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~~Mark Buchanan~~
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~~Bohr and Kalckar, 1937~~

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Challenges in the description of the atomic nucleus: unification and interdisciplinarity

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The modern theory of nuclear structure results from the merging of the liquid drop and of the shell model, which contribute the concepts of collective excitations and of independent–particle motion, respectively.

These apparently contradictory views became unified as a consequence of the particle–vibration coupling mechanism ?. The resulting clothed bosonic and fermionic degrees of freedom constitute the physical, elementary modes of nuclear excitation which diagonalize the many–body nuclear Hamiltonian.

The ~~different~~ associated spectroscopic amplitudes provide, together with the theory of reactions ?, the elements to calculate the absolute value of ~~the~~ differential cross sections and transition rates. In particular, those associated with: **a)** inelastic scattering, Coulomb excitation and γ–transitions, **b)** one–particle and, **c)** two–particle transfer processes. These spectroscopic amplitudes and associated formfactors also provide the input to work out the optical potentials needed in the calculation of the absolute cross sections, quantities which can be compared directly with the corresponding experimental data. ~~A fact which implies a higher~~ level of unification of the variety of facets of theoretical nuclear physics. That between structure and reactions, let alone that between the physics of bound and continuum states.

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The above elements testify to the need for a new

This unification, still in the making, will prove essential to meet the challenges resulting from experimental developments. Also those coming from other areas of physics, that is, from interdisciplinary research.

[8-10]

The importance of such talk across the borders can hardly be overemphasized. Without the input from condensed matter, the theory of nuclear pairing as we know it today would not be ?. Nor the ~~simple~~ description of two–nucleon transfer reactions, mainly as a successive process?, Process which can be calculated with high accuracy, rendering quantitative the probing of pairing in nuclei ?. Let us now go back to **a)**, **b)** and **c)**.

[3,6,7].

[11]

Processes **a)** and **c)**, specifically probe collective modes. The first ones those associated with correlated particle–hole (ph) states. The second ones those corresponding to (pp) and (hh) states. That is, pairing vibrations. In particular, the newly discovered Giant Pairing Vibrations (GPV) ?, in the two–nucleon transfer reactions ^{12}C(^{18}O,^{16}O)^{14}C and ^{13}C(^{18}O,^{16}O)^{15}C.

[12,13]

[14]

[16]

Reactions of type **b)** give specific information concerning the single–particle content of nuclear levels ?. Also those lying in the continuum as testified by the analysis ? of the reaction ^{9}Li(d,p)^{10}Li ? populating the virtual and resonant ~~$s_{1/2}$ and~~ $p_{1/2}$ valence states at threshold, and responsible for the new magic number N = 6, and for many of the exotic properties of the nucleus ^{11}Li ?. In particular, of the fact that most of the pairing ~~binding~~ the neutron halo Cooper pair to the ^{9}Li core is due to the exchange ~~between the two neutrons~~ of the Giant Dipole Pigmy Resonance (GPDR) of ^{11}Li, and of the low–lying quadrupole vibration of ^{8}He, as testified by the absolute value of the differential cross section associated with the states populated in the reaction ^{1}H(^{11}Li,^{9}Li)^{3}H ?.

$s_{1/2}$

[15]

[17,18]

binds

lying at

[19,20]

New frontiers of interdisciplinarity and unification are being forced open by work on double charge–exchange ($2n, 2p$) and neutrinoless double beta decay ($\beta\beta(0\nu)$),

energy with which

In this way [redacted] the three channels contributing to to the ^{40}Ca $\rightarrow$ ^{40}Ar reaction will be properly characterized,

contributing to

constituting

this last ~~process constituting~~ an important element in testing the standard model. Nuclear matrix elements entering the calculation of $\beta\beta(0\nu)$ can be, in principle, extracted from the absolute value of $(2n,2p)$ differential cross sections ?? [21-25]. In particular, of the ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar process ? [26].

To quantitative

~~To quantitative~~ control the accuracy with which one is able to calculate the elements ~~entering~~ $d\sigma(\theta;{}^{40}\text{Ca}\rightarrow{}^{40}\text{Ar})/d\Omega$, the absolute value of the single charge–exchange process ^{40}Ca(^{18}O,^{18}F)^{40}K and of the two–neutron and two–proton transfer reactions ^{40}Ca(^{18}O,^{16}O)^{42}Ca and ^{40}C(^{18}O,^{20}Ne)^{38}Ar have to be calculated, and the results compared with the experimental findings [27].

no new line

~~In this one will be in posses of the elements~~

~~Likely, one has in this way the elements to be quantitative concerning these three processes,~~ in terms of GT wavefunctions for the first one, and of pairing vibrations for the last two. With a number of provisos, however. First, all these vibrations have to be renormalized in terms of self–energy and vertex corrections arising from the coupling to low–lying collective (ph) excitations, and through the mixing of particle and hole states in the case in which the collective mode is a pairing vibration. Second, within the context of double charge exchange, both GT and pairing vibrations have to be extended to other multipolarities different from 1^+ and 0^+ respectively. Last, but not least, the ground state of both ^{16}O and ^{40}Ca contain $np-nh$ (coexistent) deformed components which have to be properly dealt with in the quest of a quantitative description of the ^{40}Ca$\rightarrow$^{40}Ar process. The need for a broad interdisciplinary background ~~is~~ becomes apparent.

Further insight concerning how to quantitatively deal with the GT modes ~~is~~ could be provided by a study of the reactions ^{96}Mo(d,^{2}He)^{96}Nb and ^{96}Zr(^{3}He,t)^{96}Nb, processes involved in the ^{96}Mo$\rightarrow$^{96}Zr double charge exchange reaction [25]. This is in keeping with the fact that in this case, essentially a single 1^+ state (0.69 MeV) already implies closure ~~in the present case~~. To test all these elements, structure, reactions and few–body practitioners have to join efforts, eventually unifying their specific tools into basic physical concepts common to all of the approaches.

Summing up, it is not so much a new, eventually richer and more complete, Hamiltonian to diagonalize that one needs to further nuclear theory, but a deeper insight into the (finite) many-body physics which is at the basis of the atomic nucleus and thus a new type of nuclear theoretician.

Like a renaissance subject, able to combine in a single person the construction worker and the carpenter, the architect and the engineer, the painter and the sculptor, our theoretical researcher should be equally conversant in structure and reactions, in condensed matter as well as in standard model physics, finding (him/her) self equally at ease discussing with theoreticians than with experimentalists. And the sooner we allow young mids to open up to this scenario, the better. Also in keeping with the fact that experimental developments, to whom theoreticians are asked to contribute in terms of the physical input, require many years of planning. A planning which can, at the same time, imply the stop of experimental data–taking, and thus of a partial drought concerning the starting point as well as the nourishment of the theoretical endeavor. [28, 29]

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