THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,
Volume 4, Number 1/2003, pp. 0–00

HEISENBERG LECTURE: SUPERSYMMETRY IN THE SPECTRA OF ATOMIC NUCLEI

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Talk given at the Symposium: "Werner Heisenberg und die Wissenschaft, das Denken und die Kunst", Alexander von Humboldt Club, Bucharest, October 16 and 17, 2001, Goethe-Institut, Bucharest, Romania.

This Symposium of the Humboldt Club in Bucharest is dedicated to the work of Werner Heisenberg. At the occasion of the hundredth anniversary of his birthday the aim is to recall the impact of Heisenberg's work not only on physics and related fields but also on philosophy and on our present understanding of science. Werner Heisenberg discovered and formulated the laws of quantum physics, the concepts and the tools we use every day. These discoveries resulted from his ambitious goal to reveal the fundamental laws of physics and to understand these laws within the logical and structural aspects they imply for the understanding of nature and of thinking. In this way he was aware of the potential of this fundamental new approach and applied the concept of quantum phenomena to physics, chemistry, biology, and to logical-philosophical questions.

Being invited here as first speaker of this Symposium it is appropriate, I think, first to recall a few dates out of his vita and essentials of his work, and then to address to a timely subject, which is, as I hope to show, related to the work of Werner Heisenberg.

1. ABOUT THE VITA OF WERNER HEISENBERG

Werner Heisenberg was born in Würzburg, 1.12.1901, his father was professor for Greek language. He studied in München in 1920, attending Sommerfeld's seminar. Werner Heisenberg identified the question about the basic laws determining the quantum structure of the atoms as the most challenging topic of his time and he concentrated his study exclusively on this. Due to Sommerfeld he had early contact with Göttingen and there with Niels Bohr. A Fulbright award in 1924 allowed him to stay longer in Kopenhagen with Bohr. As post-doc in Göttingen he published in 1925 "Über die Quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen", his fundamental paper. In 1927 he formulated the uncertainty-relations, became full professor in Leipzig, and addressed himself to questions of nuclear physics. In 1932 he published "Über den Bau der Atomkerne". In this year he also received the Nobel prize. In 1939 he decided to keep staying in Germany, motivated by Max Planck to "wait for the time after". He directed the "Uranprojekt" and changed in 1941 to the Kaiser Wilhelm Institut in Berlin. After the war, in 1946, he tried to organise recovery of physics in Germany with the Max Planck Institut für Physik in Göttingen. The Alexander von Humboldt Stiftung was inaugurated in 1953 with Werner Heisenberg being the first "Präsident". I think it was important for him to return to others, what he as young scientist received as support. In post war Germany he played a dominant role to reestablish and reintegrate science in Germany. With "his" Max Planck Institut für Physik he moved to München in 1958. His specific scientific topic at that time was field-theory. He deceased, 1.2.1979, in München.

Recommended by Cornel HAȚEGAN
member of the Romanian Academy

2. ABOUT THE PHYSICS OF WERNER HEISENBERG

Heisenberg replaced the laws of Newton by operator equations which govern the physics of the quantum world. The dynamics of a system is expressed by the time dependence of a state function or state vector Ψ, and the probability to "find" the particle is proportional to the complex conjugate square of this state function or vector $|\Psi|^2$. The system is determined by an operator expressing the energy as function of respective variables, namely the Hamiltonian Operator H which is applied to the state functions or state vectors Ψ:

$$\mathrm{i}\hbar\dot{\Psi}=\boldsymbol{H}\Psi \tag{1}$$

The structure of this equation implies stationary states if:

$$\boldsymbol{H}\Psi=E\Psi \tag{2}$$

with E being a constant. These states are discrete in energy, they are labeled by quantum numbers, say n, so we have eigenenergies E_n and eigenfunctions Ψ_n. According to the symmetry properties of the Hamiltonian several quantum numbers may appear.

In the limit of large quantum numbers n the results of quantum physics are consistent with Newton, in this sense there is no contradiction.

The Hamiltonian Operator $\boldsymbol{H}$ is a function of variables, as position (x, y, z), momentum (p_x, p_y, p_z), angular momentum (l_x, l_y, l_z), spin angular momentum (s_x, s_y, s_z) etc. These quantities are operators, too, and there are relations in between these operators as:

$$\begin{aligned} xp_x - p_x x &= -\mathrm{i}\hbar,\ldots \\ l_x l_y - l_y l_x &= \mathrm{i}\hbar l_z,\ldots \\ s_x s_y - s_y s_x &= \mathrm{i}\hbar s_z,\ldots \end{aligned} \tag{3}$$

These commutator relations are the origin of Heisenberg's uncertainty relations. In addition, they may reduce the number of allowed terms in the Hamiltonian Operator.

Physics is especially interesting if it refers to systems of a few degrees of freedom or to systems of high symmetry where the results may be expressed in a few terms. Heisenberg always tried to identify symmetries and/or to study systems with a few eigenstates. A good example is the spin-isospin concept with two-dimensional eigenstates, Heisenberg used in his early concepts of nuclear forces. They allow group theoretical classifications. Within quantum mechanics the symmetries of the group provide a definite scheme of quantum numbers, eigenstates and eigenenergies, independent of the specific nature of the problem. Thus the two-state symmetry $U(2)$ of spin s =1/2 systems applies to very different fields of physics.

Heisenberg applied group theoretical classifications to extend his early studies of atoms to "larger" systems in molecular and solid state physics, and to "smaller" systems in nuclear and elementary particle physics. To all of these important areas Heisenberg formulated basic laws and concepts which still determine our thinking.

In the following part of my talk I address to a field of physics I am actively involved. It is a field of nuclear physics and in there the spectra of heavy, complex nuclei, which are the subject of ongoing experimental research in Munich [1,2,3]. Here, symmetry classifications and quantum concepts, derived to understand the atom, and modern and speculative concepts of elementary particle physics like the concept of supersymmetry are applied.

3. SPECTRA OF NUCLEI

The excitation energy spectra of heavy nuclei, in general, are very complex. Symmetry considerations, which, of course, are related to the identification of a limited number of relevant degrees of freedom, provide a kind of order and thus a means to discuss physics.

3.1 Even-even Nuclei and the Interacting Boson Approximation

Introductory remarks:

To discuss the structure of an atomic nucleus, a system of (many) protons and neutrons, the canonical way is to start with the concept of a shell structure, as we know it from the electron shell of the atom. The electrons as well as the protons and neutrons have spin s = 1/2, they are Fermions. This is why each of the states with all its quantum numbers, the early Heisenberg derived for the hydrogen atom, can be filled only once, with one electron in the spin-up state and one electron in the spin-down state. In this way the electron shells become an extended rigid system. If energetically nearby orbitals are filled completely we have spherical, closed shells, where all the orbital and spin angular momenta couple to zero. If there are no additional electrons, the atom is inert: one of the noble gas atoms. Their respective number of electrons are called "magic" numbers. For these atoms the energy to remove an electron or to excite an electron into a higher state is especially large. The occupied and the empty states are separated by a "shell gap". Thus atoms with one electron (or two electrons) above the closed shell have a simple structure, they are hydrogen (or helium) like, so-called alkalis (or earth-alkalis). Their orbital energies derive from a potential which deviates from the point-charge Coulomb potential but remains spherical. Referring to a closed shell, also the atoms with one electron less, the halogens, are easy to discuss: There is a symmetry in between electron-particle and electron-hole states. The interaction of the electrons with each other yields a mean potential (which is well determined because of the quantum structure of the core and is included in the modified Coulomb potential) and a residual interaction, which is quite relevant already for the case of helium.

For the atomic nucleus, where we don't have the central charge, an individual nucleon experiences the average field from the other nucleons. As for the atoms, Jensen and Goeppert Mayer identified a shell structure for the atomic nucleus, too. Because of a different shape of the effective potential the magic numbers are different from those for the atom. The lead isotope ^{208}Pb, with N = 126 and Z = 82, has both a closed neutron and a closed proton shell. Correspondingly, the excitation energy of the first excited state is very high, as for noble gas atoms, while the neighbouring nuclei with one additional or missing nucleon, the valence nucleon, have excitation spectra of especially simple structure.

The interacting boson model:

If, however, we have to consider nuclei with a large number of valence nucleons we face an extremely complicated situation: A many-body system with a strong (and complicated) interaction cannot be calculated at all. The way out are classical concepts as introduced by Aage Bohr, Mottelson and Weeler, or group theoretical considerations as introduced by Arima and Iachello (1975) [4]. The aim is to find "simplicity in complexity", that means to identify a few relevant degrees of freedom. They start from the observation that valence neutrons (and protons) are especially strongly bound if they form pairs with total angular momentum J = 0 or J = 2. Because of the integer values of J these pairs are bosons, the s and d bosons, and considered in their model, the **I**nteracting **B**oson **A**pproximation (**IBA**), as the only relevant degrees of freedom. These bosons, being either in the s or d state, have, because of the respective $2J$+1 magnetic substates, ν = 1+5 = 6 allowed eigenstates, Hence their interaction is treated within the group formalism of $U(6)$ symmetry.

The Hamiltonian, in general, is the sum of a number of terms of lower symmetry than $U(6)$. Allowed symmetries are $U(6)$, $O(6)$, $U(5)$, $O(5)$, $SU(3)$, $O(3)$, $O(2)$. Each term is the product of a constant giving the energy scale and a Casimir operator representing the respective group properties. Interesting are those cases where some of these terms do not appear and the remaining ones form a chain of subsequently broken symmetry (The $U(6)$ symmetry is broken in a regular way). Then we have analytical solutions both for the eigenenergies and the eigenstates, determined by a scheme of quantum numbers. The energy scale factors remain as the only values to be determined.

Comparing, for example, even-even nuclei with an increasing number of neutron and proton holes with respect to the closed-shell core ^{208}Pb, we observe nuclei with $U(5)$, then $O(6)$ and finally $SU(3)$ structure and nuclei with structures in between. Nuclei with a definite symmetry structure are said to exhibit a "dynamical symmetry". The $U(5)$, and $SU(3)$ dynamical symmetries are related to the vibrational and rotational models of Bohr and Mottelson. The intermediate $O(6)$ dynamical symmetry resulted from the group of $U(6)$ as a prediction. The discovery that ^{196}Pt, with Z = 78 and N = 118 or N_p = 2 and N_n = 4 bosons with respect to ^{208}Pb as core, is well described by $O(6)$ symmetry was one of the big achievements of **IBA**, compare Fig. 1.

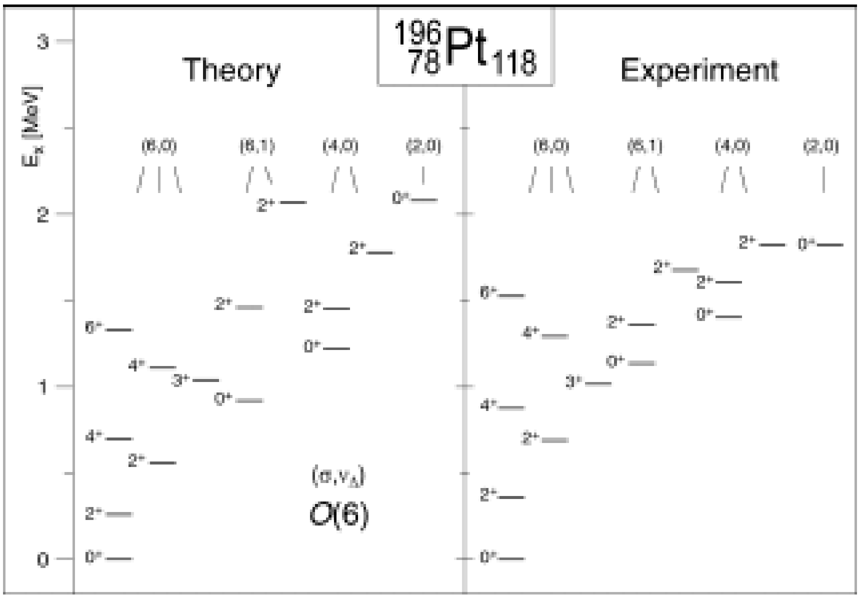


Figure 1: Excitation spectrum of ^{196}Pt, at the left side the prediction for pure $O(6)$ dynamical symmetry, on the right side the experimental levels. The model is further supported by the agreement in between predicted and observed gamma ray transition probabilities, not shown in this figure.

The IBA model turned out to be very successful for medium-heavy and heavy nuclei. I should note here that especially Romanian physicists contributed very much to reveal the various aspects of these rich structures.

The case of $O(6)$ dynamical symmetry results from a $U(6) \supset O(6) \supset O(5) \supset O(3)$ group decomposition and yields a spectrum of excitation energies:

$$E = E_0 + C_1\sigma(\sigma+4) + C_2\tau(\tau+3) + C_3 L(L+1) \qquad (4)$$

with relations in between the quantum numbers σ, τ, L, which are restricted by N_p+N_n.

The formalism is analogue to the case of a rigid rotor in an external magnetic field: The kinetic energy of rotation is proportional to the square of the angular momentum l^2 and thus invariant against the choice of all the three spacial coordinates: We have $O(3)$ symmetry. An external magnetic field will break this symmetry, but invariance against the choice of the two coordinates perpendicular to the field remains. We have $O(2)$ symmetry and accordingly the energy spectrum:

$$E = E_0 + C_1 L(L+1)\hbar^2 + C_2 m\hbar \qquad (5)$$

and the relation $m = L, L\text{-}1, L\text{-}2, ..., \text{-}L$ in between the quantum numbers.

3.2 Odd-even Nuclei and Supersymmetry

For the description of odd-A nuclei a fermion needs to be coupled to the N boson system. Because of the interaction the fermion will create excitations of the core. This can be done within a semi-microscopical approach which relies on seniority in the nuclear shell model [5].

An alternative to this interacting boson-fermion approach is the construction of Hamiltonians exhibiting dynamical Bose-Fermi symmetries that are analytically solvable. In both approaches the boson-fermion space is spanned by the irreducible representation (irrep) $[N] \times [1]$ of $U^B(6) \otimes U^F(M)$, where M is the dimension of the single-particle space.

A significant step towards unification was made in the early eighties when Iachello and coworkers embedded the Bose-Fermi symmetry into a graded Lie algebra $U(6/M)$ [6,7]. This is the algebra invented for particle physics beyond the standard model, relating to each Boson a Fermion and vice versa. In our case the supersymmetric algebra is applied to the Hamiltonian, thus we discuss a "dynamical" symmetry.

The supersymmetric irrep $[N\}$, then, spans a space that describes both an even-even nucleus with N bosons and an odd-A nucleus with N-1 bosons and an odd fermion. In some cases, the dynamical supersymmetry leads to an analytically solvable algebraic Hamiltonian with fixed parameters for both nuclei. If this is the case, one concludes that these nuclei exhibit a supersymmetry.

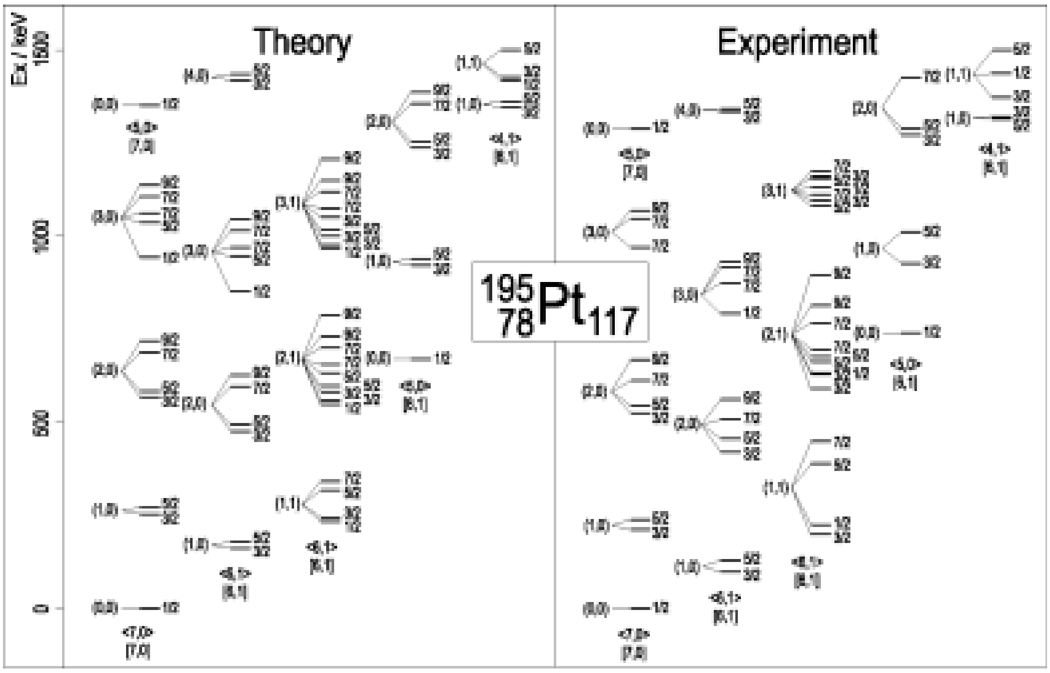


Figure 2: Level scheme of negative parity states in ^{195}Pt. The left side shows the theoretical prediction assuming a supersymmetric dynamical symmetry, with the respective quantum numbers $[N_1,N_2]$ $\langle\Sigma_1,\Sigma_2\rangle$ below and (τ_1,τ_2) left of each band, the right side the experimental data. The levels at lower excitation energies are known since some time, those at higher excitation energies originate from our work, as described in the following. The model is further supported by the agreement in between predicted and observed neutron transfer spectroscopic factors.

One successful case is the description of ^{195}Pt within U(6/12), compare Fig. 2, where the model assumes, that the fermion is restricted to the orbits with j = 1/2, 3/2 and 5/2. Considering those as arising from the coupling of a pseudo spin part with s' = 1/2 with a pseudo orbital part with l' = 0 and 2, the following reduction is obtained: $U^F(12) \supset U^F(6) \otimes U^F(2)$ which allows the coupling of the pseudo orbital part with the bosonic generators at the $U(6)$ level [8]. This supersymmetry can thus be applied in all mass regions providing that the relevant single particle orbits have j = 1/2, 3/2 and 5/2. Another one is $U(6/4)$ which uses the isomorphism between the $U^F(4)$ group describing the space for a 3/2 fermion, and the bosonic $O(6)$ group [7]. The experimental level scheme also includes results of our study, discussed below.

In Fig. 2 the surprisingly good agreement between theory and experiment for ^{195}Pt shows convincingly that supersymmetry predicts in a nearly perfect way the low energy spectrum of this odd-even nucleus.

3.3 Odd-odd Nuclei and the Extended Supersymmetry

A step further is the extended supersymmetry [9], which deals with boson-fermion and neutron-proton degrees of freedom, allowing the description of a quartet of nuclei, using the same algebraic form of the Hamiltonian. The quartet consists of an even-even nucleus with $(N_\nu+N_\pi)$ bosons, an odd-proton and an odd-neutron nucleus with $(N_\nu+N_\pi)$-1 bosons and an odd-odd nucleus with $(N_\nu+N_\pi)$-2 bosons and a proton and neutron. This, of course, is an assumption, to see to what an extend symmetry concepts may determine nature. Thus supersymmetry, if it works, relates the often very complex structure of the odd-odd nucleus to the much simpler even-even and odd-A systems. The only way to study the existence of extended supersymmetry is to test its predictions for odd-odd nuclei [10].

Our studies in this respect, compare Refs. [1,2,3], is still ongoing.

The aim is to provide such a test for the $U_\nu(6/12)\otimes U_\pi(6/4)$ extended supersymmetry which is described in Refs. [9,10,11]. In order to be able to exhibit a dynamical symmetry, a physical system has to fulfil certain conditions. In the case of extended supersymmetries these constraints strongly limit their occurence. To be applicable for the $U_\nu(6/12)\otimes U_\pi(6/4)$ scheme the even-even core should exhibit the $O(6)$ symmetry of the IBM. The odd proton has to occupy a dominant $j = 3/2$ orbit and the odd neutron the $j = 1/2$, 3/2 and 5/2 orbits. Nuclei exhibiting the $O(6)$ symmetry are found near semi-closed shells like the Xe and Pt region [12,13]. An isolated $j = 3/2$ orbit is only found in the case of an occupied $2d_{3/2}$ orbit, when nucleons form three to six holes below the 82 shell closure. Besides in the *sd* shell $j = 1/2$, 3/2 and 5/2 are occupied together above the 28 shell and below the 126 shell closure. Thus, for nuclei near stability the $U_\nu(6/12)\otimes U_\pi(6/4)$ scheme can only occur in the Au, Ir region for the negative-parity states formed by the $\nu(3p_{1/2},3p_{3/2},2f_{5/2})\times\pi 2d_{3/2}$ configurations. It is encouraging that, indeed, the supersymmetry was observed to be approximately valid in ^{198}Au [9,14] and ^{194}Ir [11], the two best studied odd-odd nuclei in this mass region. However, it was realised from the beginning that the ultimate candidate for the test is the odd-odd nucleus ^{196}Au [9] since the quartet ^{194,195}Pt, ^{195,196}Au contains the nuclei ^{194}Pt and ^{195}Pt, which are considered to be the best example of the U(6/12) supersymmetry [15].

If the Hamiltonian is built out of Casimir operators of groups forming a group chain, its eigenvalues are analytical as a function of the quantum numbers classifying the irreps. In case of $U_\nu(6/12)\otimes U_\pi(6/4)$ this leads to the expression [9]:

$$\begin{aligned} E &= A\left[N_1(N_1+5)+N_2(N_2+3)\right]+B\left[\Sigma_1(\Sigma_1+4)+\Sigma_2(\Sigma_2+2)\right] \\ &+B'\left[\sigma_1(\sigma_1+4)+\sigma_2(\sigma_2+2)+\sigma_3{}^2\right]+C\left[\tau_1(\tau_1+3)+\tau_2(\tau_2+1)\right] \\ &+DL(L+1)+EJ(J+1) \end{aligned} \tag{6}$$

with A, B, B', C, D and E being free parameters to set the energy scales and $[N_1,N_2]$, $\langle\Sigma_1,\Sigma_2\rangle$, $\langle\sigma_1,\sigma_2,\sigma_3\rangle$, (τ_1,τ_2), L, J the quantum numbers correlated to the irreducible representations of $U(6)$, $\overline{O}(6)$, $O(6)$, $O(5)$, $O(3)$ and Spin(3), respectively. The reduction rules then lead to the level schemes in the different nuclei. These can be found in [7,8,11]. In addition to the analytic expressions for the excitation energies the supersymmetric scheme also provides analytic results for the wave functions. These do not depend on the parameters given above and can be tested via the calculation of electromagnetic transition rates and single particle transfer reaction amplitudes. Especially the transfer experiments provide a very stringent test of the existence of supersymmetry via the distribution of single nucleons into the predicted wave functions.

4. RECENT EXPERIMENTS

Although the negative-parity states in ^{196}Au were unknown, except for the 2^- ground state, some years ago a test of the supersymmetric description of this nucleus was indirectly provided via unpolarised transfer reactions [10,16]. The measured angular distributions of differential cross sections allowed a selective observation of p and f transfers which populate those states that are provided by the coupling of a neutron hole, occupying the relevant $p_{1/2}$, $p_{3/2}$ or $f_{5/2}$, $f_{7/2}$ orbits, to ^{197}Au. Since the experimental level scheme of ^{196}Au was still poorly known, an experimental study of ^{196}Au was started in a Fribourg/Bonn/Munich collaboration [1,2,3,19]. The experimental program includes in-beam gamma-ray and conversion electron spectroscopy following the reactions ^{196}Pt(d,2n) and ^{196}Pt(p,n) at the cyclotrons of the PSI (Villingen, Switzerland) and the University of Bonn, and, very recently, additional data from $\gamma\gamma$ correlation studies at the Yale accelerator [2].

At the MP Tandem accelerator of the Munich Universities high resolution transfer experiments to ^{196}Au were performed, using (p,d), polarised $(\vec{d},t)$ and polarised $(\vec{d},\alpha)$ reactions [1] . In case of the (p,d) and

($\vec{d}$,α) experiments, the nucleus ^{195}Pt was measured in parallel in order to obtain a reference data set [3]. The nuclei were investigated with 26 MeV protons and with ± 60 % vector polarised deuterons, having an energy of 25 MeV (for the ($\vec{d}$,t) reaction) and 18 MeV [for ($\vec{d}$,α)]. The beam intensity in the original experiments was several hundred nA on target. The targets of ^{197}Au and ^{196}Pt had a thickness of approx. 100 μg/cm^2 and the ^{198}Hg target of 37 μg/cm^2. In this year we put in operation a new polarised source, developed by ourselves, and have ten times more beam to continue this kind of studies.

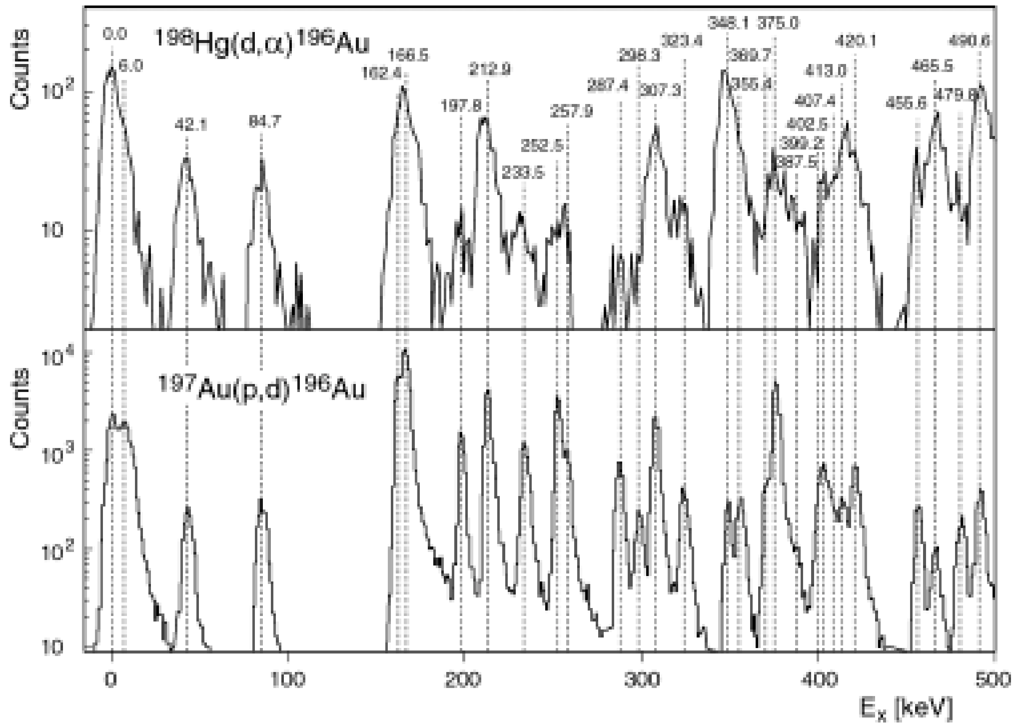


Figure 3: Part of the spectra observed at the Q3D magnetic spectrograph for the ^{198}Hg($\vec{d}$α)^{196}Au (upper part) and the ^{197}Au(p,d)^{196}Au (lower part) transfer reactions for a scattering angle of 25° with respect to the beam axis. We used 18 MeV vector polarised deuterons on a 37 μg/cm^2 ^{198}Hg target and 26 MeV protons on a 67 μg/cm^2 ^{197}Au target, respectively. Shown is the excitation energy range between 0 and 500 keV.

Because of their excellent energy resolution (4 keV FWHM), the (p,d) transfer reactions were used to provide the energy calibration of the ^{196}Au spectra, using the ^{195}Pt data to establish a correlation between measured channels and excitation energies. The achieved uncertainties of the excitation energies are less than 1 keV. These spectra establish a new and for low excitation energies almost complete level scheme of ^{196}Au. In total, 47 states were resolved for the first time in the energy range of 0 to 1350 keV [19] including the resolved ground state doublet with an energy spacing of approximately 6 keV, as shown in Fig. 3. These excitation energies allowed later to set the observed γ transitions [2].

Since the energy resolution of the ($\vec{d}$,t) reaction was worse (7 keV FWHM), the spectra were analysed using the level energies deduced from the (p,d) data. From the polarised measurement angular distributions of differential cross sections $d\sigma(\theta)/d\Omega$ and analysing powers $A_y(\theta)$ are obtained which provide the l and j values of the angular momentum transfers. In case of ^{196}Au the neutron shells $p_{1/2}$, $p_{3/2}$, $f_{5/2}$ and $f_{7/2}$ have to be considered in the analysis of negative parity states while positive parity states are mainly populated via the $i_{13/2}$ transfer leading to a clear distinction of the two parities. Since the ground state spin of the target nucleus ^{197}Au is $J_A = 3/2$, the angular momenta J_B of the final states which are observed by the angular momentum transfer j are in the range: $|J_A - j| \leq J_B \leq J_A + j$. Consequently, up to four different j transfers can contribute to the cross section of an excited state in ^{196}Au. The determination of the contributing transfers and the respective spectroscopic strengths G_{lj} was done by a numerical fit of the data using the relations:

$$d\sigma(\theta)/d\Omega = \sum_{lj} G_{lj}\sigma^{lj}(\theta) = \sum_{lj} v_j^2 (2j+1) S_{lj}\sigma^{lj}(\theta) \tag{7}$$

$$A_y = \left(\sum_{lj} G_{lj}\sigma^{lj}(\theta) A_y^{lj}(\theta) \right) \cdot \frac{1}{d\sigma(\theta)/d\Omega} \tag{8}$$

with σ^{lj} and A^{lj}_y the normalised angular distributions of DWBA calculations, S_{lj} the spectroscopic factors and v_j^2 the occupation probability of the respective neutron orbit j. Using least-squares fitting, spectroscopic strengths G_{lj} are obtained. For the low-spin states of interest here, our extended set of data yields almost complete level schemes of ^{196}Au and ^{195}Pt with definite assignments for ^{195}Pt and assignments or restrictions on the spins in ^{196}Au depending on the observed j values. Furthermore, the analysis is confirmed by the additional polarised $(\vec{d},\alpha)$ experiment which provided a definite spin assignment for 17 levels, in addition to a number of 2^- and 3^- states, assigned because of the observed sequence of j transfers.

5. EXPERIMENTAL RESULTS

In order to compare the transfer strengths to the theoretical predictions one needs to define the theoretical transfer operator. In all calculations made up to now the transfer operator between nuclei having the same number of bosons N was taken to be the operator a_j which creates a fermion in the supersymmetric models. The advantage of this simple operator is that analytic results can be derived [10]. Nevertheless, the transfer operator provides a poor description of the observed fragmentation of the strength [16]. Here, we use a semi-microscopic transfer operator obtained from the mapping of the single-nucleon creation operator onto the boson-fermion space [18] because the experiment deals with the transfer of a single nucleon. This yields in the case of a hole:

$$T^{lj} = \frac{v_j a_j^+}{K_\alpha} - \sum_{j'} \sqrt{\frac{10N_\pi}{(2j+1)N^2}} u_j (u_j v_{j'} + v_j u_{j'}) \times \left\langle \frac{1}{2} l'j' \,|\, Y_2 \,|\, \frac{1}{2} lj \right\rangle s^+ (\tilde{d} a_{j'}^+)^{(j)} \frac{1}{K_\alpha} \frac{1}{K_\beta} \tag{9}$$

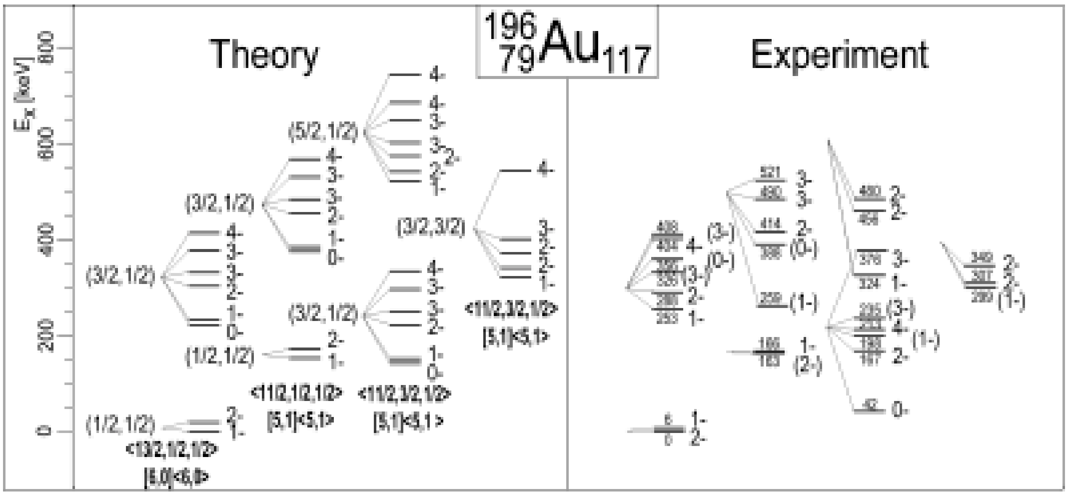
with $u_j^2 = 1 - v_j^2$. K_α and K_β are normalisation constants described in [18]. The semi-microscopic operator contains the simple operator as a first approximation. Both depend on the same number of parameters v_j. These parameters are not free but can be obtained from the experiment. We fixed them by directly using the ^{197}Au$(\vec{d},t)^{196}$Au data to be $v_{1/2}{}^2 = 0.33(5)$, $v_{3/2}{}^2 = 0.30(5)$ and $v_{5/2}{}^2 = 0.49(7)$. The second term in Eq. (9) induces the additional fragmentation. For ^{195}Pt the comparison of theoretical and experimental level schemes are shown in Fig. 2 and for ^{196}Au in Fig. 4.

The theoretical spectra are obtained from a common least squares fit of Eq. (6) to levels in ^{194}Pt, ^{195}Pt, ^{195}Au and ^{196}Au and will be presented in more detail in a forthcoming paper [19]. The resulting parameters are A = 52.5, B = 8.7, B' = -53.9, C = 48.8, D = 8.8 and E = 4.5 (all in keV) [2]. They are close to the original prediction which did not consider levels of ^{196}Au in the fit [10].

In Fig. 4 for the low energy part of the spectrum of ^{196}Au the data are compared with the prediction from extended supersymmetry. Even if not all details are reproduced, we observe a surprising over all agreement.

A further test is provided by the transfer strengths. The spectroscopic factors vary over orders of magnitude and are shown in Fig. 5 for the $J^\pi = 1^-, 2^-, 3^-$ states in a logarithmic scale. The calculation reproduces the experimental distributions irrespective of deviations in details, probably due to level mixing. In addition to the prediction of the very rich excitation spectra this agreement further supports that extended supersymmetry plays a dominant role, or, stated otherwise, that for the low energy spectrum of these nuclei symmetry breaking degrees of freedom are remarkably weak.

In view of the extreme complexity of heavy transitional odd-odd nuclei and the few parameters needed to describe simultaneously and nearly quantitatively almost one hundred excited states in four different nuclei, we conclude that the lowest excited states are related by the concept of supersymmetry in atomic nuclei. This conclusion is also supported by the fact that the Au, Ir nuclei are situated in the only region of the nuclear chart where the constraints for $U_\nu(6/12) \otimes U_\pi(6/4)$ are fulfilled. The question is now raised what is the microscopic basis that makes supersymmetry valid in atomic nuclei. Up to now, only few arguments



have been given [20] and one definitely needs more explanations.

Figure 4: The excitation energy spectra of negative parity states of ^{196}Au. At the left side the prediction from the model of extended dynamical supersymmetry, on the right side the experimental levels. In the theoretical prediction the respective quantum numbers are also indicated, below each band $<\sigma_1,\sigma_2,\sigma_3>$, $[N_1,N_2]$ $<\Sigma_1,\Sigma_2>$ and on the left side of each band (τ_1,τ_2).

6. SUMMARY

Evidence is observed for the existence of (extended) supersymmetry from the study of the odd-odd nucleus ^{196}Au using the ^{197}Au($\vec{d}$,t), ^{197}Au(p,d) and ^{198}Hg($\vec{d}$,α) transfer reactions [1] and combining this with recent information from $\gamma\gamma$ correlation studies [2]. High resolution ^{196}Pt(p,d)^{195}Pt and ^{196}Pt($\vec{d}$,t)^{195}Pt transfer experiments performed in parallel yielded at the same time an improved level scheme of ^{195}Pt [3]. Using extended supersymmetry, a single fit of the six parameter eigenvalue expression yielded a complete description of all observed low-lying excited states in the four different nuclei forming the supermultiplet.

The detailed comparison of the transfer amplitudes for the states up to 500 keV in the odd-odd member of the supermultiplet ^{196}Au using a semi-microscopic transfer operator provides evidence that this description is correct.

Acknowledgements

I appreciate significant contributions from A. Metz, H.-F. Wirth, R. Hertenberger and Y. Eisermann, University of München, N. Warr, J. Jolie, University of Fribourg, now Köln, J. Gröger, C. Günther, University of Bonn, and R. Krücken, R. Casten et al. from Yale. The work was supported by the Swiss National Science Fund and the Deutsche Forschungsgemeinschaft (grants IIC4 Gr 894/2 and Gu 179/3-2).

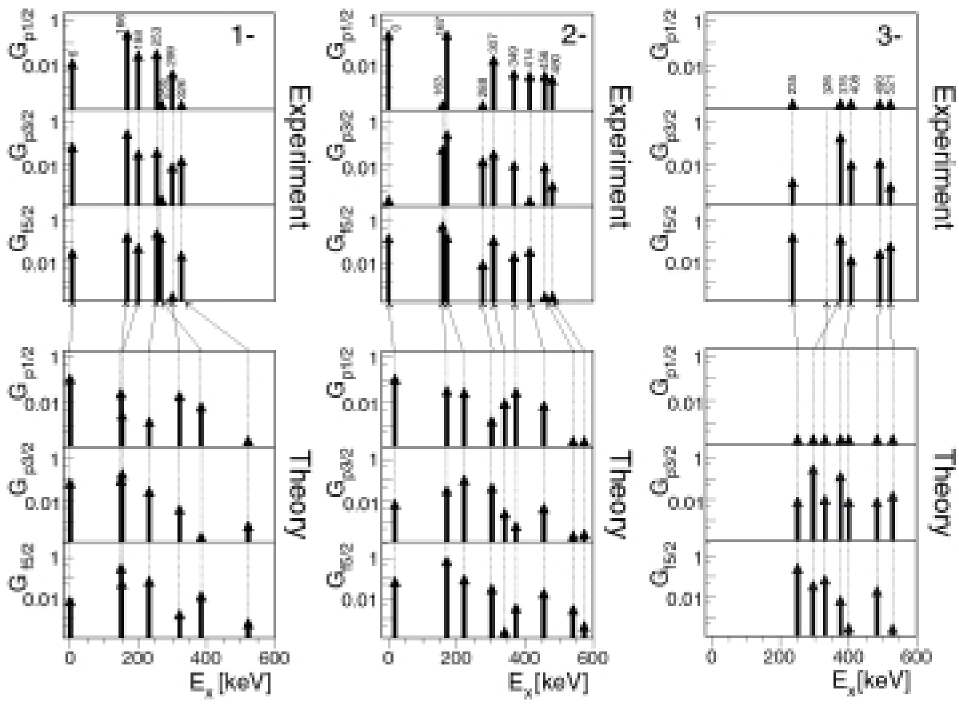


Figure 5: Comparison of the experimental (top) and theoretical (bottom) neutron transfer strengths for the 1^-, 2^- and 3^- states in ^{196}Au in the energy range of 0 to 600 keV. The resulting correlations are shown by arrows. Note the logarithmic scale of the plots.

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Received August 12, 2002