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Lessons from two paradigmatic developments; Rutherford's nuclear atom and halo nuclei

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Abstract. In its initial 1911 version, underpinned by discoveries in alpha-scattering experiments, Rutherford's atom model made a gross separation of neutral matter; A veil of light negative matter surrounding a tiny impenetrable heavy positive core. The model had however little to say about the atomic (electronic) architecture and dynamics, hence did not make it straight to the catwalk of physics of those days. Three quarters of a century later, in 1985, new discoveries in collision experiments revealed existence of abnormally large light nuclei, but could say less about the nuclear architecture. History sometimes repeats itself: Like Bohr's ad hoc planetary model (1913) changed the fate of Rutherford's discovery, again Scandinavian inspired ideas on architecture, this time nuclear halos, changed our paradigm for the heart of matter. We comment on the need for a concerted Rutherfordian effort between theory and increasingly complete reaction experiments if further ground-breaking progress is going to be made in halo physics, and physics in vicinities of neutron and proton driplines, and generally in the more widely growing field of many-body open quantum systems, where structure and reactions come together.

1. Nuclear science and paradigms

"You're always at the crest of the wave", someone said to Rutherford. "Well, after all, I made the wave, didn't I?" Rutherford replied. Lord Snow recalls this line in his essay "Rutherford" [1] from his Cambridge memories, the man and the new tone of science – the tone of Rutherford. The *wave*, the *paradigm* for *how* to ask questions to Nature, how to *experimentally* observe constituents of matter, grew out of Rutherford's laboratory here in Manchester, into our days' reaction and particle physics.

"It's rather odd," said G. H. Hardy (the mathematician), one afternoon in the early Thirties, "but when we hear about 'intellectuals' nowadays, it doesn't include people like me and J.J. Thomson and Rutherford." Again from Lord Snow [2], novelist and scientist with access to both camps, who watched the new science grow, and also the growing divide between the *two cultures*, about which he later expressed deep concern in his famous essay.

We love to be on the Catwalk of physics, but what about our standing in society? Hardy's and Snow's concerns are very much relevant also in our times, and we may wisely spend some of the 1911 and 1913 celebrations reflecting on our paradigmatic status, and lessons learned.

The title of our contribution may appear somewhat "intellectual" and definitely not Rutherford's tone. Rutherford, a well read man, certainly knew that the Greek had created the word *paradigm* for and how to make cosmological models, but it was not used in the physics of his days. It has however reappeared with Thomas Kuhn's controversial book [3] *The Structure of Scientific Revolutions* (1962).

2. Not on the 1911 Catwalk of Physics

When Rutherford's nuclear atom model was introduced in the spring of 1911, it was met with indifference and scarcely considered to be a theory of the constitution of the atom. The paper was published in May in Philosophical Magazine (with Rutherford as single author), with the title **The Scattering of α and β Particles by Matter and the Structure of the Atom** [4]. The experimental observations were those obtained jointly with his 'boys' Geiger and Marsden, to whom he gives proper reference already in the first paragraph of the paper.

The new conception of the atom was not mentioned in the proceedings of the 1911 Solvay Congress (where Rutherford participated), nor was it widely discussed in the physics journals. Thus the nuclear atom *did not make it straight to the catwalk of physics of those days*.

This we learn from Helge Kragh's book "Quantum Generations – A History of Physics in the Twentieth Century" [5], and he gives reasons for it. In its initial version the model, based on **scattering experiments**, made a separation between central heavy and surrounding light matter, but it had little to say about the structure of the negatively charged (electron) veil, thus provided little guidance for ongoing *atomic* experiments. Rutherford understood the situation rather well, and probably felt that some of his young people were moving too fast concerning wider implications of their joint discovery. As we will see below, *his scattering theory even left the electrons out!*

By 1913 Rutherford's model was underpinned by much improved data on alpha scattering, but still would have had little new to add on the *atomic architecture*. *The fate of the model had however changed with the arrival in Manchester of a young Dane, Niels Bohr*. He turned Rutherford's picture of the nuclear atom into a proper, albeit still ad hoc, quantum "planetary" theory of the nuclear atom. Ten years later he obtained the 1922 Nobel Prize in Physics "for his services in the investigation of the structure of atoms and of the radiation emanating from them". No mention of the "Heart of Matter"!

Physics will celebrate the completion of the Bohr-Rutherford nuclear atomic model two years from now, in 2013.

3. Identifying the Heart of Matter – Rutherford's paradigm

So what is the core of *our* celebration, and its relevance today? It was in Rutherford's lab in Manchester that the heart of matter was **identified**. It was in Manchester, with continuation in Cambridge, that the constituents, the proton and the neutron were discovered. Excellent reasons for celebration. The war came in between: Rutherford introduced the name *proton* for the stripped Hydrogen, and visions for a neutron first in his 1920 Bakerian lecture.

If we ever speak about Rutherford and a paradigm, it is linked to Rutherford's *scientific practice*, his epistemological way to extract and develop lessons and knowledge. This practice also includes the formation of his research team, an international workforce of young people, in a British setting: Rutherford's boys, happy for their shares in the venture - among them Niels Bohr. *Copenhagen, future Mecca for quantum and nuclear physics, drew inspiration from the spirit of Manchester*.

Rutherford's 1911 paper [4] is convincing reading, ready to be used also in our days' teaching. His Manchester team truly pioneered the way **we** do *collision studies*. Rutherford cleverly used what was available at the time, Nature's own heavy bullets; alpha particles, from transmuting

nuclei. Few knew that business better. Rutherford had just got the 1908 Nobel Prize (in Chemistry!) for the discovery.

4. How well did Rutherford know his favourite probe – the alpha projectile?

In a standard binary collision, a reasonably well known projectile collides with a target body, probing unknown aspects of the latter. Rutherford's projectile, the alpha particle (${}^4\text{He}$) is the most compact light nucleus, with a well determined charge radius of 1.681(4) fm, significantly smaller than 1.961(4) fm for ${}^3\text{He}$, the recent very precise number reported in Science, 8 July, this summer. We also know that neutral Helium is the smallest of all atoms with a 0.3 Å radius. But, how well did Rutherford know his child, the alpha particle?

Rutherford had by 1908, as outlined in his Nobel lecture [6], done the studies that confirmed the physical nature of the alpha rays as atomic Helium, deprived of its negative charge. His 1911 paper assumes not only implicitly, but makes explicit assumptions indicating that *he thinks the alpha is a point-like bullet on atomic scale* (Å). Thus he states in his 1911 paper [4] that, "We shall suppose that for distances less than 10^{-12}cm the central charge and also the charge at the alpha particle may be supposed to be concentrated at a point." (Rutherford used, almost consistently for a decade or so the name *central charge*, Nicholson seems to have been the first to use the name *nucleus* [5].)

Thus Rutherford assumes consistently that both alpha and target are within 10 fm size. This impression is strengthened when Rutherford, like we would have done, starts his analysis by calculating the *distance of closest approach* for the kinematic conditions 8 MeV for his alpha beam on a gold-like central charge of 100 units. It is educational to read Rutherford's simple language and deep considerations. The distance of closest approach (~ 34 fm) is small enough on atomic scale, but large enough on the nuclear scale, to justify a point-like (or equivalently, we may add, small sphere) approximation for the nuclei.

Rutherford's 1911 paper may be described as a theoretical consequence study of purely elastic Coulomb scattering, used to understand *surprising features of already measured transverse scattering*, and in particular backward. It is written in a very modern way with focus on the observables relevant for the essential emergent features of the phenomena. This does not necessarily classify Rutherford as a theorist in disguise, but shows his valuing of theory and math in putting pieces together.

5. Into the Heart of Matter – Missed Opportunities?

While the *atom* (Greek for indivisible) was a technically inaccessible mental construction in Democritus' times, Rutherford's experiments probed the charge density structure of the atom. Although tiny (but heavy), Rutherford foresaw a complex nature for the new "heart of matter", but he could say less about **its** inner workings. There were limitations. His natural source alpha beam was limited to less than 10 MeV! Exploring the secrets of the *nucleus*, called for new acceleration principles and penetrating probes to be developed. This did not, however, prevent Rutherford from speculating about nuclear structure. Already in 1913, assisted by new and improved experiments, he briefly discusses nuclear structure in his new textbook on *Radioactive Substances and their Radiations* [7], see [5]. We will return to this. Rutherford's nuclear paradigm is already getting a conceptual content, a *what*, not only a *how*.

Heavy gold (platinum) targets had initially been chosen because since medieval times craftsmen had mastered the art of hammering the soft metal to incredible thinness, optimising *single scattering*. In the following years, gaseous **light** targets were also used, such as Nitrogen, allowing the energy restricted alpha beam to bring the collision partners close enough for **the first man-made nuclear reactions** to occur; *nuclear disintegration*, ejecting Hydrogen (a proton) and Oxygen. This happened after the interrupting world war, the year before Rutherford left for Cambridge, opening up a new stage in the history of modern alchemy.

In 1956, nearly half a century later, Heydenburg and Temmer [8] measured complete angular distributions for low energy alpha particles from electrostatic generators, on ^4He target. Below a relative energy of 400 keV, i.e. well below the Coulomb barrier (about 2 MeV), the Mott interference formula for scattering of identical bosons (two spin-0 alpha particles) reproduces the oscillatory scattering very well, but not the Rutherford formula! All this in the language of two decades after 1911, when quantum mechanics and spin statistics had become part of the paradigm. Temmer addresses this seemingly missed opportunity in his 1988 paper "How Rutherford Missed Discovering Quantum-Mechanical Identity", see [8].

6. On the 2011 Catwalk

A nuclear atomic model, the so-called Saturnian model had been suggested already in 1904 by a Japanese, Hantaro Nagaoka, who also visited Manchester [5]. Rutherford refers to this and Nagaoka's communication in Phil. Mag. in his own 1911 paper. Lacking experimental underpinning, no conclusions could be drawn at that time concerning nuclear versus atomic dimensions. It took even longer, a quarter of a century from 1911, before the **nucleus** got its first ruling model, the liquid drop model (1936), crucial for understanding fission in following years. In 1949 it was challenged by the nucleon based nuclear shell model, rewarded by the 1963 Nobel Prize. Nuclear structure got its second and last Nobel Prize in Physics in 1975 for "the connection between collective motion and particle motion".

But the nucleus had new surprises in store. Upgraded/new accelerators and experimental techniques opened up for journeys away from the stability line to the coast lines of the nuclear chart, the *driplines*, where nuclei in their struggle to survive, form exotic islands and where the continued journey takes the traveller into the world of open quantum systems.

The last year has welcomed two newcomers from the neutron dripline on the catwalk of physics, ^{22}C and ^{24}O , both with 16 neutrons and not the old magic 20. They appear to be the last hadronically stable carbon and oxygen isotopes. Both have made headlines in a variety of modern media, also beyond nuclear physics. While ^{22}C is highlighted as the heaviest *Borromean* halo nucleus (a bound three-body structure of cluster constituents $^{20}\text{C} + n + n$, with no mutual binary bound states) discovered up to now, ^{24}O is not Borromean, but a new *doubly magic* nucleus with $Z = 8$ and $N = 16$.

7. Nuclei with Exceptionally Large Radii

The experimental study of ^{22}C at Riken in Japan, by Tanaka and collaborators [9] is in spirit very similar to the pioneering studies by *Isao Tanihata* and his collaborators at Berkeley in 1985. By creating beta-radioactive dripline nuclei in flight as secondary beams, they may be studied in reactions with known targets. Thus 25 years ago, Isao Tanihata and his collaborators, pioneered for this purpose the use of secondary beams produced by projectile fragmentation in heavy-ion collisions. This opened new perspectives on *nuclear architecture*. Focus is now shifted to the projectile, the target in inverse kinematics.

Late in 1985 Tanihata and collaborators published two consecutive papers, a Physics Letters [10], **Measurements of Interaction Cross Sections and Radii of He Isotopes**, and a Physical Review Letters [11], **Measurements of Interaction Cross Sections and Nuclear Radii in the Light p -Shell Region**. While Rutherford's low energy alpha scattering (2 MeV/nucleon) probed the central charge localization of the atom by limiting it to significantly less than the distance of closest approach, Tanihata's secondary beams were derived from projectile fragmentation of high energy primary beams of 800 MeV/nucleon, suited for extracting nuclear sizes from measured interaction cross sections.

The theory in Tanihata's Physics Letters article is even simpler than in Rutherford's work, and he refers to it as *operational*. Still it is sufficient, in the spirit of Rutherford, to make some essential observations. Tanihata assigns each collision partner an "interaction" radius,

calculates a geometrical cross section as π times their squared sum, and puts this equal the measured interaction cross section. Thus he could calculate differences between unknown radii and a reference one. Exploring experimentally collisions between unstable ${}^6\text{He}$, ${}^8\text{He}$ and also stable ${}^3\text{He}$, ${}^4\text{He}$ projectiles and light target nuclei, the team made the observation that the interaction radii of the unstable isotopes were about 1.5 times those of the stable, deviating significantly from the usual $A^{1/3}$ rule. Attempts to reproduce this with theoretical many-body models failed.

In their Physical Review Letters article, Tanihata's team extended their He study to all (at that time) Li isotopes, including the radioactive ${}^{11}\text{Li}$, (and also ${}^{7,8,10}\text{Be}$), all on the same light targets. They now derive an ${}^{11}\text{Li}$ interaction radius 0.7 fm larger (1.3 times) than that of ${}^9\text{Li}$. With need to explain this and the abnormal Helium observations (like Rutherford's ricocheting alphas), the team brings in heavier Glauber type *reaction theory* to link the interaction cross sections to nuclear matter distributions and RMS radii for the collision partners. The markedly increased sizes of ${}^6\text{He}$ and ${}^8\text{He}$ however remained, leading the authors to suggest the existence of thick neutron **skins**. Likewise the huge ${}^{11}\text{Li}$ abnormality remained; an RMS matter radius of 3.14(16) fm is what normally is associated with a nucleus with 2-3 times the nucleon number of ${}^{11}\text{Li}$. In spite of their efforts in the theory analysis, the team had no real explanation, and had to round off the paper with the remark, "*It suggests the existence of a large deformation and/or of a long tail in the matter distribution due to the weakly bound nucleons.*"

This way it stayed for more than a year, until (again) clarification came from Scandinavia, and again **on a conceptual level**.

8. Halo Nuclei

The challenge of understanding this and similar consecutive observations, became of interest for the nuclear physics community and among theorists in particular, only after the Scandinavian experimentalists P. Gregers Hansen and Björn Jonson in 1987 put forward an *ad hoc* **halo theory**, conceived according to the legend in a lunchroom conversation at the Niels Bohr Institute with the late Danish theorist Jens Bang. Hansen and Jonson turned the idea into a Europhysics Letters [12] "**The Neutron Halo of Extremely Neutron-Rich Nuclei**", with proper reference to discussion with Bang. Thus the name **halo nuclei** came into being.

"No doubt the positively charged centre of the atom is a complicated system in movement, consisting in part of charged helium and hydrogen atoms" [7]. This sentence is from Rutherford's 1913 textbook alluded to earlier. Alphas pop out of nuclei, so why should they not pre-exist within? Clustering, in particular alpha clustering in nuclei has a rich but also controversial history, with the three-alpha Hoyle resonance state as a landmark.

Clustering, a true emergent aspect of nuclear structure, has had a revival with halo physics. Rutherford would have been pleased to learn that much of our present understanding has been derived from Helium, from the beta-unstable but hadronically very loosely bound isotopes ${}^6\text{He}$ and ${}^8\text{He}$. While the Helium atom is an alpha with a veil of two electrons, the ${}^6\text{He}$ nucleus is an alpha with a veil – a halo – of two neutrons, ${}^8\text{He}$ four neutrons. Since neither a *neutron - neutron* nor a *neutron - alpha* pair can form bound states, a new binding mechanism has been discovered, different from one dominated by a mean field, the atom model for the electrons.

A second quote from Rutherford's 1913 textbook shows that he was puzzled by the question of nuclear binding, "*It would appear as if the positively charged atoms of matter attract one another at very small distances for otherwise it is difficult to see how the component parts at the centre are held together*" [7]. Now we know more after pioneering theory work by Efimov and Migdal (who would have been 100 this year), and twenty years of few-body modelling of Borromean nuclei.

Hansen and Jonson refer to Migdal in their ground-breaking paper; "This suggests that for a nuclear potential that leaves a single neutron marginally unbound, the additional attractive

contribution from the nn interaction will frequently be sufficient to bind two neutrons to the nucleus. This special case of three-body problem has been considered by Migdal [13], who finds that several nuclei should exhibit a bound state of this kind, which may be interpreted as a dineutron near the nuclear surface. He also points to the possibility that cluster states more complex than dineutrons may exist”.

Hansen and Jonson made a *phenomenological* model with a point-dineutron, useful in the spirit of Rutherford for understanding important aspects of the new halo phenomenon.

9. Dripline Exotics

It took a few more years before the halo assumption was properly underpinned experimentally, and the concept of Borromean halo nuclei coined [14] and explored for the most exotic, two-neutron halos, bringing the field to the catwalk, not only of nuclear physics, but physics more generally. We started by observing that Rutherford’s 1911 paper really was one on scattering theory. We end by stressing that the future needs better reaction theory if we are going to fully explore the landscape of resonances and an unknown variety of many-body open quantum systems, in cluster formulations and possibly in self-organized ab initio approaches, the preference of our young computational theorists.

We need Rutherfords also today, who can combine experiment and visionary theoretical modelling.

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