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# SUMMARY OF THE SCHOOL

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While it is always difficult to render the scientific structure of a conference in a summary talk, it is even more difficult to write such a talk. A summary talk profits from the atmosphere of the meeting, the camaraderie developed in everyday's contacts, lectures and meals. However, all that makes a conference different from reading a collection of articles, evaporates by the time of writing. Last but not least, facts and ideas not well understood, that in a talk can be thrown underneath the carpet, cannot be dealt with in the same cavalier way in a write-up!

All this to say that it took me several weeks to start writing this paper; the delay, however, did not make the task easier. On the contrary!

The XXIII Mazurian Lakes Summer School was an ambitious conference. What is worse, it succeeded in its ambitions, bringing together such disparate subjects as chaos and astrophysics. In my talk I classified the Conference subjects in the following way:

— **astrophysics**
— **subjects of general interest**
— **chaos**
— **radioactive beams ( unstable particle beams)**
— **heavy ion reaction mechanisms**
— **nuclear structure at large deformation.**

## 1. Astrophysics

The two principal astrophysical subjects treated at this Conference:

— the problem of cooling of neutron stars (Haensel)
— nuclear reactions in dense stellar matter (Yakovlev)
both dealt with the development of stellar objects.

When matter is compressed by gravitational forces, neutron stars are the final product of the thermonuclear evolution of stars with mass $M \geq M_{\odot}$. Contrary to naive belief, neutron stars contain a sizeable proportion of $p, e^-$ and other particles (this fraction, entering through the so called threshold condition, plays indeed a major role in the cooling of neutron stars) and are, moreover, rather hot objects ($T \sim 10^{11} K$, while the temperature of the interior of our Sun is only $\sim 10^7 K$). The rate of cooling of neutron stars is a foremost parameter determining our picture of the Universe (matter density): given the observed number of neutron stars, the rate of their cooling determines their real number and hence, matter density in the Universe in general.

Today we assume with good reasons that the neutrino emission from neutron stars is determined by the so called Urca processes, direct or modified. A typical direct Urca process is neutron decay, $n \rightarrow p + e^- + \overline{\nu}_e$, or its inverse, the electron capture by protons, $p + e^- \rightarrow n + \nu_e$. The stellar mass decides the rate of cooling: a 30% larger mass cools down a neutron star in hundreds of years as compared to millions of years for a $1.3 M_{\odot}$ star. Obviously such a star is much longer observable, hence our previous conclusions about the density of mass in the Universe.

The four paths of the destiny of a star were discussed by Yakovlev. The destiny is written in the mass of the stellar core: stars with massive cores collapse into black holes, those with a less massive core become white dwarfs and eventually give rise to novas and, for the least massive cores, neutron stars. On the other end of the scale, the most massive stars end up in the total outburst of a nuclear explosion. The details of the four paths are determined by the various regimes of stellar nuclear burning modes, from thermonuclear to pycnonuclear. The character and the rate of burning decide about the life-span of the star; they are calculated using classical nuclear physics methods.

Another liaison between nuclear and astrophysics was discussed by Schutz. Although the problem was typically nuclear — determining the hot, active zone in nucleus-nucleus collisions — it was introduced in 1954 by two astrophysicists, Hanbury-Brown and Twiss, who used intensity, instead of amplitude interferometry to determine the size of stars. In other words, one measures counting rates $|\psi_i|^2$, *not* interference patterns $|\psi_i + \psi_j|^2$. The technique consists of measuring small angle correlations of emitted light particles: photons, pions, protons. Such measurement of the $^{86}$Kr+$^{58}$Ni reactions at 60 MeV performed at GANIL with photons detected by the *TAPS system* yielded $R = 13.2\ fm$ for the radius of the emitting zone. This value contradicts most of the so far obtained results (13.2 fm is almost twice the radius of the composite $^{144}$Gd nucleus !), and, perhaps, it is due to the overwhelming $\pi^+\pi^-$ annihilation present in the $\gamma$-spectrum; what, however, if it is correct and, for instance, the sizes obtained by $p-p$ correlations stem from an incorrect treatment of the final-state interaction? Briefly, what if the HBT method has intrinsic difficulties when applied to the nuclear case?

## 2. Problems of general interest

The so called spin crisis was discussed by Moroz. It has been known for some time that protons behave in the deep inelastic scattering of electrons as multiple (threefold) entities. These small entities, called partons, were interpreted as valence quarks, Dirac-sea quarks and/or gluons. They all contribute to the spin of the proton, their combined effect is expected to yield $\frac{1}{2}\hbar$. Well, it does not: the (model dependent) analysis gives 14% of $\frac{1}{2}\hbar$ in the most favorable case and 1% in the least favorable case. Now, the $\frac{1}{2}\hbar$ spin and the partons are a reality; their consequence, however, the missing spin, is a crisis.

What do the theorists say? New analysis of the data may improve the results but new experiments planned at HERA (30 GeV polarized electrons), RHIC (polarized protons) and SLAC (50 GeV polarized electrons) will be necessary to shed more light on the problem.

Buda reported on measurements of dilepton yields from the $^4$He+$^{24}$Mg and the $^3$He+$^{25}$Mg reactions, populating, respectively $T = 0$ and $T = 0$ and 1 states in $^{28}$Si. The main goal of this experiment was to look for the $E0$ strength coming from Giant Monopole Resonances. The resonances decay via $e^+e^-$ pair emission, whereas single $\gamma$-emission is not allowed. An excess of dileptons over the "converted photons" has been observed, indicating the presence of an $E0$ yield.

The problem of *nuclear radii* was attacked by several speakers. Pomorska and Pomorski introduced a new empirical formula for the nuclear radius of a nucleus $A(Z,N)$:

$$R = 1.25\,[1 - 0.2\frac{N-Z}{A}]\,A^{\frac{1}{3}}\,.$$

This expression which emphasizes the isospin correction (14% for $^{238}$U) gives the charge distribution radius and was obtained from fitting the radius of even-even isotopes.

Several speakers (Jastrzębski, Polster, Grabowska) discussed the various stages (annihilation, INC, preequilibrium, evaporation and $\gamma$-decay) of the interaction of antiprotons with nuclei. Jastrzębski described a beautiful method of determining the nucleon halo by distant annihilations of antiprotons. Such annihilations produce pions, which, because of the distance, do not hit the nucleus, leaving a cold $A - 1$ residual nucleus. Should such a nucleus be radioactive — and this is a restriction of the method — we can detect it and thus deduce the probability of a nucleon halo around the nucleus. There is a strong experimental correlation between the binding energy and the probability of the peripheral halo: nuclei with weaker binding are more likely to exhibit the halo.

To conclude this section we mention the interesting work reported by Dąbrowski and Henino on exotic nuclei, respectively the $\Lambda$ problem and the study of the $\Delta$ nucleus dynamics (obtaining the so called contact term $g_{\Delta}\Delta$) by creating $\Delta$ nuclei by charge exchange coherent processes such as $(^3He, t\pi^+)$.

## 3. Chaos

This subject was one of the principal themes of the Conference, and as expected, the source of lively discussions. It was introduced by Świątecki, applied to nuclear dynamics rather than to statics (systematics of nuclear levels). My own intellectual dilemma with chaos in nuclear physics was its relevance to the field: for instance, the main achievement of the chaos theory in nuclear dynamics is the derivation of the two dissipation formulas, the window formula and the wall formula, *after* these expressions were derived by other (semiclassical) methods. Thus I needed considerable private tutoring to familiarize with the subject.

The first result of this tutoring is that there is at least one result in nuclear physics that could not be obtained by standard methods: the energy distribution of fission fragments calculated by using the chaos theory shows much better agreement with experiment than that calculated by nuclear methods. Of course, this is not the only application to nuclear dynamics. Here, chaos is evolving into a theory of fission and nucleus-nucleus collisions paving the way to a unified picture of these two sets of phenomena. The calculation of the so called extra push, the additional energy needed for a symmetric system to roll over the saddle point, is one example.

Fluctuations in multiparticle dynamics were discussed by Płoszajczak. One of the starting points of his discussion was that large fluctuations in nature do not cancel. Example: clusters of galaxies in the Universe, where one would expect a uniformly distributed dust. Płoszajczak's model of nuclear fragmentation, the inactivation–fragmentation model, is based on following the path of the nuclear collisions. This path may lead to consuming all the energy, thus taking a blind alley (inactivation) or sharing the energy with other nucleons and, eventually, leading to fragmentation. The physical input to the model is rather modest; nevertheless the model is able to qualitatively reproduce sets of fragmentation data, for some data, *e.g.* the famous Aladin data (see Section 5), even better than qualitatively.

Hasse introduced ordered structures in atomic and nuclear physics. A typical radius of such a structure is the so called Wigner–Seitz radius

$$a_0 = \frac{3}{2}\frac{q^2}{K},$$

where $K$ is the restoring force and $q$ the electrical charge. The dimensionless parameter that determines the nature of such objects

$$\Gamma = \frac{\text{Coulomb energy}}{\text{thermal energy}} = \frac{q^2/a_0}{kT},$$

renders ordered structures for $\Gamma \sim 170$ to 200.000 with typical values of the radius $a_0 \sim 10 - 50\ \mu m$ for atomic objects. Such objects are of practically macroscopic dimensions. Presently, calculations showing the birth of these objects and experiments to go with, are available. They show magic numbers, just like the atomic and nuclear shell structure.

What are these objects? Solids? Liquids? They should be thought of as the result of a phase transition for increasing the number of particles. No doubt we shall hear more about them.

## 4. Radioactive beams

A popular name for beams of unstable particles, radioactive beams are an increasingly interesting and important technology of producing beams, that may open a whole new domain of nuclear physics. Their interest lies in the fact that they consist of neutron-rich *viz.* proton-rich nuclei far from the stability line; colliding with conventional targets, these beams lead to hitherto unexplored nuclei. At present, radioactive beams are available and operational at the Louvain–la-Neuve cyclotron. The light, neutron deficient nuclei $^{13}$N and $^{19}$Ne are produced with an intensity of $\sim 10^9$ *pps*; the intensity for the neutron-rich nucleus $^{6}$He is much less ($\sim 10^6$ *pps*). Still, according to Huyse, this is only the beginning.

What can one do with such a facility? Recent results at the GSI-SIS fragment separator were presented by Münzenberg. In a typical reaction like $^{86}$Kr+$^{9}$Be at 500 MeV/nucleon, fragments up to $^{75}$Ni are produced. Even allowing for the very low production rate of such extreme fragments, it is obvious that radioactive beams provide an excellent access to nuclei that exhibit exotic features. An application of such a technique is the discovery of the $^{11}$Li halo. The signature for this object was the momentum distribution of neutrons from the break-up of 300 MeV/nucleon $^{11}$Li on a Pb target. The measured distribution was much narrower than that predicted by the conventional Goldhaber single-particle model, indicating a neutron cloud at large distances from the center of the $^{11}$Li nucleus.

At the same GSI-SIS laboratory, cooled secondary beams were for the first time successfully stored in the storage ring. This makes possible direct measurements of masses and binding energies of exotic nuclei, with a mass resolution $\Delta M/M \sim 10^{-5}$!

## 5. Heavy-ion reaction mechanism

This subject was discussed extensively at the Conference. The range of energies spanned from 10 to 1000 MeV/nucleon and the analysis includes a variety of approaches.

Gadioli, emphasizing the role of non-equilibrium processes in cooling the hot composite systems created in a nucleus-nucleus collision, pursued the goal of obtaining a unique set of parameters for non-equilibrium processes induced by light and heavy ions. The equilibration of the composite system proceeds by nucleon-nucleon collisions and its mathematical treatment is the well-known (Boltzmann) master equation. The physical ingredients of the calculation are the Pauli blocking factors and the $N-N$ cross sections (from the $G$-matrix approach). The emission of nucleons is calculated using the detailed balance principle, that for the clusters is done according to the coalescence model (the coalescence radius being an additional parameter). The quality and the extent of the obtained fits to the data are rather impressive.

The four papers that follow all deal more or less directly with nuclear fragmentation and clustering in nuclear matter. Each paper from a different point of view.

Budzanowski introduced the Nuclear Big Bang: The dense and hot Universe ultimately evolved into clusters of galaxies; should hot and dense nuclear matter created in energetic central nucleus-nucleus collisions also evolve into clusters? The answer is neither unique nor simple. Against this attractive but naive picture, the present general belief is that clustering has a better chance at lower densities, roughly those corresponding to internucleon distances just out of the reach of the attractive nuclear forces. Just to get feeling, for an average $N-N$ distance of 2 fm, the necessary density is $\rho \approx 1/6\ \rho_0$. This is where Budzanowski starts. How to reach such a density? For a high-energy nucleus-nucleus collision this density can be reached at the so called freeze-out stage. But then the hot composite system may decay by both sequential and instantaneous modes. Unfortunately, the respective decay times $\tau_s$ and $\tau_i$, are of the same order of magnitude and offer no clue for disentangling the two modes. Hence, other signatures have to be looked for. A commonly accepted conjecture concerns the connection between clusterization and a phase transition. A classical signal of a phase transition in a system is a constant temperature with increasing energy (remember the well known high-school picture showing the diagram of the $T$ *vs.* $E$ dependence for boiling water). Evidence for such a phenomenon was reported by Budzanowski in the measured coincidence spectra of evaporation residues + evaporated particles of $^{32}S+^{58}Ni$: the deduced temperature of $T \sim 5$ MeV remained constant when the excitation energy increased from $E^* = 240$ to 540 MeV.

The quantum molecular dynamics (QMD) approach to nucleus-nucleus collisions at high energies (Aichelin + Stöcker 1986) was discussed by Reisdorf. The problem is how to produce clusters in a nuclear gas of given temperature $T$, density $\rho$, excitation energy $E^*$ and isobaric entropy $S/A$. These global parameters are mutually dependent; their relation is given in a comprehensive way by, for instance, the Quantum Statistical Model (QMS, Stöcker + Hahn). Analyses of the central Au+Au collision at several hundred MeV/nucleon performed by the Strasbourg component of the GSI-FOPI collaboration, indicate, for cluster formation, a limit for the temperature $T$ from 10–15 MeV and entropies $S/A$ from 2–2.5. Obviously, large entropies would not lead to clusterization; this requirement restricts the region of the $T$ *vs* $\rho$ plane where clusters could be generated.

How to reach this region? Essential is the blast scenario: to get to the clusters a cooling mechanism should be devised. What does the nuclear gas cools from? Simple expansion is not sufficient, since the gas does not do the work. We are just at the beginning of our understanding of the clusterization phenomena and the blast development. Reisdorf insists that the two aspects are correlated: the blast is the key to the cooling mechanism needed to form clusters.

The problem of multifragmentation was discussed by Trautman, in particular how to reach the so called spinodal region in the $S/A$ *vs.* $\rho$ plane where clustering can be generated. At the GSI-ALADIN facility the so called unconditional partition of intermediate mass fragments (IMF) was discovered in the collisions of 600 MeV/nucleon Au projectiles with targets of C, Al, Cu and Pb. The experiment (see figure in Trautman's contribution) showed that the distribution of IMF's with $3 \leq Z \leq 30$ is totally independent of the mass of the target and for this particular energy, symmetric around $Z_{\text{bound}} \approx 40$. The distribution, however, showed an energy dependence: symmetry was reached only at incident energies between 250 and 400 MeV/nucleon. This "Rise and Fall" is most likely a statistical phenomenon, as seen from the comparison with available statistical calculations.

The realm of nucleus-nucleus collisions at intermediate and relativistic energies, including changes in the bulk properties of nuclear matter during these reactions and features of transport descriptions were discussed by Danielewicz. The old problem of understanding clustering is in the difficulty of finding a suitable path in the $E/A$ *vs.* $\rho$ plane, leading to the $(\frac{\delta P}{\delta \rho})_{\frac{S}{A}} \leq 0$ region, the region of the low density where the pressure decreases as the density increases. The compressibility of nuclear matter plays a foremost role and one uses nucleus-nucleus collisions to evaluate the nuclear stiffness. Fixing the momentum dependence in Nb+Nb and Ar+Pb data at 400 MeV/nucleon, one obtains values of the compressibility coefficient of nuclear matter $K \approx$ 180 MeV, which would indicate a soft, momentum dependent equation of state for nuclear matter.

## 6. Nuclear structure at high deformation

"Zucker kommt zu letzt" states a German saying. The reason this saying comes to mind is the trend of revival of nuclear structure investigations carried by the experimental break-through in $\gamma$-detection. It is sufficient to glance at some of the transparencies presented at the Conference showing the comparison of "old" $4\pi$ detector systems with the new ones (*e.g.* EUROGAM) to see this point.

The subject of superdeformations (experimental discovery 1986 by Twin et al. Greiner pointed it out already in 1983), still the leading subject in nuclear structure studies, was discussed by Janssens and de France. The phenomenon, as we understand it now, is essentially a shell effect: when deformation increases reaching ratios of the axes 2:1, the shell order changes so much that one finds other gaps and different magic numbers. The important physical quantities are the moments of inertia and the character and magnitude of the pairing. They determine the nature and the magnitude of the deformation.

The most striking discovery in nuclear structure in the last year or so are the so called *identical bands.* These are bands in different nuclei which have similar moments of inertia $\Im$ and whose decay energies differ by very little when one considers corresponding energy levels. The empirical expression for the latter statement is usually written as:

$$E_\gamma^A(I') = E_\gamma^B(I) \pm 2\,\mathrm{keV}\,,$$

for bands $A$ and $B$ in two different nuclei. In other words, when one looks at these bands side by side, one cannot see the difference. More than 30 of such bands have been discovered until August 1993; striking examples are shown in the contributions by Janssens and de France.

Why would this problem defy common credence? Most of the models involve the scaling factor $\Im \approx mR^2 \sim A^{\frac{5}{3}}$. Consequently,

$$\Delta E_\gamma / E_\gamma \approx \Delta\Im/\Im \sim 0.01 \,,$$

for, *e.g.*, $A = 150$. Experimentally, however,

$$\Delta E_\gamma / E_\gamma \sim 0.001$$

*i.e.* there is a discrepancy of a factor 10! Although theoreticians have come up with several fancy models (pseudo-SU(3) symmetry, supersymmetry, quantized pseudo-spin alignment, cancellation of terms which contribute to $\Im$), no definite explanation has so far emerged.

The structure of exotic, far from the stability nuclei, was discussed by Nazarewicz. These are neutron- or proton-rich nuclei around the so called drip line, where the separation energy of the last nucleon,

$$S_n = E^{ee}(N) - E^{eo}(N-1) \leq 0 \,.$$

There are, at present, abundant spectroscopic data on these nuclei, to such an extent that drip-line nuclei could be used as a tool for learning about the isospin dependence of effective forces. Reliable spectroscopic calculation are, however, less abundant. Owing to the extreme isospin conditions, these calculations are, as a rule, far extrapolations. Also, shell effects become weaker, gaps filled. The vicinity of the drip line influences the surface of a nucleus: diffuseness becomes so large, that the very concept of the nuclear surface loses its sense.

For all these reasons, systematic studies of the spectroscopy of drip line nuclei should always include calculations based on different approaches. Nazarewicz presented two sets of calculations, based, respectively, on the relativistic mean field (RMF) and the Hartree-Fock (HF) approaches. Some general features emerge from these calculations:

— the proton drip-line is rather insensitive to a particular set of parameters; in view of the large Coulomb barrier for the extreme members of a set of isobars, this behaviour is not unexpected;
— the neutron drip-line, on the other hand, responds rather sensitively to the change in parameters;
— the already mentioned diffuseness of the surfaces appears to be more pronounced for the neutron than for the proton drip line; on the other hand, the radius (always in a Saxon–Woods parametrization) is essentially isospin independent.

## 7. Summarizing the Summary

Attending every single session in totality, which is the privilege and the curse of the Summary speaker, one gets a feeling where the results come from. It is quite clear that most of the presented results come from large research centers and big international collaborations. This is equally so for quantity and quality. In this respect, *nobody beats the big ones.* The impact of this state of affairs is already felt and will be felt more and more. Is it good or bad for nuclear physics to follow the path of elementary particle high-energy physics and eliminate the emotional and intellectual pleasure of setting-up and running an experiment and later on analysing the data in matters of weeks, not years? Would this mean a better efficiency in the forthcoming years of financial squeeze? I do not know. Theoreticians still tend to cluster in small teams, but there also the single author becomes more and more rare.

Which brings us to the perennial, sometime jocular, experiment *vs* theory confrontation. A secret (secret de Polichinelle, though) that I would like to whisper in the ears of my fellow experimentalists, is that, at present, experimental results seem to be more elaborate than the results of calculations. Take, for example, the domain of intermediate and relativistic heavy ion nuclear physics, were the predominant theoretical tools are thermodynamical and transport theories. If in a theory the input is statistics and combinatorics, it is hard to expect detailed information in the output (remember the famous "Sewer-pipe principle" enunciated by Marshall Blann in Rudziska 71).

Finally, let me mention my impression that we are witnessing a strong revival of nuclear structure studies. The structure and the character of super-deformed nuclei is a continuing challenge, made more accessible by the advance in the $\gamma$-detection technology. I foresee a comeback of nuclear structure physics, both experiment and theory, as a renewed focal point of nuclear physics in the mid-nineties.