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A REVIEW OF SOME SCIENTIFIC PAPERS BY PROF. STANISŁAW SZPIKOWSKI

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ABSTRACT

A short review of the most important (arbitrary choice) papers published by Prof. Stanisław Szpikowski (1926–2014) is presented.

Professor dr hab. Stanisław Szpikowski began his adventure with physics as the experimentalist. As the research-and-teaching vice-assistant in the Cathedral of Experimental Physics of the Maria Curie-Skłodowska University (UMCS) he started to work on thermodiffusion measuring the thermodiffusion coefficients for different elements and their isotopes (Kilka uwag dotyczących doświadczalnego wyznaczania stałej dyfuzji termicznej dla izotopów, Annales UMCS, Sectio AA, vol. VIII (1953) 35–56). Next he prepared some experiments which allow to observe some parameters and evolution of thermodiffusion in gases (Wyznaczanie stałych potencjału wodoru, dwutlenu węgla i mieszaniny $H_2 - CO_2$, Annales UMCS, Sectio AA, vol. XIV (1959) 1–27; Przebieg termodyfuzyjny mieszaniny $H_2 - CO_2$ w zależności od czasu temperatury, ciśnienia oraz składu mieszaniny, Annales UMCS, Sectio AA, vol. XIV (1959) 29–48; Thermodiffusion process of gases in a horizontal tube, Folia Soc. Scient. Lublinensis, Sectio C, 2 (1962) 116-119; Thermodiffusion process of gases in a horizontal tube. Experimental part, Folia Soc. Scient. Lublinensis, Sectio C, vol 5/6 (1965/66) 3–5). On the other hand, it was the first time when Prof. Szpikowski started to think about theoretical physics. He considered the contemporary theory of thermodiffusion using the simplified thermodiffusion equation:

$$\frac{\Gamma_k}{n} = -D_{12}\nabla c_k + (-1)^{k+1}\frac{D_T}{T}\nabla T, \tag{1}$$

which contains the measurable thermodiffusion constant α:

$$\frac{D_T}{D_{12}} = \alpha c_1 c_2. \tag{2}$$

The coefficients Γ_k ($k = 1, 2$) are the streams of lighter and heavier isotope, n denotes the gas density (mixture of isotopes), $c_k = n_k/n$ is the concentration of light ($k = 1$) and heavy ($k = 2$) isotope in the normal gas. D_{12}, D_T are the diffusion and thermodiffusion coefficients, respectively.

The thermodiffusion constant α was calculated by Nier a few decades earlier (A.O. Nier, Phys. Rev. 56 (1939) 1009). He obtained this coefficient for the n-step process as the following expression:

$$\alpha = \frac{{}^n c_2^0 - c_2}{c_1 c_2} \frac{\frac{T_1}{T_0} + 1}{n \log \frac{T_1}{T_0}}. \tag{3}$$

After some analysis this thermodiffusion constant for n-step process was improved by Szpikowski who included in calculation the processes of higher order:

$$\alpha = \frac{\frac{T_1}{T_0} + 1}{\log \frac{T_1}{T_0}} \left\{ \frac{{}^n c_2^0 - c_2}{n c_1 c_2} + \frac{(n-1)(c_1 - c_2)}{2n^2} \frac{{}^n c_2^0 - c_2}{n c_1 c_2} \right\}, \tag{4}$$

where c_1^l, c_2^l are the concentration of light and heavy isotope in the cold ($l = 0$) and hot ($l = 1$) containers. T_0, T_1 denote temperatures of the cold and hot container.

These investigations allowed him to defend the Ph.D. thesis at the Maria Curie-Skłodowska University, Lublin, in 1960. The supervisor of his Ph.D. was Prof. Armin Teske.

After obtaining Ph.D. he turned the subject of his research to theoretical physics, or more precisely to the theoretical nuclear physics. This decision coincided with his visit at the University of Manchester, England, where he joined the group of B.H. Flowers (1979, Lord Flowers of Queen's Gate). This was a beginning of theoretical physics researches at the MCS University in Lublin.

The first studies in theoretical physics were devoted to the nuclear shell model calculations. These calculations were done for energy levels in the nucleus K^{40} (*Shell Model Calculations of the Energy Levels in* K^{40}, Acta Phys. Polonica, 25 (1964) 169–177). At this time, the nuclear shell model calculations were the hottest topic in nuclear physics. Still, until today shell model is one of the most important models of nuclear physics.

During work at the University of Manchester Prof. Szpikowski found also a good atmosphere to learn quite new and very effective method based on the Lie groups theory. Collaboration with B.H. Flowers resulted in a new group theoretical classification scheme of nuclear shells. In fact, about ten years earlier Flowers invented the classification scheme for the single j-shell (Proc. Roy. Soc. A 210 (1951) 197; Proc. Roy. Soc. A 212 (1952) 248), however, the generators of the corresponding group conserved the number of particles: they were generated by infinitesimal operators constructed from the fermionic creation/annihilation operators a_{mm_t}, where $m = \pm 1/2$ is the projection of the total angular momentum and $m_t = \pm 1/2$ is the projection of the isospin of a nucleon, respectively:

$$\left(a^+a\right)^{JT} \begin{array}{l} \nearrow \quad (a^+a)^{(J,0)} \to (a^+a)^{(J_{odd},0)} \to (a^+a)^{(1,0)} \\ \\ \searrow \quad (a^+a)^{(0,1)} \end{array} \tag{5}$$

Conservation of the particles number by the generators does not allow to incorporate the pairing interaction in the nuclear Hamiltonian which seems to be the most important part of the nuclear residual interaction. The resulting states can be labelled as:

$$|j^n;\, (nT)\, \alpha_1(st)\, \alpha_2(JJ_0)\rangle\,. \tag{6}$$

To include nuclear pairing interaction into the classification scheme the authors: Flowers and Szpikowski (*A generalized quasi–spin formalism*, Proc. Phys. Soc. 84 (1964) 193–199; *Quasi-spin in LS coupling*, Proc. Phys. Soc. 84 (1964) 673–679) generalized the idea of the quasi-spin method invented by Anderson, Wada, Takano and Fokuda who constructed the quasi-spin operators for only one kind of particles sitting on the single j-shell:

$$Q_+ = \frac{\sqrt{2j+1}}{2}\left(a_j^+ a_j^+\right)^{J=0}, \quad Q_- = (Q_+)^\dagger, \quad Q_0 = \frac{1}{2}\left(\hat{n} - j - \frac{1}{2}\right) \tag{7}$$

One of the most important features of this formalism was a possibility of analytical solutions for energies and eigenfunctions of the corresponding Hamiltonian. In this case, the generalized pairing Hamiltonian in j^n configuration can be written as:

$$H_p = H_p(Q_+Q_-,\, Q_0) \tag{8}$$

and the analytical form for the eigenenergies is:

$$E_p = H_p\left(-\frac{1}{4}(n-v)(2j+3-n-v),\ \frac{1}{2}\left(n - j - \frac{1}{2}\right)\right). \tag{9}$$

Szpikowski and Flowers extended the quasi-spin idea for the case of nucleons (two kinds of particles). They identified the resulting group as the orthogonal group in five dimensions $\mathrm{SO}(5)$. The generators of this group include the pairing operators for nucleons:

$$\begin{gathered}
S_+^k = \textstyle\sum_{m>0} \left((-1)^{j-m} a_{jmk}^+ a_{j-mk}^+\right), \quad k = p, n, \\
S_+^{np} = \textstyle\sum_{m>0} \left((-1)^{j-m} (a_{jmp}^+ a_{j-mn}^+ + a_{jmn}^+ a_{j-mp}^+\right), \\
S_-^q = (S_+^q)^\dagger, \quad q = n, p, np, \\
T_+ = \textstyle\sum_{m>0} \left(a_{jmn}^+ a_{jmp} + a_{j-mn}^+ a_{j-mp}^+\right) = (T_-)^\dagger, \\
T_0 = \tfrac{1}{2} \textstyle\sum_{m>0} \left(a_{jmn}^+ a_{jmn} + a_{j-mn}^+ a_{j-mn}^+ - a_{jmp}^+ a_{jmp} - a_{j-mp}^+ a_{j-mp}^+\right), \\
S_0^{np} = \tfrac{1}{2} \textstyle\sum_{m>0} \left(a_{jmn}^+ a_{jmn} + a_{j-mn}^+ a_{j-mn}^+ + a_{jmp}^+ a_{jmp} + a_{j-mp}^+ a_{j-mp}^+ - 2\right).
\end{gathered}$$

The corresponding pairing Hamiltonian and the eigensolutions can be written as:

$$\langle H_P\rangle = -G\langle \textstyle\sum_{k=n,p} S_+^k S_-^k + \frac{1}{2} S_+^{np} S_-^{np}\rangle \tag{10}$$

$$= -\tfrac{1}{4}G\{(n-v)(2j+4-\tfrac{1}{2}n-\tfrac{1}{2}v) - 2T(T+1) + 2t(t+1)\}.$$

This is an important result which allows to understand more deeply the nature of pairing interaction among nucleons.

One of the unsolved problems for the $\mathrm{SO}(5)$ quasi-spin is lack of one physical quantum number required for full classification of states. Prof. Szpikowski tried to solve this problem introducing the additional commuting operator which allows to make the classification of states in respect to the chain

$$\mathrm{SO}(5) \supset \mathrm{SO}(3) \tag{11}$$

unique. The additional observable was constructed as the four-body operator being the product of the operators which annihilate and create two pairs of nucleons, each pair with $J=0, T=1$:

$$\beta_- = \frac{1}{4}(S_-^{np})^2 - S_-^n S_-^p, \quad \beta_+ = \beta_-^\dagger, \quad \beta = \beta_+\beta_-. \tag{12}$$

In this case, the complete set of commuting operators is given by:

$$\beta, S_0^{np}, T^2, T_0. \tag{13}$$

However, this solution, though correct, gives rather complicated construction of required states and representations. In this sense it is unsatisfactory.

Independently of this problem, there is a question: why the quasi-spin classification is better than the standard spectroscopy based on the unitary group (Racach, Flowers):

$$\mathrm{U(2j+1)} \supset \mathrm{Sp(2j+1)} \supset \mathrm{SO_J(3)}. \tag{14}$$

In the old standard case the highest symmetry is characterized by “trivial” quantum numbers n, T. In addition, the highest group is unnecessarily complicated and different starting groups are required for different j.

In case of the quasi-spin spectroscopy (Flowers, Szpikowski):

$$\mathrm{SO(5)} \times \mathrm{Sp(2j+1)} \supset [\mathrm{SU_T(2)} \times \mathrm{U_N(1)}] \times \mathrm{SO_J(3)} \tag{15}$$

the highest symmetry is represented by a simple group. The physical quantum numbers n, T are related to some subgroups. They allow to use the Wigner-Eckart theorem. The same starting quasi-spin group is required for different j and, in addition, both $\mathrm{SO(5)}$ and $\mathrm{Sp(2j+1)}$ are labelled by the seniority v and the reduced isospin t.

The second important contribution of Prof. Szpikowski into nuclear spectroscopy is the other chain of quasi-spin operators related, not as previous one to j-j scheme, but to l-s coupling.

In this case, Szpikowski and Flowers also found the appropriate quasi-spin group. It is isomorphic the $\mathrm{SO}(8)$ and it is generated by the following combinations of creation and annihilation operators:

- Single $l+s+t$ level

$$\begin{tikzcd}
 & (a^+a)^{(L_{odd},0,0)} \arrow[r] & (a^+a)^{(1,0,0)} & \\
\left\{\begin{matrix} (a^+a^+)^{(LST)} \\ (aa)^{(LST)} \\ (a^+a)^{(LST)} \end{matrix}\right\} \arrow[ur] \arrow[dr] & & & (a^+a)^{(010)} \\
 & \left\{\begin{matrix} (a^+a^+)^{(0ST)} \\ (aa)^{(0ST)} \\ (a^+a)^{(0ST)} \end{matrix}\right\} \arrow[r] & (a^+a)^{(0ST)} \arrow[ur] \arrow[dr] & \\
 & & & (a^+a)^{(001)}
\end{tikzcd}$$

In this case one gets the important isoscalar pairing $T=0$.

Both quasi-spin classifications seems to be important contribution of Prof. Szpikowski to nuclear physics. They determined also his scientific research program for next several years. As a result is the set of some publications. The most important papers from this series are:

- *The Search for the Common Symmetry of Pairing + Quadrupole Forces in Nuclear Theory* (coauthor: K. Pomorski), Acta Physica Polonica, B1 (1970) 3–12
- *On the New Quasi–Particle Factorization of the j–shell* (coauthor: K.T. Hecht), Nuclear Physics A158 (1970) 449–475
- *Factorization of the $j=7/2$ shell of Neutron and Protons. Transformation coefficients to States of Good Particle Number* (coauthors: W.A. Kamiński K.T. Hecht), Atomic Data na Nuclear Data Tables, 16 (1975) 311–381
- *Alpha–Clusters in Nuclei with $41 \leq A \leq 45$* (coauthor: M. Trajdos), Nuclear Physics A272 (1976) 155–173
- *An IBM Analysis of a single j–shell of neutrons and protons* (coauthors: J.P. Elliott i T. Evans), Nucl. Phys. A435 (1985) 317–332

About the 80's a new idea of treating nuclei as the system of bosons became the new scientific challenge of Prof. Szpikowski. The Interacting Boson Model allowed to use similar algebraic methods as in the quasi-spin problem and related works. In the simplest case, the successful s,d model consist of the monopole and quadrupole bosons: s^2, d_μ^+ generated the group $\mathrm{SU}(6)$:

$$s^+s,\, (d^+\tilde{d})^L{}_M,\, s^+\tilde{d}_\mu,\, d_\mu^+s \text{ where } L=0,1,2,3,4. \tag{16}$$

An important property of this group is that it allows for a few group chains which are able to describe some vibrational, rotational and transitional nuclei. For example, the vibrational chain contains as the subgroups the same groups as those required by the five dimensional harmonic oscillator (Bohr Hamiltonian), so successful in description of nuclear quadrupole motion:

$$\mathrm{U}(6) \supset \mathrm{U}(5) \supset \mathrm{O}(5) \supset \mathrm{O}(3). \tag{17}$$

At that time, the basis for the Bohr Hamiltonian was unknown, because it was a difficult task to construct the basis including required physical groups. However, it turned out that by analogy to the quasi-spin approach, there exists an alternative solution based on another group chain:

$$\mathrm{SU}(1,1) \times \mathrm{O}(5) \supset \mathrm{U}(1) \times \mathrm{O}(3). \tag{18}$$

This idea allowed to construct the basis for the vibrational case of the Interacting Boson Model (IBM) and, at the same time for the Bohr Hamiltonian: $|vNn_\Delta LM\rangle$, where v is the boson seniority number, N denotes the total number of bosons, Δ can be interpreted as the maximal number of boson triplets coupled to the angular momentum $L=0$, and as usually L, M describe the angular momentum of the system. The most important papers concerning the IBM models are listed below:

- *The orthonormal basis for symmetric Irreducible Representations of $O(5) \times SU(1,1)$ and its application to Interacting Boson Model* (coauthor: A. Góźdź) Nucl. Phys. A340 (1980) 76-92
- *Complete and orthonormal solution of the five-dimension spherical harmonic oscillator in Bohr-Mottelson collective coordinates* (coauthor: A. Góźdź) Nucl. Phys. A349 (1980) 359–364
- *Interacting Boson Model and 3^- nuclear states in even–even nuclei* (coauthor: K. Zając) [in] Symmetries in Science VII, Plenum Publishing Corporation, N.Y. 1994, 545–555

Supersymmetry is a general concept which is mostly applied on the fundamental level, e.g. in field theory. Because of successes of both fermionic and bosonic nuclear models the idea of using supersymmetric algebra seemed to be a natural consequence. Prof. Szpikowski was interested in a possibility of existence of nuclear supersymmetry. However, after some work and a series of papers

- *Search for Supersymmetry in Light Nuclei* (coauthors: P. Kłosowski and L. Próchniak) Nucl. Phys. A487 (1988) 301–318
- *Supersymmetry scheme for nuclei $32 \leq A < 40$* (coauthor: L. Próchniak) Acta Phys. Polonica B24 (1993) 557–571
- *Binding energy of the sd-shell nuclei in the supersymmetric model* (coauthors: L. Próchniak and W. Berej) J. Phys. **G23** (1997) 705–715

it turned out that it is very difficult to show the existence of supersymmetry in real nuclei. Independently of this, the idea of nuclear supersymmetry is still an open and interesting problem, maybe on more fundamental level, like the field theoretical/quark model of nuclei.

Prof. Szpikowski was always interested in principles of quantum mechanics. The first, second and third edition of his textbook on quantum mechanics (S. Szpikowski, *Podstawy mechaniki kwantowej*, Wydawnictwo UMCS, 1999, 2006, 2011) are good introduction to problems of quantum physics. This textbook was systematically updated. This subject was a kind of hobby of Prof. Szpikowski, not only on the level of physics but also as a philosophical problem. For example, the problem of time in quantum mechanics (*Czas w mechanice kwantowej (Time in*

Quantum Mechanics), Roczniki Filozoficzne 25 (1977) 11–24) where he tried to analyse the following questions:

- If the current of time – also biological – is different in various frames of references, does it seem to be supported by quantum mechanics?
- If the micro-objects exist between measurement points and if they exist how do they behave?

It is a pity, however, these problems are very fundamental and they do not have accepted solutions till now.

Prof. S. Szpikowski published 85 research articles, 19 conference papers, 7 review articles, 7 books and scripts. He also wrote 5 popular articles about physics and more than 50 publications (a part of them is now nearly unavailable) on different subjects.

Below, there are listed practically all papers published by Prof. S. Szpikowski and his collaborators.

LIST OF PAPERS

I. SCIENTIFIC PAPERS

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