

ELECTRON SPECTROSCOPY AND NUCLEAR STRUCTURE

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The present status of the relationship between in-beam electron spectroscopy and nuclear structure studies is briefly outlined. The main potential possibilities of that relationship are also discussed. Finally, the strong personality of Gaja ALAGA, with a deep humanism enhanced by a pure scientific mind, is evoked in the present scientific, economical and social context prevailing in Europe.

1. Introduction

Electrons were discovered (in 1897) by J. J. Thomson as constituents of all atoms shortly after the discovery of uranium natural radioactivity (found by Becquerel in 1896). Later Rutherford showed (between 1903 and 1905) that the radiations emitted spontaneously during that process are an admixture of three different kinds: α , β and γ -rays (identified to helium atoms, electrons and penetrating photons respectively). Further experiments analysing the beta-rays with direct magnetic deflection and semi-circular focusing discriminated an electron line spectrum overlapped with a continuous electron spectrum. Finally, the atomic nucleus hypothesis was confirmed by the analysis of α -ray scattering data investigated by Rutherford, Geiger and Marsden (1911—1913) in thin metallic foils.

The combination of all these facts not only justifies the usual denomination given to such magnetic deflection experiments as the preliminary steps of nuclear and electron spectroscopy but also proves the close relationship existing between them since their origins.

A detailed comparison between the evolution of the experimental methods and techniques developed during this century in these spectroscopic branches is

an interesting and instructive topic. However, such a theme exceeds by far the scope of this work due to its large extension and complexity. Furthermore, the relationship between the evolution of such experimental tools and our knowledge of nuclear structure is still a more ambitious and difficult topic as can be judged from many classical reviews and treatises dealing with nuclear¹⁻⁴⁾ and electron spectroscopy⁵⁻⁷⁾.

In such a context, the aim of this work is to outline the present status of the relationship between in-beam electron spectroscopy and nuclear structure studies following an earlier discussion⁸⁾ on the same theme. In particular, we attempt to answer a few general questions rather pertinent nowadays:

- (i) What nuclear structure information can be obtained from electron spectroscopy?
- (ii) Is it possible to increase the contribution of electron spectroscopy to nuclear structure studies to the same extent as was achieved in atomic, molecular and solid state physics?
- (iii) Can such improvement lead to a closer cooperation between nuclear experimentalists and theorists?

The first question (i) is illustrated by a few typical applications of electron spectroscopy to nuclear structure investigations developed in Section 2 of this work. Most of these examples are taken from a few theoretical investigations concerning nuclear structure studies dealing with electron and nuclear spectroscopy data. Such studies started in the early seventies with the development of intermediate coupling particle vibration models applied to odd mass gold isotopes in collaboration with Vladimir Paar and Charles Vieu helped by a strong support of Gaja Alaga.

After the *Topical Conference on Problems of Vibrational Nuclei* (organized at Zagreb in 1974 by Gaja Alaga and co-workers) this work was extended to other nuclear theoretical descriptions. Indeed, particle vibration and particle rotation descriptions of odd mass gold isotopes were compared at that meeting⁹⁻¹⁰⁾. However, according to these results, a generalization of the particle asymmetric rotor model, developed earlier by Hecht and Satchler¹¹⁾ was required for a complete description of positive and negative parity states of odd mass gold isotopes. Such an extension was performed by Stig Erik Larsson, Georg Leander and Ingmar Ragnarsson working then at Lund¹²⁾ following our request at Zagreb to the late Sven Gösta Nilsson. This generalized model was applied by Charles Vieu and co-workers to the description of low and medium excited levels of odd mass gold isotopes¹⁹⁻²²⁾. Furthermore, a detailed comparison between the particle vibrator and particle rotor descriptions of such nuclei was also performed in the frame of the same collaboration.

The application of such deformed basis description to odd mass transitional nuclei led to extensive studies, made by Wladislaw de Wiclawik and co-workers, of potential energy surfaces of odd Z even N isotopes (i. e. $Z = 75, 77, 79, 81$; $N = 92-126$)²³⁻²⁹⁾. Their results describe the general trend of the static properties of such nuclei. In particular, the variation of the excitation energy of the first $9/2^-$ level of odd mass Tl, Au, Ir and Re isotopes with the nuclear charge number, Z , agrees with the results of such calculations³⁰⁻³²⁾.

The comparison between these different types of theoretical descriptions of transitional nuclei was extended also to other regions of the nuclear chart³³⁻³⁵. Moreover, the same type of comparison gives further insight into nuclear level statistical representations introduced earlier by T. Ericson³⁶ and applied later to the nuclear level spectra of transitional nuclei³⁷⁻⁴¹.

The second question (ii) is an extension of the previous one analysing the potential possibilities and practical limitations of both research fields (i. e. electron spectroscopy and nuclear structure) in their present status of development. A brief discussion concerning a few general features of electron spectroscopy and related techniques is developed in Section 3.

The last question (iii) reminds us of many long discussions held with Gaja Alaga—still felt as agreeable and strongly stimulating souvenirs— with actual interest in the present scientific, economical and social context prevailing in Europe (Section 4).

Finally, a few general *conclusions* are drawn in Section 5 from these reflections and discussions.

2. *Electron spectroscopy applied to nuclear structure investigations*

Electron spectroscopy made an important contribution to the understanding of nuclear structure since the earlier studies of that important topic. Indeed, such a contribution was conveyed mainly through the study of internal conversion and beta-decay, alone or combined with X and γ -rays as well as atomic particles spectroscopy (see for instance the introduction of K. Siegbahn to his treatise⁵). In particular, the combined experimental data of internal conversion electrons and gamma rays determined the following nuclear properties:

- (i) The nuclear angular momenta and parity differences between the initial and final states involved in an electromagnetic transition;
- (ii) The branching ratios, multipolarity admixtures and internal conversion coefficients (ICC) of all transitions occurring between such states;
- (iii) The nuclear level half-life of the initial state and the reduced transition probabilities, $B(\sigma L)$, of their deexciting EM transitions;
- (iv) The directional and angular correlation coefficients of the same transitions;
- (v) The electric charge number of the nucleus where the internal conversion occurs.

The first item (i) is the simplest and most accurate method of determining spin and parity differences of nuclear excited states related by EM transitions (occurring between them). Furthermore, the experimental investigation of the internal conversion process is essential for determining internal conversion coefficients and total intensities of strongly converted transitions. Finally, a γ -ray transition alone does not give any definite information on the nuclear charge number of the γ -ray emitter while the corresponding IC electrons converted in different atomic levels give a definite Z assignment, provided the resolving power of

the electron spectrometer analysing the IC spectra is high enough to separate the different IC lines.

The correlation between the experimental data on beta-decay and nuclear structure is more complex and less obvious than the corresponding correlation concerning EM transitions between nuclear states. This different behaviour is due to the much smaller coupling constant of the weak interaction than the coupling constants of nuclear and EM interactions. Consequently, the properties of nuclear quantized states are mainly determined by nuclear and electromagnetic forces without a noticeable influence of the weak interaction (responsible for beta-decay). Nevertheless, the existence of several selection rules controlling the spin and parity changes of nuclear initial and final states of beta-decay allows a deduction of these nuclear magnitudes from the analysis of the beta-decay experimental data.

More generally, the investigation on the apparent failure of nuclear energy and momentum conservation in beta-decay led W. Pauli to the neutrino hypothesis adopted later by E. Fermi in the first theory of this decay process. Furthermore, the observation of parity non-conservation in beta-decay, led to important developments in the theory of weak interaction far beyond the nuclear structure research field. However, the importance of beta-decay for nuclear structure studies remains relevant for the experimental determination of several nuclear properties. Among the large number of such nuclear determinations the following are quoted:

- (i) Spins, parities and mixing ratios of EM transitions following beta-decay may be deduced from β - γ circular polarization asymmetry measurements.
- (ii) The spin of an initial nuclear level, decaying through several beta branches into different final nuclear levels with known spins, may also be determined from the corresponding branching ratios.
- (iii) Nuclear matrix elements of allowed transitions, M_F , may also be deduced from β - γ circular polarization correlation data. In the case of mixed transitions the same matrix elements can be deduced from the ratio between Fermi and Gamow-Teller matrix elements (derived from β - γ circular polarization measurements) and the experimental ft values.

There are many other examples of different topics in nuclear spectroscopy stressing the importance of electron spectroscopy for nuclear structure investigations. A few of these topics with actual interest and good prospect of future development are discussed in the following sections (2.1—2.8). For clarity, the order of such topics follows their increasing complexity and the special features of the low and high energy domains are discussed separately.

However, considering the frequent assumption of nuclear shape transitions of odd A transitional nuclei at high and very high spin, it would be very useful to investigate systematically their EO transitions in order to check experimentally the validity of such assumption.

2.1. Nuclear isomeric states and EM transitions

The experimental determination of the reduced transition probabilities of EM radiations deexciting a nuclear excited state with known half-life, τ , requires the measurement of the transition energies and internal conversion coefficients as well as branching ratios and mixing ratios of such transitions. All these quantities

can be deduced (at least in principle!) from the analysis of internal conversion electrons provided the following three main conditions are fulfilled: (i) availability of an electron spectrometer with enough resolving power and luminosity: (ii) use of an electron source -either radioactive sample or target plus particle beam- having strength and dimensions compatible with the problem to be investigated; (iii) strong reduction of the background due to disturbing effects (i. e. electron scattering) or spurious radiations (production of photoelectrons and δ -rays).

The same physical quantities can also be determined experimentally without internal conversion measurements (i. e. deduced from the analysis of direct γ -ray spectra and the study of γ - γ angular correlations) provided the theoretical ICC coefficients give accurate predictions. This accuracy is reasonable in most cases except, as a rule, for low energy transitions (where the internal conversion is preponderate over photon emission and the influence of the atomic screening effect on the theoretical ICC values is more important) and whenever nuclear dynamical effects on the internal conversion process must be considered. Furthermore, when low and high energy γ -ray angular correlation measurements are required, it is also important to investigate the corresponding low energy internal conversion — high energy γ -ray angular correlation. Consequently, the search and detailed study of nuclear isomeric states (as well as their deexciting transitions) leads, in general, to the investigation of internal conversion electrons.

The electromagnetic properties of nuclear excited states (like the reduced transition probabilities between them) are more sensitive and accurate to test the wave functions corresponding to different nuclear models than the spins, parities and excitation energies of such states. This is another argument supporting this kind of investigation. However, it should be noticed that the internal conversion coefficients corresponding to low energy transitions [$E(e^-) \leq 20$ keV] and the multipolarities of high energy weak transitions are particularly difficult to determine experimentally. Such difficulties arise mainly from the following facts:

- (i) The fast variation of ICC with the transition energy (for instance, $\alpha_K(E2) \sim \sim E^{-7/2}$ and $\alpha_K(M1) \sim E^{-5/2}$) and the smaller differences between distinct multipolarities.
- (ii) The sharp variation of the electron detection efficiency in the low energy region and its small value for high energy electrons.
- (iii) The partial overlap between IC and Auger electrons in the low energy domain where the δ -rays are very intense in the forward direction of a charged particle beam, near the target (see Figs. 1, 2).
- (iv) The competition between pair-production and internal conversion in the high energy domain.

The existence of such difficulties added to the specific problems involved in half-life measurements of nuclear excited states explains the small amount of information available on the reduced transition probabilities compared to the large number of nuclear states known in many nuclides. However, a considerable progress has been made in the investigation of nuclear reduced transition probabilities in spite of that limitation (see, for instance, Warburton⁴²⁾ and Morinaga-Yamazaki⁷⁾). In conclusion, a great deal of progress is expected in this topic due not only to its considerable theoretical interest but also to recent developments made in the experimental methods and techniques of electron spectroscopy dealing with fast recoil ions (see, for instance, Refs. 43—50).

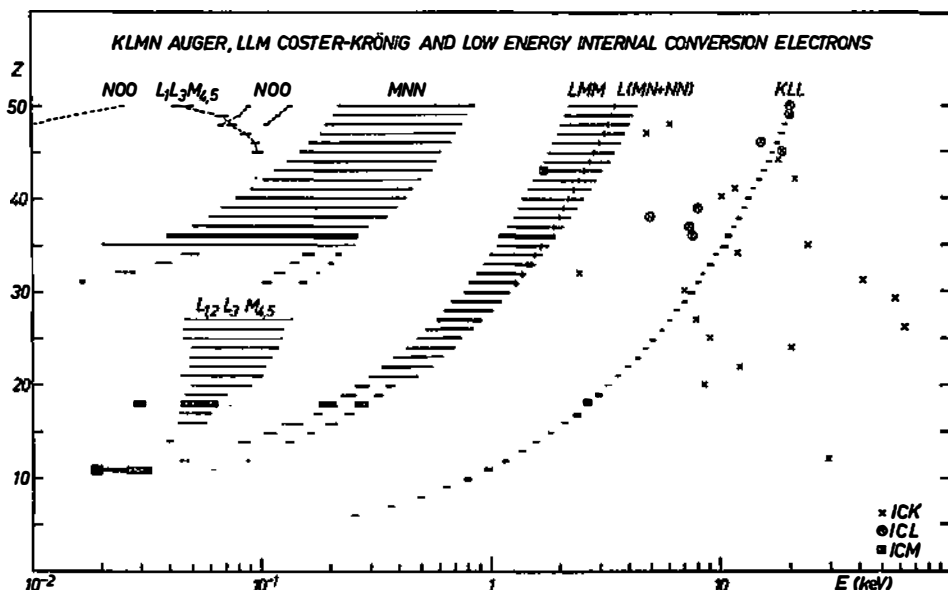


Fig. 1. The K and L Auger, LLM Coster-Krönig and low energy IC electrons emitted by light and medium nuclides ($Z < 50$). The full drawn energy intervals correspond to Auger and Coster-Krönig transitions. Only the lowest IC lines of these nuclides are represented. (see Ref. 89)

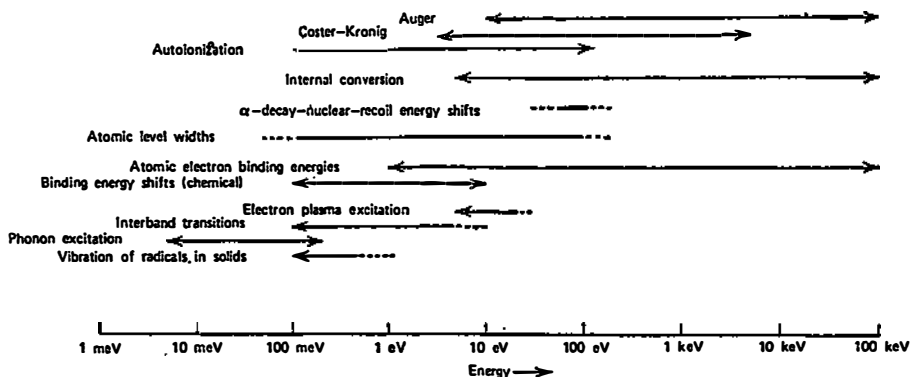


Fig. 2. Atomic and solid state effects related to low energy electrons. This figure (taken from Ref. 90) and the previous one illustrate the very high complexity of low energy electron spectra. Moreover, the in-beam IC «prompt» spectra are also overlapped with a continuous background due to d -electrons.

2.2. Electric monopole transitions

The electric monopole transitions, EO, between nuclear levels with the same quantum numbers can take place when an orbital electron moving under the influence of the nuclear Coulomb field penetrates inside the nucleus. The investigations of these transitions gives important information on the nuclear shape. In-

deed, the EO reduced matrix elements depend exclusively on the nuclear wave functions and the isotopic shift can be considered as the static analogue of such transitions⁵¹). Furthermore, if the initial and final states of an EO transition have both zero angular momentum — as occurs exclusively in even nuclei — the emission of electromagnetic radiation (i. e. γ -rays) is strictly forbidden. In such cases only internal conversion — or pair production — can take place. On the other hand, if the angular momentum of such states is different from zero both γ -rays and internal conversion electrons are emitted. Consequently, the study of EO transitions is restricted in the former case to the measurement of internal conversion electrons while both γ -rays and internal conversion electrons must be studied (mainly by measuring e - γ and γ - γ angular correlations) in the latter case.

Finally, most available information on EO transitions concerns even nuclei⁵¹⁻⁵²). Indeed, only very little data is available on odd mass nuclei. However, considering the frequent assumption of nuclear shape transitions odd A transitional nuclei at high and very high spin, it would be very useful to investigate systematically their EO transitions in order to check experimentally validity of such assumption.

2.3. *Unique parity states and their system of levels*

The negative parity levels of odd mass Tl, Au, Ir and Re isotopes are usually interpreted as particle (quasi-particle, particle-cluster)-vibrational (or rotational) bands built on a single proton subshell belonging to the $h_{9/2} - h_{11/2}$ spin orbit-doublet. Indeed, the components of such a doublet are weakly coupled together and can be linked *separately* (with good accuracy) to a vibrating — or rotating — core.

The simplicity of this interpretation made the experimental investigation of those states particularly attractive. Such an investigation was performed with the already mentioned methods applicable to nuclear isomeric states and transitions. Consequently, the study of internal conversion electrons is also a powerful tool for investigating unique parity states and their system of levels.

A typical example of such power is illustrated by the comparison [see Refs. 10 and 15] between the amount and accuracy of data deduced from radioactive and nuclear reaction studies of odd mass light gold isotopes ($^{189-193}\text{Au}$). In the heavier quoted isotope, for instance, only three negative parity levels were assigned exclusively by nuclear reactions studies while 45 levels were identified by radioactive studies alone. Of course, the number of nuclear levels without specific spin and parity assignments is of little theoretical interest. However, their existence stimulates extensive internal conversion studies for making such assignments and testing the theoretical predictions. Figs. 3 and 4 illustrate this kind of experimental test of different particle vibration and particle-rotor models predictions.

Finally, from the analysis of a large amount of experimental and theoretical results concerning these levels, a few questions arise:

- (i) What are the main features of these different theoretical descriptions?
- (ii) To what extent do they differ from each other and the experimental data?
- (iii) Is it possible to draw general conclusions from these investigations concerning the symmetry of nuclear structure?

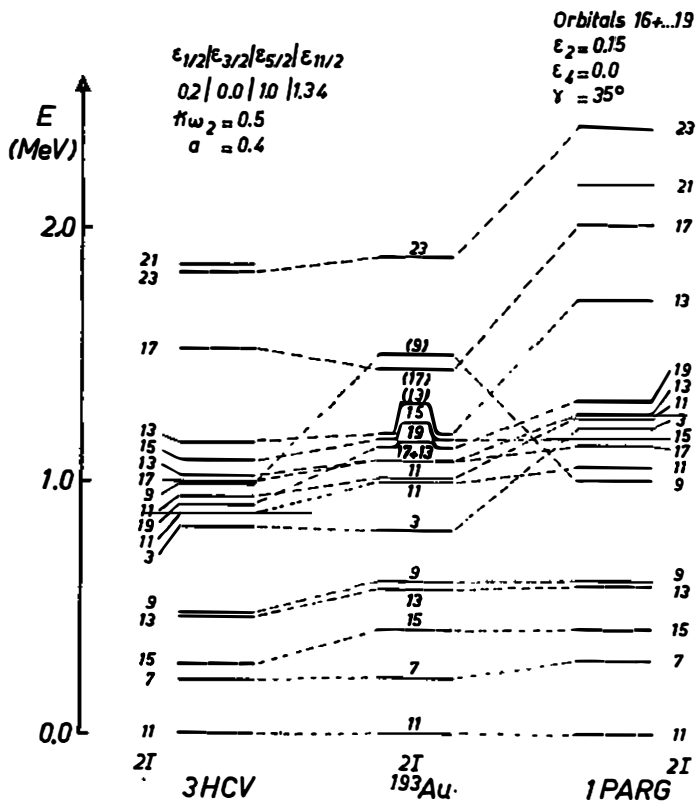


Fig. 3. Comparison between the experimental and theoretical negative parity states of ^{193}Au . The parametrization adopted in the 3HCV model calculations is the same as previously used for the positive parity states. In the 1PARG calculations are included the 16^{th} , 17^{th} , 18^{th} and 19^{th} proton Nilsson orbitals which are coupled to an asymmetric core with $\epsilon_2 = 0.15$, $\epsilon_4 = 0.0$ and $\gamma = 35^\circ$ deformation parameters.

The recent theoretical developments show the need for a large amount of accurate experimental data concerning the electromagnetic properties of medium and high excited levels. Indeed, with increasing nuclear level excitation energies sharper differences appear between the theoretical predictions of the mentioned nuclear models^{13, 14, 18, 20}. Consequently, new experimental methods must be developed for the investigation of such states. The present theoretical and experimental developments made in several nuclear laboratories scattered around the world (particularly active in Europe, America and Japan) increase our hopes for satisfactory answers in the near future to the first two questions (i, ii) and later answer to the more fundamental question (iii).

2.4. Systems of levels with several different particle configurations

The interpretation of the positive parity levels of odd mass Tl, Au, Ir and Re isotopes needs the coupling between several different particle configurations. For this reason, the single j -shell approximation adopted for the description of their

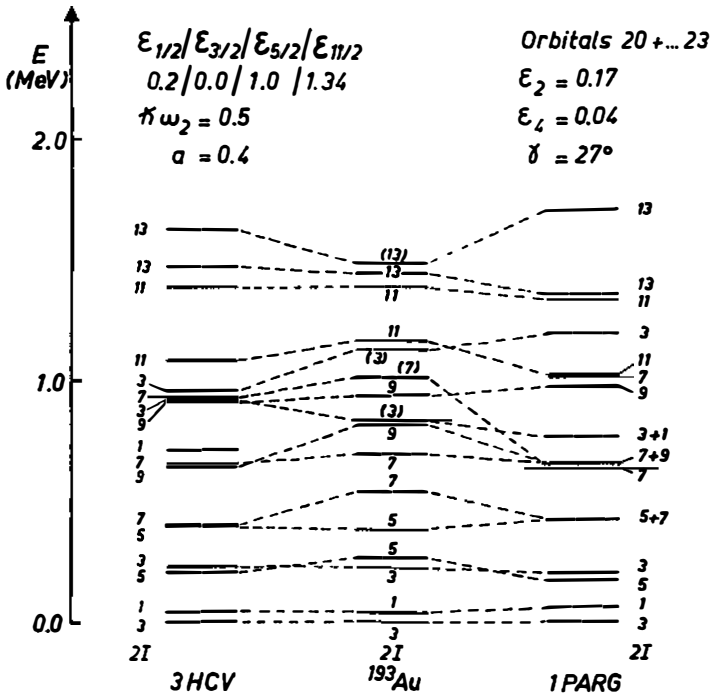


Fig. 4. Comparison between the experimental and theoretical positive parity states of ^{193}Au . The theoretical level spectra labelled by 3HCV and 1PARG correspond to three holes cluster vibration and generalized particle asymmetric rotor models, respectively. The 3HCV level spectrum is obtained by coupling a cluster of three proton holes (lying in $3s_{1/2}$, $2d_{3/2}$, $2d_{5/2}$ and $1h_{11/2}$ subshells) to N quadrupole phonons ($N \leq 3$). The single proton energies, ε_j , relative to the $2d_{3/2}$ subshell, the quadrupole phonon energy, $\hbar\omega_2$ and the cluster-vibrator coupling strength, a , are given in MeV. The 1PARG level spectrum is obtained by coupling the $20^{1/2}$, $21^{1/2}$, $22^{3/2}$ and $23^{3/2}$ Nilsson orbitals to the same asymmetric rotor with $\varepsilon_2 = 0.17$, $\varepsilon_4 = 0.0$, $\gamma = 27^\circ$ deformation parameters. This figure and the previous one (taken both from Ref. 17) illustrate to what extent do nuclear model predictions differ.

unique parity states fails for these levels and more general models are required for their description.

Such models of the vibrational type (like those of Kisslinger-Sorensen⁵³⁻⁵⁶ and Alaga⁵⁷⁻⁵⁹) have already existed for a long time. However no rotational model of that kind was developed until the extension of Hecht-Satchler model¹¹ including many single particle configurations¹². The development of this generalised particle asymmetric rotor model makes it possible to attempt the first complete particle rotor description of all the positive and negative parity levels of odd Tl, Au, Ir and Re isotopes considered^{13,18}.

The same remark previously made for the negative parity states of the light gold isotopes is still valid: a larger amount of accurate experimental data was obtained from the analysis of radioactive studies than that of nuclear reaction studies with heavy ions. However, the energy domain of nuclear bound states populated by artificially induced nuclear reactions (or nuclear excited states populated by

the decay of such bound states) is much larger than the domain of nuclear excited states populated by radioactive decay. Consequently, both types of experimental investigations (radio-activity and nuclear reactions) have complementary aspects and require their close association for a deeper and wider knowledge of nuclear structure (see Fig. 4).

Among the special topics developed in the frame of the Lund-Orsay-Zagreb collaboration concerning the odd mass transitional nuclei the following three should be mentioned:

(i) The particle cluster vibration and the particle asymmetric rotor model descriptions of odd Au isotopes. This topic includes the comparison between experimental and theoretical nuclear level spectra as well as EM properties of states with both parities. The influence of the truncation of the configuration space as well as of the adopted parametrization on the theoretical predictions of such models was also investigated in detail for the gold isotopes.

(ii) The potential energy surfaces and the nuclear deformations of odd mass Tl, Au, Ir and Re isotones. This investigation compared the semi-empirical and theoretical quadrupole deformation parameters of the ground states and lowest negative parity states of these nuclei. Furthermore, this study dealt also with the prolate-oblate potential energy differences as well as the search for shape transitions. Finally, the possible influence of hexadecapole deformation on these nuclei was also thoroughly investigated²⁰).

(iii) The spherical and deformed descriptions of the lowest $9/2^-$ level in odd Tl, Au, Ir and Re isotopes. This work started with semi-empirical estimates of the excitation energies of such levels. Afterwards, such estimates were compared to different theoretical values deduced either from spherical constrained Hartree-Fock BCS calculations or from potential energy differences calculated with the Nilsson microscopic model³⁰⁻³²). A comparison between all such results is illustrated by Fig. 5.

Finally the extensive experimental data testing these theoretical predictions was derived in many cases from electron spectroscopy measurements. Consequently, this is another typical example of the usefulness of this kind of measurements.

2.5. *Low spin and high excited nuclear levels*

Neutron capture is one of the different ways of populating high excited nuclear levels with low angular momentum. The experimental investigation of these states is particularly favourable whenever a large amount of pure isotopes with big neutron capture cross sections is available. Indeed, such cases are particularly favourable for using high resolution γ -ray and electron spectrometers with small transmission (like those of photon crystal diffraction and electron deflection by a flat magnetic field). The operation of this kind of spectrometers (plus pair spectrometers with anti-Compton devices) *in beam* with a high flux of neutrons — available at the Laue-Langevin Institute — is a powerful tool for (n, γ) and (n, e) spectroscopic studies⁶⁰⁻⁶⁶). Furthermore the identification of a large number of low spin excited levels (including many with high excitation energy) favours the application of

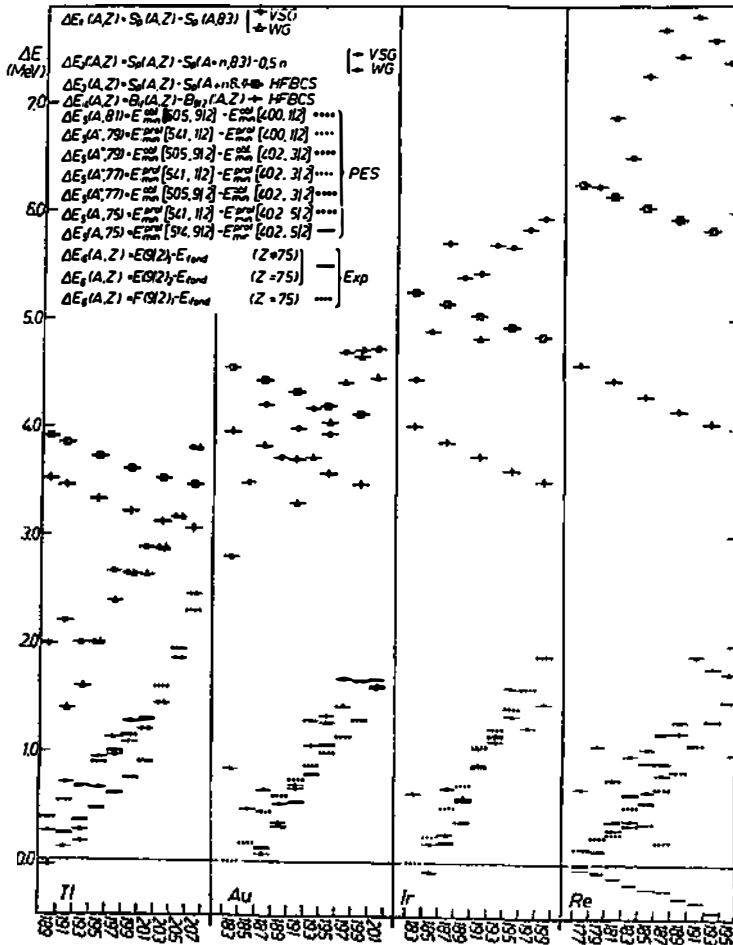


Fig. 5. The spherical constrained Hartree-Fock BCS calculations versus the Nilsson model are illustrated by the $(9/2^-)$ level excitation energy of odd mass Tl, Au, Ir and Re isotopes (see Ref. 32). The ΔE_1 and ΔE_2 , energy differences are semi-empirical estimates derived from mass tables (VSG: Viola, Swant, Graber; WG: Wapstra Gove). The ΔE_3 and ΔE_4 energy differences are theoretical estimates obtained by Hartree-Fock BCS calculations. The ΔE_5 energy differences are theoretical estimates deduced from Nilsson's potential energy surfaces. The experimental data are represented by full, thick lines.

Ericson's statistical method³⁶⁾ for those nuclides where it has been possible to identify the spin and parity of many states³⁷⁻⁴⁰⁾.

The comparison between the experimental number of levels distribution corresponding to different isotopes gives qualitative information on the relative completeness of the experimental data. i. e., estimates the number of missing levels. Furthermore, the same method tests the overall description of a nucleus given by each nuclear model as well as illustrates the relationship between the individual and the statistical descriptions of nuclear excited levels²⁷⁻⁴⁰⁾ (see Figs. 6 and 7).

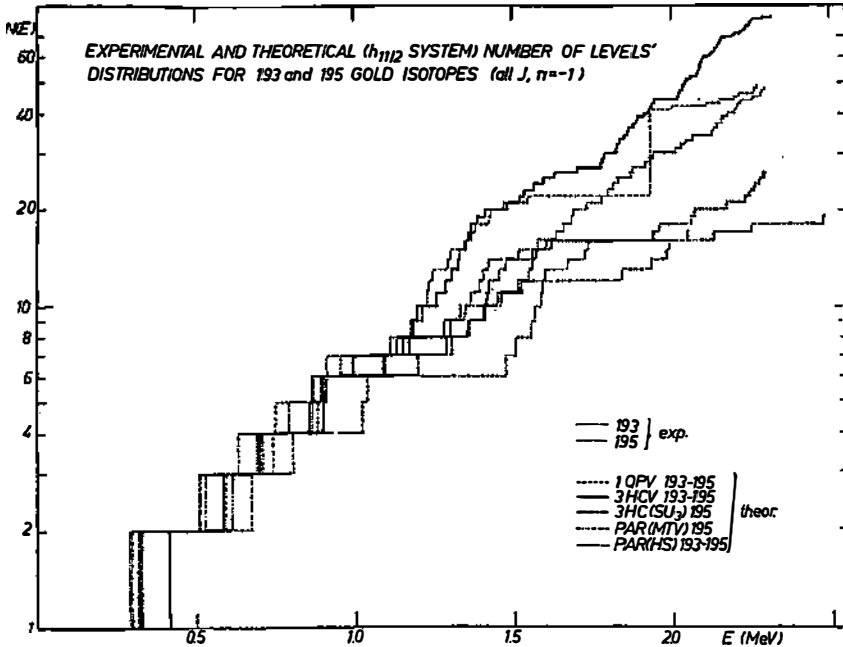


Fig. 6. Experimental and theoretical number of levels distributions of $1h_{11/2}$ system of levels in $^{193,195}\text{Au}$. The theoretical distributions are those of the one quasi-particle vibrational model (1QPV), the three holes cluster vibrational model (3HCV) and the particle asymmetric rotor model of Meyer-ter-Vehn, PAR (MTV), as well as of Hecht-Satchler, PAR (HS). The theoretical distribution corresponding to the generalised particle asymmetric-rotor model (taking into account several Nilsson protons orbitals) is not represented in this figure (reproduced from Ref. 24).

The «weak point» of such in-beam studies at present is mainly the lack of «time information» concerning short-lived isomeric states populated by neutron capture decay⁶⁷). There are however interesting possibilities of future development in that research field. One of them is given by the study of mono-energetic positrons emitted after pair production of high energy fast ($E1$) transitions occurring in medium (or heavy) atoms ionized in the K shell⁶⁸). For such cases it is possible to evaluate nuclear half-lives within the time scale 10^{-14} — 10^{-16} s, i. e., slightly longer than the duration of the electron cloud rearrangement filling an electron vacancy in the K-shell. However, there are several technical difficulties to overcome in order to improve the experimental conditions for the investigation of such weak positron lines⁶⁹). Nevertheless, a considerable extension, of the half-life data concerning high excited levels (in the energy range 1—2 MeV) would give a more critical test of the available nuclear models and theories. In particular, the recent development of very high resolution crystal spectrometers able to extract lifetimes from Doppler broadened lineshapes of nuclear transitions open new interesting possibilities in this research field⁶⁷⁻⁶⁹). The same can be expected from in-beam electron-gamma charged particle coincidence spectroscopy studies following nuclear transfer reactions populating this kind of levels [i. e. (d, p) and (p, t) reactions].

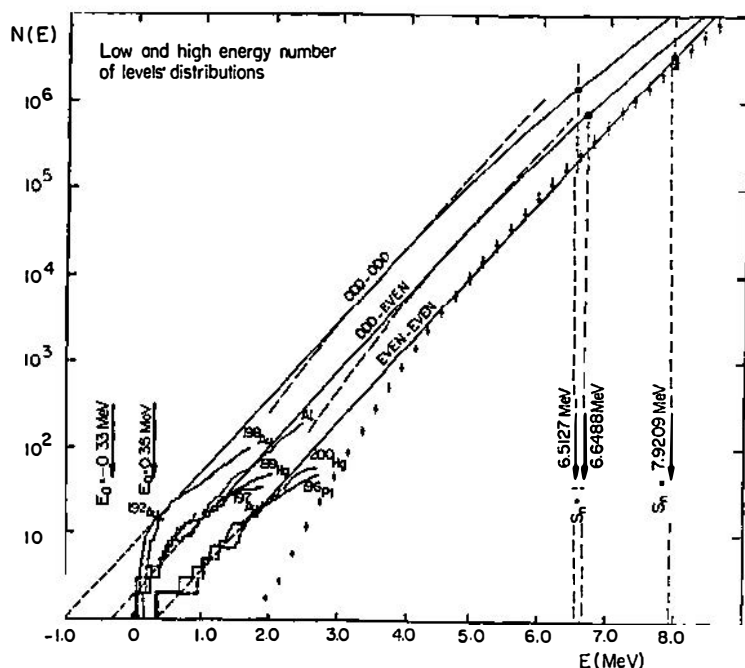


Fig. 7. A few low energy experimental number of level distributions (deduced from radioactive studies and represented on the right hand side of the figure) are compared to the theoretical distribution calculated with the Alaga model (labelled by Al) as well as to the semi-empirical Gilbert-Cameron distributions, derived from neutron capture resonance data (see Refs. 36, 37 and 40). This figure and the previous one illustrate the application of Ericson's statistical model to medium and high excited nuclear levels.

2.6. High and very high spin states. Yrast traps

The spin and parity assignments of high excited levels ($E > 2$ MeV) populated by nuclear reactions induced with fast accelerated ions are uncertain in many cases. The same is true for isomeric levels including a few with known half-lives.

The lowest $27/2^-$ state assigned by the Jülich Group⁷³⁻⁷⁴⁾ to the light odd gold isotopes (i. e. $^{189,191,193}\text{Au}$) on the basis of their γ -ray angular distribution measurements is a particularly interesting case. Indeed, according to these investigations, such a state should be interpreted as a three proton holes cluster, $(\pi h_{11/2}^{-3})_{27/2}$, with the single proton angular momenta totally aligned i. e., $I = 11/2 + 9/2 + 7/2 = 27/2$. This momentum is the maximum total spin value of such configuration allowed by the Pauli-principle applied to the particule cluster. New calculations on the Alaga model applied to these isotopes were made at Orsay in order to investigate if this qualitative interpretation could be confirmed — or rejected. According to the preliminary results⁷⁵⁾ already obtained the predicted excitation energy [$E(27/2^-) = 3.92$ MeV] is much higher than the observed value [$E(27/2^-) \cong \cong 2.2$ MeV], using the same model parametrization as for the calculation of the lower excited levels.

However, two questions normally arise:

- (i) It is possible to describe with the Alaga model both low and high spin states of $^{189,191,193}\text{Au}$ using the same set of model parameters (or a slightly different one)?
- (ii) What is the influence of the configuration space adopted in the calculations (i. e. number of particle states, phonons and truncation energy)?

Another possible explanation of this discrepancy is the uncertainty concerning the spin and parity assignments of these levels. Indeed, the »stretched« $E2$ transitions assignment was originally grounded on a qualitative comparison between the experimental transition probabilities and the single particle estimates of theoretical $E2$ and $M2$ transitions. Furthermore, later IC measurements on gold-189 did not confirm the spin and parity assignments of such short lived ($T_{1/2} = 11$ ns) isomeric state⁷⁶⁾.

This example and the previous questions show the interest of in-beam electron spectroscopy studies for nuclear structure investigations concerning high spin states. In particular, the search for »yrast traps« (i. e. nuclear isomeric yrast states with very high angular momenta, I , occurring when $E1$, $M1$, $E2$ or $M2$ transitions to lower excited states with spin $I-1$ and $I-2$ are forbidden)⁷⁷⁻⁷⁹⁾ is an interesting topic which is still underdeveloped.

2.7. Nuclear levels of the »continuum« and their EM deexcitation

For several years there has been a considerable development in the study of γ -ray multiplicity distributions corresponding to heavy ion induced reactions⁸⁰⁾. In particular, the angular momentum distribution of the residues evaporated from the compound nucleus produced in a given nuclear reaction was deduced from a few investigations (see Ref. 81). However, the multiplicities of the EM transitions deexciting such levels are not accurately known and usually assumed $E1$ or $E2$. Nevertheless, the multiplicities of EM transitions deexciting levels belonging to the *quasi-continuum* fed by (α , 4n) reactions were deduced also from internal conversion measurements⁸²⁾. This investigation was carried out with a mini-orange electron spectrometer coupled to a pair of γ -ray spectrometers [one Ge (Li) and another Na (Tl)]. From the analysis of the corresponding experimental data, it was concluded that the observed $E1$ transitions, more energetic than 1 MeV, are admixtures of stretched and non-stretched transitions.

The same method was applied also to the investigation of the average multiplicity of transition deexciting other levels from the quasi-continuum populated by heavy ion induced reactions⁸³⁾. Moreover, the recent development of new types of electron momentum selectors with good transmission and resolution makes simultaneous measurements of the average multiplicity and multipolarity (corresponding to a given nuclear reaction channel) possible. In this way, our knowledge on the mechanisms of such reactions will be increased.

2.8. Beta-decay, nuclear structure and fundamental interactions

Beta-decay covers a very wide research field where electron - and positron-spectroscopy played an important role in the development of both nuclear structure

and elementary particle physics. However, in spite of the large number of investigations carried out in that research field it remains a very attractive and powerful source of important information⁸⁴⁾.

For instance, the measurement of the total β_{\pm} decay energies of nuclei far from stability is an important source of experimental data involving refined experimental methods and techniques of on-line nuclear spectroscopy. Indeed, such energies are important physical magnitudes for the construction of accurate nuclear decay schemes. Other examples of interesting problems of β -decay, more complex — both theoretically and experimentally — than the previously mentioned theme, are the »shape factors« and the total reduced transition probabilities (log ft) corresponding to such decays. In particular, the latter magnitude requires an evaluation of the total yield of excitation of different nuclear levels per nuclear decay which needs extensive — and accurate — internal conversion measurements. For that reason, relatively few reliable data is available for log ft values concerning nuclei with very complex level schemes (like most odd mass heavy nuclei). Among these the odd Au isotopes are interesting examples^{85–86)}.

Finally, the investigation of isobaric analogue states in light nuclei is another research topic involving in-beam electron, positron, and γ -ray spectroscopy. Furthermore, this topic gave important information on the symmetry properties of the fundamental interactions between elementary particles^{77–79)}.

3. Potential possibilities and practical limitations of electron spectroscopy

All the topics (2.1–2.8) previously discussed illustrate the importance of electron spectroscopy (particularly remarkable when coupled to γ -ray spectroscopy) as a powerful tool for investigating the nuclear structure. However, the technical problems involved in electron spectroscopy are, in general, much more varied and complex than those arising in γ -ray spectroscopy. Consequently, it is not surprising that an »efficient« nuclear spectroscopist looking for interesting problems which are »technically easy« would be wise to avoid electron spectroscopy and to restrict himself mainly to γ -ray spectroscopy or charged particle spectroscopy with the simplest detection techniques (fast scintillators and semiconductor detectors operated at room temperature). In such conditions, it is easy to understand why some nuclear physicists consider electron spectroscopy as a »technical game« requiring not only skill but also a lot of spare time. Nevertheless, it is essential to keep in mind that such an attitude is mainly grounded on economical criteria for the maximum scientific output (i. e. number of scientific publications) obtained with a given personal and instrumental investment.

The previous remark lead us to hope a sharp change in that situation whenever the increasing complexity of large γ -ray multidetector arrangements (as well as a more clear conscience of their inherent limitations for the analysis of low energy transitions) will make more attractive — or even indispensable — electron measurements. For that reason, it is important to review the experimental possibilities and limitations of different electron spectrometers used in nuclear structure investigations (Subsection 3.1). Furthermore, the radioactive samples, targets and particle beams used for electron spectroscopy measurements are also essential tools in nu-

clear structure investigations (Subsection 3.2). Moreover, the close imbrication of several atomic and nuclear phenomena occurring simultaneously (or within the time scale of a given experiment) makes essential a sharp reduction of the background due to secondary effects or spurious radiations using a wide variety of different experimental methods (Subsection 3.3).

3.1. *Present and future scope of electron spectrometers*

There is no «universal» type of electron spectrometer solving all kinds of nuclear spectroscopic problems. Instead, there is a wide variety of instruments with different potential possibilities and practical limitations for dealing with a given spectroscopic problem. In particular, there are instruments specially designed — or suitable — for different purposes. The most frequent requirements are the following:

- (i) electron momentum (energy) analysis with the highest resolution in a narrow interval or a moderate resolution in a broad momentum (energy) range.
- (ii) electron-X-ray and electron-gamma coincidence measurements for angular distributions or correlations.
- (iii) electron-electron and electron-charged particle coincidence measurements for angular distributions or correlations.
- (iv) half-life measurements.

The existing electron spectrometers are usually classified according to four main different types: electrostatic, magnetic, semiconductor and momentum (or energy) selectors. Furthermore, these instruments are operated either alone (as single electron spectrometers) or combined to other spectrometers (as multiple spectrometers of the same kind-like e-e spectrometers — or different kind — like e- γ spectrometers). The electron-electron spectrometers used for angular distribution measurements are assemblies of identical instruments. However, for e-e coincidence measurements alone it is possible also to use different instruments (for instance, a large and a small spectrometer of the same kind). Finally, the momentum (or energy) selectors are usually combinations of magnetic spectrometers (of flat as well as axial type) and cooled Si (Li) spectrometers. Electrostatic and magnetic spectrometers have also been combined for special purposes (like the study of very low energy electrons).

Each type of spectrometer has its specific features with potential possibilities and inherent limitations which must be taken into account when planning a particular experiment. Moreover, there is a wide variety of instruments belonging to each type with a large choice of magnetic spectrometers. Nevertheless, in spite of such wide instrumental variety the research field of electron spectrometer design and construction is certainly far from being fully developed. This is due to the increasing requirements for high resolution spectroscopy as well as more selective geometrical and temporal specifications.

Two opposite tendencies can be considered for the present and future evolution of such instruments according to their size: conception of new very large and very small spectrometers. The latter tendency seems stronger than the former one

not only for economical reasons but also for other important arguments: (i) easier combination to other types of radiation detectors; (ii) better angular definition of the electron beam; (iii) smaller electron time of flight spread (between the electron emission and detection). However, the miniaturized electron spectrometers have two major drawbacks compared to the large instruments: (i) much larger scattering effects on the walls of the electron spectrometer boundaries; (ii) weaker radiation shielding of the electron detector from the direct radiations emitted by the electron source. Furthermore, the scattering effects are particularly disturbing for X and γ -ray detectors placed around the electron-source. Consequently, the insertion of electron momentum selectors into multi-gamma ray detectors is a delicate matter still on an exploratory phase of development.

3.2. *Crucial importance of radioactive samples and targets*

The influence of radioactive samples — as well as targets — on the results of different nuclear measurements depends not only on the sample characteristics but also on the type of measurement. Furthermore the nuclear — as well as the atomic — measurements are usually classified according to the relationship between the means of producing and measuring stable (or radioactive) samples. The simplest classification of that kind is the classical distinction between off-line, on-line and in-beam measurements.

3.2.1. *The off-line measurements* are mainly performed with radioactive samples placed far away from their production. Consequently they are delayed by the overall duration of a sequential experimental procedure: (i) sample preparation (including the irradiation interval for the artificially made nuclides), (ii) sample transport (from its irradiation place to the measuring device), (iii) preliminary operations (eventually needed) before starting the measurements.

This type of measurement is only applicable to nuclides with half-lives longer than the overall duration of the quoted procedures (i, ii, iii) as well as the minimum measurement duration (i. e. those nuclides with half-lives longer than several tens of minutes). Furthermore, there are many different characteristics of radioactive samples (i. e. isotopic and isobaric purities, shape, flatness, homogeneity, area, thickness, total and specific activities, backing) as well as their holders (shape and dimensions, physico-chemical structure) to be considered in different nuclear measurements.

The combination of these characteristics and requirements needed for a given measurement varies for each type of atomic species and depends on the sample preparation methods. Moreover, the high complexity of nuclear spectra as well as the wide differences between the nuclear properties of different nuclides (isotopic abundances, reaction cross sections, half-lives for different nuclear processes) require not only atomic purity for such samples but also high isotopic enrichment whenever high specific activities and (or) low background are needed. Consequently, the radiochemistry and nuclear chemistry techniques must be completed — and eventually associated — to the isotopic separation techniques in order to achieve the required isotopic enrichment.

Among the different methods of isotopic separation the EM separation method is particularly powerful due to the wide variety and high performances of EM

isotope separators as well as their interesting combinations with the various means of radioisotope production⁹²⁾.

There are three main types of EM isotope separators classified according to the range of their ion beam intensities: high intensity and large scale isotope separators including »calutrons«⁹³⁻⁹⁷⁾, medium intensity separators⁹⁸⁻¹¹⁰⁾ particularly suitable for the preparation of strong radioactive samples¹¹¹⁻¹¹²⁾, and low intensity separators — usually called »the scandinavian type«¹¹³⁻¹¹⁷⁾ — extensively used in many atomic as well as nuclear investigations¹¹⁷⁻¹²¹⁾. The calutrons are mainly used for the separations of large amounts of enriched isotopes while the other two types of separators are both laboratory instruments. Furthermore, when the latter instruments are equipped with ion retardation devices^{120,122-129)}, they allow a direct ion collection on conducting foils (often metallic or metallized) lying on thin backings.

The isotope separators are powerful tools for radioactive sample preparations needed by high resolution nuclear spectroscopy studies¹³⁰⁻¹³²⁾. Indeed, such samples are usually thin, small sized, accurately shaped (according to the focusing properties of the ion retarding lens) and free of spurious materials (whenever mass analysers with high resolving power are used and isobaric contaminations due to the target and the ion-source are minimised). This last feature is particularly important since many radiochemical extraction procedures use small amounts of stable carriers (with similar chemical properties as the radioelement) reducing the specific activity of the extracted sample. Furthermore, most radioactive samples prepared by fast evaporation procedures (taking usually only a few minutes) are not so homogeneous as those obtained by electromagnetic sweeping of ion-beams hitting fixed collectors or stable ion beams bombarding rotating ion collectors for a few hours^{132,133)}.

The efficiency of the available EM isotope separators with high resolving power is rather small (i. e. $\eta \sim 10^{-1}-10^{-2}$). Consequently, they require very strong radioactive targets in order to produce strong radioactive samples. In such conditions, the cost and the risk of such preparation (including the tasks of the radioactive decontamination) is considerably higher than with other standard preparation methods¹³⁴⁾. Moreover, the amount of radioactive atoms artificially made of short lived nuclei collected in this way is usually not enough to make a self-supporting radioactive target. Up to now radioactive targets of artificially produced isotopes ($T_{1/2} < 100$ days) have been obtained by direct deposition on ISOL systems. However, for long lived radioisotopes — either naturally occurring or artificially made — it is possible to prepare radioactive targets by classical means provided they are available isotopically enriched.

The EM isotope separators have two other important possibilities for the radioactive sample preparation. The first possibility results from the combination between the irradiation process and the isotope separation leading to the so-called on-line mass (or isotope) separators. The introduction of such devices reduced the time delay between the radioisotope production and the beginning of the nuclear measurements. The second possibility concerns the separation of radioactive isobars mixed in a given sample requiring very high resolution isotope separators. Such possibility is not accessible to most off-line (and on-line) separators actually operating, but is technically possible with refined ion-sources and beam optics.

Finally, the off-line measurements are well suited for the investigation of the nuclear properties of most nuclides not too far from the stability line. However, they are rather inefficient for the study of short lived nuclei artificially made within a nuclear reactor or a particle accelerator.

3.2.2. *The on-line measurements* are usually performed with a sequence of radioactive samples measured near the place of their production¹³⁵⁾. Such samples are normally collected by direct deposition, either with an on-line isotope separator (as discussed in 3.2.1.) or with a fast transport system (like an helium jet device), carrying a gaseous radioactive product from the internal (or external) irradiated target until an isotope separator. In other cases, there is also an intermediate chemical purification stage between the radioactive sample transport and the isotope separation.

The specifications of the irradiated targets suitable for on-line spectroscopy are much more stringent than for off-line spectroscopy. Indeed, when short lived radioisotopes are produced inside an irradiated solid target their diffusion through the outer surface is rather slow, below the melting point of the solid¹³⁶⁻¹³⁷⁾. One way to increase such diffusion is to divide the solid into a very fine powder (grain diameter around 1 μm) or many thin foils (thickness $< 10^{-2}$ mm). Another way is to use liquid metals (or compounds) as targets which have diffusion constants four orders of magnitude higher than solid targets. Of course the target material should have a vapour pressure not too high ($p < 10^{-3}$ Pa) at its melting point (like Ga, In, Sn, La, Pb or Bi) in order to reduce the amount of vapour diffusion towards the isotope separator¹³⁷⁾. Moreover, the radioactive atoms to be separated must be more volatile than the irradiated material (such as in the separation of radioactive Hg isotopes from melt Au targets irradiated with an accelerated proton beam). Finally, the target thickness — like in off-line measurements — is chosen essentially according to the excitation functions of the nuclear reactions producing the isotopes to be investigated and the characteristics of the particle projectiles inducing such reactions.

»Jet devices«, pulverizing the irradiated liquid target into a large amount of very small droplets and increasing radioisotope diffusion as well as evaporation, were also designed¹³⁷⁾ and integrated in on-line systems. In all such systems, the targets are either periodically (or continuously) replaced. The »consumable targets« are acceptable for inexpensive and easily available materials. However, for very rare — or expensive — products this type of target is neither advisable nor used in practice.

The influence of the target properties on on-line isotopic separations has been investigated mostly from the point of view of the extraction of the nuclear reaction products as extensively discussed in previous reviews¹³⁸⁻¹³⁹⁾. Indeed, this diffusion process sets a lower limit to the half-life of the nuclides to be investigated by such methods.

There are many different types of on-line EM isotope separators — usually called ISOL systems. They differ from the classical (off-line) separators essentially by the existence of a close (or fast) connection between the irradiated target and the ion-source of their radioactive products. Moreover, they usually have a wide range of simultaneous mass separation followed by an ion-beam transport system (delivering simultaneously or alternately several isotopically enriched beams¹³⁸⁻¹⁴³⁾).

The essential feature of ISOL systems is the reduced time interval between the radioisotope production (inside the target) and the start of the radioisotope collection (either in the ion-collector or inside any beam line issued from such ion collector). This direct ion-collection is usually performed on a thin metallized film moving, under remote control from a programming unit, between the ion collection position lying on the beam-line and the measuring position inside the analysing spectrometer. In the older ISOL systems instead of a thin film a large amount of individual sample holders were used for the radioisotope ion-collection¹⁴⁴⁾. However, in both cases the essential sample requirement — specially for high resolution low energy electron spectroscopy measurements — is high specific activity deposited on a small line (or spot) over a very thin backing. Finally, the telemanipulation of the targets and ion-sources as well as their automatic replacement are other important features of the ISOL systems prescribed mainly by the radioactive safety requirements. Indeed with such facilities it is possible to prepare radioactive targets¹⁴⁵⁻¹⁴⁶⁾ as well as radioactive beams¹⁴⁷⁾.

The combination of a wide choice of isotopic collection times and measuring intervals for the different radioactive collected samples extends the research field of on-line measurements far beyond the corresponding field of off-line measurements. This is true not only for on-line separators but also for fast chemistry and the jet devices suitable for the study of short lived nuclear reaction products.

3.2.3. *The in-beam measurements* are exclusively performed with an accelerated particle beam (or a neutron beam) irradiating a stable (or radioactive) target placed inside (or outside) the measuring device (called an in-beam spectrometer).

All the radiations due to the different interactions between the particle beam and the target may be analyzed with in-beam spectrometers (see Refs. 2 and 148—153). A few of these radiations are quite strong ones (mainly due to atomic interactions with large cross sections) and many rather weak (due to nuclear transitions and interactions with small cross sections). Furthermore, a few of these processes occur within very different time intervals. Such time differences allow the use of fast timing spectroscopy methods in order to discriminate the corresponding radiations.

All targets suitable for in-beam measurements must have at least the same requirements as radioactive samples needed for off-line (or on-line) measurements of the same kind and degree of accuracy. Furthermore, for in-beam experiments it is essential to replace periodically the irradiated targets when their structure becomes strongly perturbed by radiation damage or when the background radiation (due to the accumulation of the decay products inside the target) becomes too strong compared to the prompt (or short-delayed) radiations to be analyzed. Consequently, the importance of the target life is a major difference between in-beam and on-line measurements¹⁵⁴⁾ except when the direct ion collection inside an isotope separator takes place on very thin and fragile foils. Indeed, most in-beam measurements — except those including recoil separators or non-solid targets — require mechanically and thermally stable targets which usually are not indispensable for on-line measurements (where the measured sample is different from the irradiated target).

Nowadays there is a wide choice of bombarding particles either neutrons or accelerated ions with many different charged states and quite different kinetic

energies, flowing continuously or bunched in pulsed beams. The interaction of such beams with a given target depends strongly on the beam characteristics as well as on the target structure. In particular the focusing conditions and the timing properties of the bombarding particles are much more important for in-beam spectroscopy than off-line (or on-line) spectroscopy. This is specially true for high resolution electron (or charged particle) in-beam measurements as well as fast timing measurements¹⁵⁵⁻¹⁵⁶ (where the shape and dimensions of the beam impact on the target strongly influences the accuracy of the measurements).

The particle identification after nuclear reactions involving medium and heavy nuclei is not accurately performed with time of flight techniques (used with success in the reactions between light nuclei). Moreover, such an identification requires the experimental determination of the atomic charge and mass numbers (Z and A) plus the charge state (q) of the recoil ions (which usually differs from Z except for light nuclei collisions at moderate energies as well as heavy ion collisions at GeV energies). Furthermore, that charge state is also strongly perturbed by a chain of radiationless transitions (Auger and Coster-Krönig) occurring in the electronic cloud rearrangement after a nuclear decay ionizing an inner atomic shell. Finally, when these multiple charged ions collide with other atoms (or ions) their charge state changes again. Consequently, the characterisation of heavy ions requires accurate methods for the experimental determination of their charge states, i. e. the so-called charge spectroscopy methods.

The electromagnetic separation of the recoil ions issued from nuclear reactions is one of such methods. Its basic principle is essentially the same as the EM isotope separation. For that reason the recoil separators were developed in close connection with ISOL systems (see their earlier studies¹⁵⁷⁻¹⁵⁸) and later development reports¹⁵⁹⁻¹⁶²). However, there is an important difference between the ISOL systems and the recoil separators. Indeed, the ISOL systems have an irradiated target plus an ion source while the recoil separators have only a target. Consequently, the nucleus to be investigated in an ISOL system is stopped by a solid or a gas target, reonized, accelerated, deflected and detected within a time interval taking at least ten milliseconds. Instead, the recoil ion separators remove the recoil ions produced in the target from the elastically scattered particles around the incoming direction ($\sim 0^\circ$) of the accelerated particle beam. Such scattered particles produce a background several orders of magnitude greater than the recoil ion beam to be investigated (peak/background $\sim 10^{-12}$). Then, the subtraction of such a background is essential for the recoil ion investigation.

The main advantage of the recoil separators compared to the ISOL systems is the much shorter time delay between the recoil ion production and detection ($1 \mu\text{s}$ in recoil separators instead of $10^4 \mu\text{s}$ in ISOL systems). However, the comparison between their overall efficiencies is not so straightforward. Indeed the recoil separators use much thinner targets than ISOL systems (i. e. $50 \mu\text{g}/\text{cm}^2$ instead of $5-10 \text{mg}/\text{cm}^2$ for heavy ion induced reactions and $2-200 \text{g}/\text{cm}^2$ for spallation reactions). Furthermore, the efficiency of the different types of ion sources used in ISOL systems depends on the physico-chemical properties of the irradiated targets and separated isotopes. Moreover, the need of relatively large solid angles for recoil ion collection reduces the mass resolving power of such devices compared to the corresponding performances of the ISOL systems. Consequently, in the present status of technical development, these instruments have complementary performances with a partial overlap in the field of their applications.

The occurrence of very fast phenomena in particle-beam interactions extends considerably the possibilities of in-beam studies for time spectroscopy compared to the same possibilities of on-line and off-line studies. Consequently, the most typical examples of in-beam studies, outside the scope of on-line — as well as off-line — nuclear spectroscopic methods, are nuclear collisions and reaction mechanisms. The investigation of high excited nuclear states — or states with very high angular momentum — is another typical topic of in-beam nuclear spectroscopic methods. Indeed, such states are not populated by radioactive decay, or have too short half-lives unsuitable for on-line and off-line investigations. More recently the search for exotic nuclei, (rather far from the stability line) lead to the investigation of low energy nuclear excited states and their decay processes using special in-beam techniques suitable for very rare phenomena. Finally, it is interesting to remember that the fast expansion of in-beam spectroscopic methods applied to atomic structure and collisions — as well as condensed matter investigations through the development of ion implantation techniques — extended considerably these research fields and increased their relationship to nuclear investigations.

3.3. *Increasing importance of background reduction devices*

There is an extremely wide variety of nuclear spectroscopic methods and techniques developed for reducing the background of spurious radiations as well as secondary radiations. In particular, the need to increase as much as possible the electron »line« to background intensity ratio is one of the big technical problems inherent to all studies of in-beam electron spectroscopy.

There are several different ways of increasing that ratio which depend on the origin of the electron background. The most usual and important types of electron background occurring in nuclear spectroscopic in-beam studies are the following:

- δ -rays (atomic electrons ejected by the electronic cloud interacting with a fast ion or atomic particle);
- Photoelectrons (resulting from the interaction between X or γ -rays and bound electrons);
- Compton electrons (*idem*);
- Secondary electrons (due to multiple scattering of primary electrons with the source and detector materials, spectrometer baffles and vacuum walls);
- Spurious electrons (internal conversion, β^\pm decay) resulting from *radio-active nuclei* produced in the target — or neighbouring materials — by the primary beam as well as radioactive decay products issued from different nuclear reactions occurred in the target chamber.

Among the electron background suppression techniques used in electron momentum selectors the following are the most widely spread:

- i) A sweeping current operated with a constant momentum window (converted into a variable energy interval) selects a »slice« of the multichannel spectrum corresponding to the electrons »normally« transported by the lens magnetic field.
- ii) The pulsed beam techniques suppress the prompt electrons (including those mentioned above) and select the time delayed electrons.

iii) The compound nucleus deexcitation selected by the detection of a burst of prompt γ -rays with an array of very fast detectors (like BaF₂ crystals coupled to fast PM). This time filtering reduces considerably the δ -ray background as well as the prompt transitions.

iv) Time of flight filtering of the radiations emitted by the recoil ions collected on a very thin catcher foil avoiding the unscattered primary beam crossing the target and the catcher (through a small hole).

v) Combinations of previous procedures (i—iii and i—iv).

vi) An electric retarding field (between the target and the spectrometer entrance) prevents all the low energy electrons from reaching the electron detector after their transport through the analysing (or guiding) magnetic field.

More generally, the electron background depends on multiple factors (quality of the electron source; performances of the electron spectrometer; type of electron detector and associated electronics).

There are many types of electron detectors which may be classified according to different criteria:

- multiplicity (number of detectors simultaneously operated in the experimental set up);
- energy domain of high efficiency (low and high energy detectors);
- energy and time resolutions;
- particle localization;
- detection medium (ionization, semi-conductors, scintillators);
- energy discrimination (single and multiple channel type);
- signal to noise ratio;
- size and shape of the detectors.

The different types of detectors have in general distinct characteristics within a large choice of properties. Consequently, there is no *universal type* of electron detector but a set of several detectors suitable for special purposes: high energy resolution in a single channel (or limited number of channels), multi-channel devices with moderate energy resolution and high time resolution.

Most electron spectrometers are operated only with a single type of detector in spite of the fact that different types could be used with better performances for various purposes. This situation is partly due to the variety and complexity of other electron spectroscopy techniques which prevents often the spectroscopist to achieve the most rational and powerful experimental set up. Of course, it would be desirable to change that situation operating each spectrometer with a set of electron detectors covering a wide range of different applications (i. e. giving the best performances and a minimum background).

A large variety of electronic units may be coupled to different types of electron detectors for coincidence measurements giving different kinds of spectral distributions: temporal (for half-life measurements) spatial (for angular correlations) and spatial-temporal (for g -factor measurements). The choice of each particular device will depend on the special characteristics and requirements of the planned experiment.

Many other different techniques are currently used in electron spectroscopy, like the following:

- electron-positron discrimination with helical baffles;
- electron-positron energies sum coincidence (used in e^-e^+ spectroscopy);
- half-life measurements with the recoil-shadow method;
- determination of the angular correlation coefficients with the P_0, P_2, P_4 baffles technique.

The automation and computation devices have expanded very quickly in the last few years and are particularly useful for on-line and in-beam measurements. Indeed, a large amount of data must be collected and analyzed in a short time during all these measurements in order to reduce as much as possible the accelerator — or reactor — beam time needed for the required accuracy. With the advent of micro-processors and mini-computers a great improvement was achieved in the automatic operation and data analysis of electron spectrometers. Among the main developments the following should be mentioned:

- i) The operation of electron spectrometers with electrostatic correctors and multi-strip sources.
- ii) The analysis of data collected with multi-detectors lying in the focal plane of flat magnetic spectrometers.
- iii) The momentum-energy conversion used in magnetic momentum selectors (working with a sweeping field) can be performed with fast microprocessors coupled to computers.

There are of course many other potential possibilities of operating an electron spectrometer easier, faster and more accurate than it is feasible to-day.

4. Remembrances and reflections on Gaja Alaga

For simplicity, we try to assemble our souvenirs and reflections on Gaja Alaga under different titles developed in the following Subsections (4.1—4.11).

4.1. Scientific intuition and research work

The most striking souvenir from Gaja Alaga is the natural kindness of his generosity — and hospitality — as well as his deep enthusiasm for both scientific and human problems.

Gaja Alaga was impregnated by a deep belief in the large possibilities of scientific development performed with the same feelings as an artist conceiving or executing his work. Indeed, his main tool was probably a deep intuition guiding him either in the search for the solutions of very complex scientific problems or helping him in the discrimination of the essential rules prevailing within a large amount of apparently uncorrelated data.

Alaga preferred to concentrate his attention on the foundations of a given theoretical description instead of attempting a semi-empirical adjustment of the theoretical predictions to the experimental data. He used to give that job the surname of »poor physics«.

At first sight such an epithet looks pejorative and injurious for the experimental physicists involved not only in metrology work but also in many other

activities of their everyday life: instrumental developments of accurate devices, tedious extensive measurements, tiring accurate experimental data analysis and lengthy interpretations of their results according to the available theories and models. However, for a man devoting his life to science — not as a casual job but with a deep motivation — such a controversial remark should not be interpreted in its pejorative sense. Indeed, Gaja Alaga could not accept the strict separation between »instrumental« or »computational« activities and their scientific motivation without a sharp reaction on account of his own conception of Science. Of course, he was aware of the need for scientific instruments, lengthy measurements, tiring data analysis and accurate interpretations. However, his aim for Physics was beyond that and attempted deeper and wider interpretation of the available scientific knowledge plus the search for new physical concepts and phenomena.

The last interpretation is typical of great physicists with an artistic mentality — like Frédéric Joliot and Salomon Rosenblum — who always fought against the multiple dangers encountered when a physicist behaved like a robot without a close control of his conscience and deep feelings.

Frédéric Joliot was very preoccupied in the last years of his life by the difficulty of conciliating individual initiative and collective constraints in large sized nuclear laboratories. Nevertheless, thirty years after his premature death, no complete satisfactory solution was found for that problem which still remains very acute nowadays.

Salomon Rosenblum, after his return from the U. S. A. at the end of the last world war, deeply disliked the idea of »press button Physics« which probably reduced his pleasure in progressing slowly towards the discovery. We wonder how he would feel nowadays with on-line computer analysis required by the investigation of carbon-12 spontaneous decay fine structure.

Gaja Alaga always seemed to follow his convictions and feelings independently of the general trends and opinions prevailing in his surrounding. Such »fighting spirit« for the success of his ideal was developed probably during the crucial years of his youth before the last world war and strengthened by the critical tribulations of his country during that war. Of course, such an attitude generated many inconveniences and drawbacks but we can hardly imagine Gaja Alaga saying something was wrong when he believed it to be right.

4.2. *Fundamental and applied research*

A different way of expressing Gaja Alaga's ideas concerning the main priorities of scientific research is his strong conviction of the importance of fundamental research and the need to develop it as much as possible free of external constraints.

The practical application of this principle is not easy to fulfil whenever economical and social forces push very hard towards applied research instead of fundamental research. At first sight it would seem to be advisable to concentrate all the manpower and material means available for the solution of practical problems instead of speculating about abstract concepts or doing expensive experiments without any apparent usefulness or practical application. This pressure is very high nowadays due to the overlap of multiple factors issued from the hard competition between different economical, social and military projects supported by the prevailing political forces. Furthermore, the disturbing effects of such a tendency are increased by many features of modern life (i. e. development of new means of comfort and

amusement increasing the attraction for higher salaries and revenues which are usually unavailable in fundamental research).

The competition between fundamental and applied nuclear research was particularly hard in Europe and North America after the end of the last world war. However, in spite of strong political and military competition between the Eastern and Western blocks nobody attempted — or at least succeeded — to concentrate all nuclear research in such countries on Nuclear Atomic Energy (or Nuclear Atomic Weapon's) Institutes which were more easy to control than University Centres.

The explanation of that paradoxical situation probably lies in the fact that most of the scientists who are deeply interested in nuclear structure problems are not attracted by the constraints of strategical and military developments. Furthermore their personal experience of nuclear research leads them to the conclusion that industrial methods are not the most suitable for fundamental investigations. The same occurs with the scientific education of new research workers. Consequently both activities spread out into University Centres, specialized Research Institutes as well as Nuclear Atomic Centres.

These different types of institutions depended often on different political authorities. Consequently their scientific activity was never intimately coordinated and only slightly correlated. In a few cases the research topics were very similar in these different institutions, but the higher administrative centralisation and closer political control of Atomic Research Centres made sudden deep changes of scientific orientation — as well as a narrow choice of research topics — easier than in the University Institutions.

Before the last world war most experimental research work on Nuclear Spectroscopy was performed in small sized University laboratories scattered in different countries (France, Germany, Great-Britain, Italy and U. S. A.). During that war, this research branch spread out in Canada and the United States and slowed down in all Europe except Scandinavia. Afterwards, the nuclear research field expanded very fast in nearly all European Countries, USSR and Japan.

Nuclear spectroscopy traditions started decreasing in the United Kingdom after the early fifties (with a large scientific attraction towards High Energy Nuclear Physics) and ten years later in Scandinavia. The rate of development in Nuclear Spectroscopy at that time was particularly high in Denmark and Sweden compared to other European countries. Such a development was characterized by intense nuclear theoretical work plus an instrumental effort on electron spectrometer design as well as EM isotope separation techniques combined either with particle accelerators or nuclear reactors.

The same tendency developed also later in France and West Germany. However, many scientific projects and fundamental investigations developed in Western European countries during the last decades received an important contribution from nuclear physicists permanently — or temporarily — immigrated from Eastern (and Central) Europe. Nevertheless, the recent political and social events which have occurred in such countries — as well as their stronger priority towards a higher economical rentability may considerably reduce their scientific manpower attached to fundamental research and increase instead the corresponding manpower doing applied research. If this prediction is fulfilled — as one can normally expect it to be according to the similar evolution in Western and Northern Europe —

there will be a serious lack of nuclear scientific manpower within one or two decades in all Europe unless it is filled up by scientific immigrants coming from other Continents.

4.3. *Scientific education and training*

A fruitful development of fundamental research requires highly qualified scientists and technicians with a good general background. Indeed, such a background is indispensable not only for an optimum use of the available research means but also — which is much more important — to allow a deep communication between different research workers, looking for the solution of a complex scientific problem involving many different theoretical concepts and experimental techniques.

Nevertheless, this educational process remains a *very slow and delicate one* in spite of the powerful pedagogical means now available (involving computers, automatic and telecommunication devices). In particular, the widespread use of computers as a powerful storage of data and information leads to the question of whether it is useful or not to have printed tables. This is probably a question of habit and sensitivity as well.

Those who are acquainted working with a pencil and a sheet of paper instead of with the key-board of a computer might prefer the tables while the others will found them useless. Probably, both tools are required and best suited in different circumstances — or occasions.

Alaga certainly preferred the sheet of paper instead of the computer screen but this is probably a question of education as well as of taste.

In the same way as the introduction of fast vehicles changed the everyday life of civilized man nobody likes to be prevented from walking whenever they wanted to. Similarly, each step of education — or technical achievement — does not suppress straight-way our previous knowledge (or usual habits) well registered in our memory without strong conflictual situations.

4.4. *Scientific background and job mobility*

In all cases and for all scientific branches, special care should be devoted for a long time to the education of young scientists. Indeed, contemporary scientific work exerts a permanent tendency towards hyper-specialisation. Furthermore, the conjugation of that tendency to the modern request (now widespread in the Western World!) for frequent job mobility with periodical professional changes makes it more difficult to achieve a deep background in a large scientific area. On the other hand, such drawback of scientific job mobility and periodical professional changes may set a limit for their systematic application. Indeed, the possibility of such changes is useful as far as it increases the chances of choosing »the right man for the right place« instead of playing »combinatorial bureaucracy« for personal opportunism or under the influence of politically strong groups. In other words one cannot exclude the need to promote the continuity of scientific and technical progress following the classical traditions but avoiding any tendency for bureaucratic sclerosis.

4.5. *Scientific coordination and selection*

We should not forget also another straightforward consequence of the general tendency to concentrate nuclear scientific research (as well as other branches of fundamental research involving large instrumental facilities) into complex organizations where individual initiative is rather limited and has many constraints. In such cases, the »scientific background« of those advising or deciding their orientation plays an essential role in the choice of the different options with their inherent possibilities and limitations for achieving the planned aim of that facility. Indeed, the choice between these options sometimes depends on the extension of the field of their application as well as the time scale of their consequences. For instance, two different theoretical schemes — or experimental projects — might look equivalent in a given context and be rather different in another context. Moreover, the discrimination between up to date and obsolete scientific theories or instruments is not always evident and straightforward from a deep and broad scientific point of view. Consequently, the current tendency to neglect (or destroy!) main pieces of previous scientific work is *dangerous* (from the scientific development point of view) and *heretical* (from a strict economical point of view). Unfortunately, it is very hard to protect the »scientific heritage« from the widespread influence of our »consumer society« and the disturbing effects of everyday life on deep scientific reflection.

4.6. *Nuclear structure research in Modern Science*

The nuclear structure investigations, according to Gaja Alaga, could bring important and fruitful information helping the development of other scientific research fields.

This idea is not new — or exclusive to Alaga's mind — but he believed strongly in its power and always acted according to this conviction. As a matter of fact every modern scientist — as well as every educated non scientist — knows (or should know) that any improvement in the knowledge of Microphysics (including molecular, atomic, nuclear and particle physics) requires the solution of new technical problems which spread out later to other scientific (and non-scientific) disciplines. Computers and servo-mechanisms are the most typical examples of such developments. Without, these devices it would be impossible to develop many peaceful applications. In such conditions, it does not make sense to accelerate the development of space — or astrophysical research — and slow down the development of nuclear physics taking into account the close relationship between these scientific disciplines and the important dependence of astrophysical research on our knowledge concerning nuclear and atomic physics. Finally, apart from these trivial — but important — examples of close correlation between the development of these scientific branches, there is a more fundamental aspect of such correlation: its influence on the creation of new physical concepts. Gaja Alaga was perfectly aware of the importance of such dependence which strengthened his deep motivation for nuclear structure studies.

4.7. *Comparison between theory and experiment*

The wide variety of nuclear theories and models developed during the last decades has not been fully exploited yet through a detailed and extensive comparison between theoretical predictions and experimental data. Indeed, the increasing

power of the computational and data analysis facilities open many possibilities in this field. However, their practical use is seriously limited by the general lack of scientific and technical manpower.

This limitation is very serious not only in the nuclear research field but also in other fundamental research branches.

One way to attenuate the effects of such a limitation is to restrict the nuclear research field to a few selected topics promoted with an »exciting label« in the so-called »scientific market«.

4.8. »Exotic nuclear physics« versus »conventional nuclear physics«

The search for new phenomena, very rare events and extremely weak effects are typical examples of »exotic nuclear physics«. This kind of research is very attractive for scientists — and non scientists — both impressed and excited by their dreaming or mysterious character. Moreover, they often involve »critical tests« of fundamental physical theories and require complex — as well as expensive — installations for their achievement plus the cooperation between large scientific and technical teams.

The material and personal means required for these scientific projects must be well balanced to the degree of ambition of their scientific aim. Otherwise they have only a small chance of being accepted by the political authorities. Once this crucial step of starting the project is made it is essential to progress as quickly as possible in order to follow the original time table within the available budget and man-power. Consequently, it is sometimes very difficult to make large changes in the middle of a big project suggested either by unexpected technological developments (or new scientific information) changing the initial aim (or the adopted scientific methods) of that project. Finally large projects are usually less personalized than small projects and more deeply dependent on the fulfillment of their aims than individual projects.

A detailed balance of »exotic nuclear physics« shows that it is closely dependent on »conventional nuclear physics« not only for the solution of many essential particular problems involved in their large research projects but also through the basic foundations of their theories and physical concepts. So it is an illusion to believe that »conventional nuclear physics« can be replaced by »exotic nuclear physics« and still promote a self-consistent scientific development of that scientific branch. Indeed, there are so many unknown (or inaccurately described) features of nuclear (and elementary particle) physics that it is extremely hazardous to reduce its development to »selected« extrapolations between a few pieces of accurate scientific knowledge.

What was said concerning »exotic« and »conventional« physics could also be repeated with »fast« and »slow« scientific progress dealing with phenomena in such a broad time scale as nuclear and atomic physics.

4.9. *Scientific deontology and the advancement of Science*

Gaja Alaga liked to help and stimulate young physicists with a great generosity and enthusiasm. He never tried to exhibit the personal work of his collaborators as if it were his own. However, when he got excited with a definite idea he could hardly resist expressing his feelings with his meridional eloquence. At these mo-

ments, he was not always understood and appreciated by his anglo-saxon and nordic colleagues. Nevertheless, Gaja Alaga was always extremely fair in the organisation of scientific meetings because he was convinced that the competition between different scientific conceptions should never degenerate into bad personal relations between their supporters.

A proof of that strict deontology is the fact many times observed in our numerous discussions with Alaga that he never made depreciative comments about the scientific work or the behaviour of other colleagues. For instance, he never tried to promote his model as the most complete one or neglect other theoretical approaches with sharp sentences such as: »I don't like it« or even worse »I don't buy it«. He certainly deeply disliked mediocrity by his own temperament and education. Furthermore, he perfectly knew that the great human projects — like the advancement of Science — are either incompatible with mediocrity or greatly disturbed by its influence. Indeed, Science is developed by human beings with their qualities as well as their faults, their attractions and their repulsions.

The most difficult task in promoting good scientific team work is to overcome mutual suspicions or ideological contradictions.

In principle music, art and science could help together — or separately — to attenuate such suspicious and improve human relations. It is interesting in this respect to remind Cecil Powell performance of promoting (and succeeding) a close collaboration between northern and southern Irish physicists within his nuclear research group.

According to him the success of such a collaboration depended essentially on the adoption of a few simple rules for the collective behaviour preventing conflictual situations between their participants.

Gaja Alaga had probably a less pragmatist approach for the organisation of scientific work than Cecil Powell but his main scientific aim — advancement of scientific knowledge and promotion of human welfare — was certainly not very different.

4.10. *Scientific traditions and the advancement of Science*

Scientific traditions are not the same in different countries. This is partly due to large differences in their cultural background as well as in their different development of particular scientific themes and techniques.

These traditions are important factors influencing the advancement of science: often promoting (or helping) such progress, sometimes delaying (or retarding) the same progress. The latter situation occurs mainly when there is a strong conflict between these traditions and new scientific ideas (or techniques).

These traditions are not static and change considerably with the increased means of communication and personal mobility. However, it would be advisable to allow a spontaneous evolution of such traditions instead of trying a »forced standardization«.

4.11. *International scientific cooperation*

Another important feature of Alaga's mind is the belief in the fruitfulness of international scientific cooperation.

This feature is not surprising considering the long tradition in the nuclear physics field developed at Copenhagen and the close relationship between Gaja Alaga and that nuclear theoretical school. Furthermore, Alaga's predilection for long talks and discussions on all kinds of problems — mainly scientific, social and political — and his deep knowledge of European problems (with a particular mention for those of Central Europe and Balkans) was a very rich source for the development of close relationships with many friends inland and abroad. In particular he supported with deep interest the project of a Nuclear Physics Research Institute coordinating fundamental research in this field and those countries. This project failed — and Gaja Alaga deeply regretted the loss of such a »battle« with the conviction that the corresponding »war« was not lost. Indeed, his belief in the usefulness of such a project could be understood on the strength of his conviction as well as on the support of his young collaborators.

One can presume from his scientific deontology that he preferred avoiding a detailed comparison between different nuclear theories and models which is »a priori« a delicate matter on diplomatic grounds. However, he had no objections to other people doing that job. Furthermore, he was willing to help them for that purpose because he thought that task was necessary for scientific development. In particular, the informal collaboration Lund-Orsay-Zagreb (promoted by »nuclear spectroscopists« for the detailed comparison between particle rotor and particle vibrator descriptions) was a good experience for developing a close relationship between different nuclear theoretical approaches. A few interesting scientific results were obtained in this joint work — apart from the great pleasure (and spiritual enrichment) enjoyed through the enthusiastic cooperation between scientists with different origins and tendencies. Considering the rather limited means and support received from the scientific authorities — apart from Gaja Alaga and Sven Gösta Nilsson — for the development of such work one can speculate about the output of such an investigation within the more favourable context prevailing nowadays. Consequently, in the present situation of easier scientific exchanges between Eastern and Western Europe, one can expect a large number of such collaborations and better conditions for making them more efficient.

Let us hope that these prospects will soon become a reality and all who like Gaja Alaga want a better relationship between Eastern and Western — as well as between Northern and Southern — scientists will feel compensated for their strong efforts towards that aim.

5. Conclusion

From this review of the relationship between electron spectroscopy and nuclear structure several conclusions may be drawn:

- i) Electron spectroscopy made an important contribution to many topics considered in this review (Section 2) and important new results may be expected in the future. The same conclusion is valid for the relationship between electron spectroscopy and α -decay as well as spontaneous (or induced) fission — which are not considered in the present review.
- ii) The research field of electron spectroscopy (like $(X + \gamma)$ ray spectroscopy) covers not only the atomic nucleus but also the electron cloud, molecular (or quasi-

molecular) and solid state structures. Furthermore the availability of highly energetic and intense heavy ion beams opens a new exciting research domain, (quantum electrodynamics of strong fields) intimately connected to in-beam electron and positron spectroscopy.

iii) There is a large amount of work to be carried out concerning electron spectrometers, momentum selectors and related techniques (development of «single» or «multi-channel» modes of operation, preparation of isotopically pure targets and new types of electron detectors, creation or improvement of new methods for electron background reduction, etc.) in spite of an extensive literature and available results on such topics. A few of these instrumental and technical problems — as well as the main features of different kinds of nuclear spectroscopic measurements (i. e. off-line, on-line and in-beam) — are briefly discussed in Section 3. However, no attempt was made to review this subject thoroughly due to its large extension.

(iv) Our remembrances and reflections on Gaja Alaga led us to review many present and past problems of experimental and theoretical nuclear research and to think about their impact on future scientific developments. In particular, we try to stress the need for a deep reflection on a few unsolved problems of modern scientific research.

- a) How to conciliate individual initiative and collective constraints in medium and large sized nuclear laboratories?
- b) What are the best criteria for selecting scientific projects?
- c) How to protect scientific authors from partial (or biased) judgements of referee's?
- d) Is it possible to conciliate (apparently sharp) opposite tendencies of contemporary science like «exotic» and «conventional» nuclear physics; very large projects and rather small ones; scientific traditions and revolutions; local, regional, national and international scientific trends, etc...)?
- e) How to believe and remain enthusiastic in contemporary Science when there are so many examples of non-scientific behaviour and widespread intolerance?

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ELEKTRONSKA SPEKTROSKOPIJA I NUKLEARNA STRUKTURA

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Naznačena je današnja veza između elektronske spektroskopije i nuklearne strukture. Diskutirane su glavne potencijalne mogućnosti te veze.