_0(i)$ and subject to an arbitrary boundary condition (BC) at the matching radius (beyond which the nuclear potential dies out), which has the annoying consequence that the wave-function slope is discontinuous thus entails a slow convergence of the basis set. In its turn the eigenchannel method considers at a given excitation energy a complete set of scattering states (eigenchannels), which diagonalize simmultaneously H and the scattering matrix S, avoiding thus the wave-function discontinuity at the channel surface. This advantage over the R-matrix method was admitted even by some of the bitter criticizers of the new method.[52] In order to cure this unsatisfactory feature, the framework devised by Danos and Greiner introduces so-called "natural" BC, insuring thus a smooth transition between the inside and outside regions. Instead of choosing an arbitrary BC like in R-matrix theory, the eigenchannel procedure gives the BC parameter in each channel in terms of the known form of the channel radial wave-function. A trial value of real eigenphase δ is assumed at a given scattering energy E and therefore also the S-matrix is known in diagonal form ($S = e^{2i\delta}$). Next, the continuity of the logarithmic derivative at the matching radius is imposed in order to obtain the eigenvalues E_λ of the complete Hamiltonian. If none of E_λ is equal to E, the S-matrix is iterated until the equality $E_\lambda = E$ is reached. The supplementary computer-time required by the Danos and Greiner method compared to the standard R-matrix involves the computation and diagonalization of a $Nm \times Nm$ dimensional matrix where N is the number of basis states retained in each channel and m is the number of eigenphases (open channels); naturally the time required for this operation increases rapidly as the matrix dimension increases. After five decades such large-matrices computations are much easy to handle and the advantage over the standard R-matrix methods, obtained via the improved convergence of the scattering wave-function expansion, makes the eigenchannel method attractive again for resonant nuclear reaction calculations.

Applications of this method have been published by Greiner and collaborators in the next years. In Refs. 53 and 54 the photon absorbtion cross section of ^{16}O was calculated and concluded that the broad structures, e.g. the splitting of the main peak indicated by the experiment, are largely reproduced within the eigenchannel framework with the inclusion of 1p–1h channels. The fact that some of the secondary peaks and other fine structures in the experimental total cross section are not accounted by the theory was attributed to the absence of 2p–2h and higher configurations. An extension of the formalism to describe resonant nuclear reactions above the two-particle threshold was proposed with Danos in Ref. 55 for nucleon channels and with H. J. Weber[56] for cluster channels, but no numerical applications were given. A comprehensive review on the eigenchannel method was published in 1973.[57]

5. Ordentliche Professor in Frankfurt am Main and Further Developments in Nuclear Collective Dynamics

In the summer of 1964 Walter Greiner accepted the chair for theoretical physics at J. W. Goethe University in Frankfurt am Main as full professor. In the first years he pursued some of the directions described previously (new applications and further developments of the RVM, eigenchannel theory and the DCM) but he also initiated new ones. One of the most significative of these concerned the nuclear response to external electromagnetic fields. In Ref. 58 he investigated with Danos and Kohr the role played by the nucleus orientation with respect to the incident photon and electric field in the excitation of quadrupole modes.

He developed together with Hartmuth Arenhövel a general formalism of photon scattering by oriented nuclei and explicit formulae for the dipole radiation in terms of orientation were provided in reference to aligned ^{165}Ho nuclei.[59,60] It was concluded that the photon scattering by oriented nuclei could be a useful tool for direct observation of the tensor polarizability of nuclei.

With two of his students, Gotthard Gneuss and Ulrich Mosel, he proposed in 1968 a new treatment of the collective nuclear Hamiltonian that is able to describe simultaneously a pure spherical vibrator and a permanently deformed rotator in the basis of the five-dimensional oscillator.[61,62] While the Faessler–Greiner model assumes that the nucleus rotates or vibrates as a whole about an equilibrium deformation and therefore is not able to describe transitional nuclei, the model dubbed in the literature as Gneuss–Greiner (GGM) is capable of describing all types of nuclei, the quadrupole degree of freedom playing the prevailing role in the low-energy properties of even–even nuclei. The main purpose envisaged by Greiner in developing this model was to obtain a reliable tool that allows the calculation of spectra and transition probabilities of an even-even nucleus of arbitrary shape. In this way it was possible to deduce from experimentally known spectra the corresponding potential energy surface (with respect to the intrinsic nuclear coordinates β and γ), which can be compared with microscopic results that are obtained after more tedious calculations. They emphasized that a number of experimental level sequences, where the earlier collective models (Bohr–Mottelson, Jean–Wilets, Davydov–Filippov, RV) failed completely, could now be reproduced. A far-reaching goal of the "five-dimensional oscillator" approach was the calculation of potential energy surfaces of nuclei undergoing fission, especially in regard to the stability of superheavies. In the years to come Walter Greiner will dedicate his efforts to this problem.

Whereas the RV model was limited to small-amplitude oscillations around the ground state deformation, the model of Gneuss and Greiner explores wide regions of the quadrupole variable and consequently, anharmonicities in the potential energy, which are included up to the sixth order in the quadrupole coordinate $\alpha_{2\mu}$, plays an instrumental role (see the review paper of Gneuss and Greiner[63] and an up-to-date presentation in Ref. 25). A limitation in the GGM is represented by the large number of parameters and the slow convergence for large deformations due to the diagonalisation procedure in spherical basis. Despite of that, the model played a historical role in the development of nuclear collective models, the anharmonicities in the low-lying vibrational states receiving for the first time in the literature a first row seat.

The GGM was improved with the significative contribution of some of Greiner's students (especially P. O. Hess and J. Maruhn, M. Seiwert, L. V. Bernus) by extending its flexibility to high spins. This new version, called the General Collective Model (GCM) or Frankfurt Collective Model[64,65] contains as new features three terms in the kinetic energy instead of two as in the GGM, and the potential energy contains many additional terms of the type $\beta^n(\cos 3\gamma)^m$ with $2 \leq n \leq 6$ and $0 \leq m \leq 4$ such that GCM uses 20 parameters instead of 8 like in GGM. These parameters are fixed by fitting the data to low-lying energy levels, reduced $E2$ transition probabilities, and quadrupole moments. Applying the Frankfurt Model to isotopic chains of Pt, Os, W, two minima (one prolate and one oblate) in the potential energy surface were obtained in several instances instead of only one like in the GGM. The isotopes with two minima exhibit a backbending structure in the yrast band due to the crossing of the lowest bands in the two minima.

At the end of the period that concerns this biographical excourse, the first papers on the ion–ion potentials are published.[66,67] Major themes such as stability and formation of superheavy nuclei, nuclear molecules, elementary matter in strong fields that will attract the attention of Walter Greiner for the next decades are coming into play after this year.

6. Conclusions

This contribution was confined to a limited but very prolific period of Walter Greiner scientific career. The large majority of subjects evoked above were included in his magnum opus on Nuclear Models.[68] Even so, the best reference in gaining a profound understanding of Greiner's work remain the original articles.

Walter Greiner always tried to convey to his students and collaborators, that they should avoid to fall in the trap of "Trockene Physik" (dry physics) and rather venture in new and exciting problems whenever possible. This situation is particularly true in theoretical nuclear physics where always new subjects are prompted by new or foreseeable experiments, problems that require dedication, assiduity and intuition in order to be solved. Walter Greiner possessed these skills.

Acknowledgments

I am grateful to Prof. A. A. Raduta who read this manuscript, expressed critical remarks and drew my attention on relevant aspects related to Walter Greiner's work that should not fall into oblivion. I also owe to Prof. P. O. Hess gratitude for helping me to improve the fifth section of the present work. To Prof. A. Faessler I am indebted for some clarifications regarding the Freiburg period. I am also indebted to Mrs. Daniela Radulescu from ITP Frankfurt for providing me with an electronic copy of Walter Greiner Dissertation. She obtained this rare document due to the kindness of Prof. Carsten Greiner. This work has been financed by the national project PN III 5/5.1/ELI-RO, Project 04-ELI/2016 ("QLASNUC"), under the financial support of Institute for Atomic Physics - IFA.

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