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New Ideas in Nuclear Structure Physics

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NEW IDEAS IN NUCLEAR STRUCTURE PHYSICS

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Abstract: Just over a century after the discovery of radioactivity by Becquerel and of new elements by the Curies, we have begun to master the techniques of performing experiments with radioactive beams. And, of course, the search for other new elements goes on. At the same time the exploitation of γ -ray arrays of increasing power pushes observation limits lower and lower in the search for new phenomena at high spins. Ancillary devices, capable of giving cleaner channel selection, also permit the study of higher-mass systems and of more exotic charge-to-mass ratios even with stable beams.

A personal selection of some of the topics of interest will be presented, as well as some comments on how relatively simple detection systems can still make major contributions to our understanding of nuclear structure and reactions.

1 INTRODUCTION

It is an honour to be asked to present the opening physics talk at this conference, timed to coincide roughly with the 60th birthday of our old friend John Sharpey-Schafer. I have known John for many years now and have always had enormous respect for him both as a physicist and as a person. I could mention various important discoveries in high-spin physics in which John was intimately

involved, such as the discoveries of band terminations and superdeformations, but I would also like to remind you that it was John who convinced the nuclear physics community of the need to do proper, clean spectroscopy using arrays of Compton-suppressed γ -ray detectors, an idea which ultimately led to the creation of such devices as EUROBALL and GAMMASPHERE.

Perhaps even more importantly he has played an tremendous rôle in attracting a multitude of bright young people into our field of research, both through his lectures in Liverpool and through his general enthusiasm for his chosen subject, manifested at many international conferences, schools and seminars. I must say that I am delighted to see how many ex-students of John are still in the field of nuclear structure research and that so many of them are here in the audience today. Of course those students who did not remain in the field have gone out into important positions in industry and teaching etc. equipped with the excellent education that a doctorate in experimental nuclear physics provides.

Having attracted this talent into research in the physics department in Liverpool, John did not forget them, not only helping them greatly with their projects but also looking after their personal and social well-being through, for example, extra-curricular sessions in some of Liverpool's more interesting nightspots as well as through bracing walks in the mountains of Snowdonia.

With the latter in mind, I would like to take you on a trip, a fairly random walk, through the hills and valleys – not of course those of North Wales but those of the N - Z plane. The landmarks we shall note on the way are rather subjective, being a collection of topics which I have heard talked about at recent conferences or recent visits to other laboratories. I offer my apologies to anyone who feels that their work should have been included if it is not.

There were a couple of advantages to being a theorist in Liverpool, as I was from 1975-78. One, of course, was that one did not need to do experiments. But the second was that from the 7th floor of the Chadwick tower we had wonderful views over the city; between the cathedrals, across the River Mersey and out to Snowdonia itself. Liverpudlians will tell you that if you cannot see Snowdonia, then it is raining...and of course if you can see Snowdonia, then it is going to rain! Usually if one could see anything at all, it was just the summit of Snowdon itself sticking out above the mist and clouds.

And so it was with the nucleus at the end of the last century, hidden beneath its clouds of electrons. Fortunately Nature provided us with isotopes of uranium which generate a radioactivity that penetrated these clouds for Becquerel to realise that something interesting lay beneath them. As she often is, Nature was kind in giving these isotopes – long enough lived to have survived since the supernova explosion which created them and spewed out much of the matter from which the Solar System was built, yet with lifetimes still short enough to give significant and easily measurable radiations.

One should perhaps interject at this stage that it is the study of nuclear structure and reactions which has given us the deep understanding we have of such astrophysical processes; where the matter of which we are made came

from, the evolution of stars – the whys and wherefores of the Hertzsprung-Russell diagram – and how the Sun produces the energy on which our existence depends. One of the major goals of nuclear physics research over the coming years will be to further extend this base of knowledge through the exploration of nuclei far from the line of β -stability which play an determining rôle in nature of our Universe. For example, understanding the production mechanisms of proton-rich stable isotopes will give considerable insights into the exotic cosmological conditions in which they are forged. Similarly the properties of certain key nuclei on the neutron-rich side of stability, waiting points on the precipitous r-process path up the side of the valley, are essential to a complete understanding of the creation of the elements more massive than iron, including the uraniums themselves (see Fig. 1).

2 SOME HISTORY AND SOME GIANTS

There are many modern versions of the sentiment but I believe that it was Samuel Taylor Coleridge (1772 – 1834) who first said:

A dwarf sees further than the giant when he has the giant's shoulders to mount on.

I would like to mention some of the giants on whose shoulders we stand:

A CENTURY OF NUCLEAR PHYSICS

1896: Becquerel discovers radioactivity

1898: The Curies discover the elements Po and Cm

1911: Rutherford finds the nucleus and sees how big it is

1932: Chadwick discovers the neutron

1935: Joliot and Joliot-Curie make the first artificial radioactive isotope by bombarding ^{27}Al with α -particles

1936: Fermi makes lots of them using neutrons:

1939: Hahn, Meitner and Frisch discover fission (neutron-induced)

1955: Mayer and Jansen invent the shell model

1956-7: Bardeen, Cooper and Schrieffer invent pairing

1962: Polikanov discovers fission isomers (^{242}Am); the first superdeformed nuclei

I would have liked to stop there because I would not like John to think that I consider anything too much after his PhD as history. However, since it plays such an important part in our everyday lives, I cannot omit:

1975: Bohr, Mottelson and Rainwater are awarded the Nobel Prize for the collective model and its relation to single-particle structure

nor the important rôle in the game played by Nilsson and Strutinsky.

Of course when Becquerel discovered radioactivity he had no real idea of what it was, though he did eliminate many of the more conventional possibilities. The Curies still did not understand what radioactivity was but they did realise that it was associated with the transmutation of the elements.

In order to understand better the nature of the nucleus, one has to cross the English Channel and go to Manchester to participate in the experiments of Geiger and Marsden. These lead to Rutherford's explanation of the backscattered α -particles in terms of an atomic nucleus of incredible smallness. This was an interesting example of international collaboration since Rutherford did indeed cross the Channel with the α -particle source purchased for these experiments from the Curies. The first, but not the last time a British experiment would be done with a beam provided by France.

The next step in our history takes us the 45 miles down the East Lancs Road from Manchester to Liverpool. The journey takes a surprising 21 years. The reason for this of course is the neutrality of the neutron which made it difficult for Chadwick to detect. Following this discovery, things rapidly begin to fall into place. Heisenberg is happy and the existence of isotopes is understood, since the mass number A is recognised as the sum of the numbers of neutrons and protons $A = N + Z$ in the nucleus.

Shortly after, Joliot and Joliot-Curie make the first artificial radioactive isotope but soon Fermi makes lots of them, exploiting the freshly discovered neutron. None of this of course is destined to take us far from β -stability.

Impressed by Fermi's success in producing new isotopes, Hahn, Meitner and Frisch set out to produce transuranic elements through neutron capture and β -decay. Their failure is of course the great success of the discovery of fission¹ and all that that entailed.

Not only did the neutron prove to be an extremely powerful experimental tool, it also provided a key to the theoretical understanding of many problems of nuclear structure. The single-particle shell model of Mayer and Jansen follows with the understanding of the two-body correlations leading to pairing phenomena coming from physicists working in an entirely different field. Many pairing phenomena are, however, unique to nuclei and such cross-fertilisations provide an essential argument for maintaining a strong research base in our subject as a part of the overall fabric of science.

¹Of course both induced and spontaneous fission do produce neutron-rich fragments far from stability and their spectroscopy has been [2] and will continue to be a major theme of research.

3 BACK TO THE FUTURE

I have mentioned the above history since John asked me to talk about the future. I say this without irony since we all know, as scientists, that to extrapolate from a single point (the present) is impossible, whereas to extrapolate from two points is merely extremely unreliable. So let us revisit the problems mentioned above and see where we are today and where we might be going.

3.1 Nuclear radioactivity; so what's new?

Since the earlier days of nuclear physics when the classification of α -, β - and γ -rays emerged, later to be followed by induced and spontaneous fission, many new modes of nuclear decay have been observed. Relatively recently, for example the extraordinary ground-state decays via emission of heavy clusters such as $^{12,14}\text{C}$, ^{24}Ne etc., giving us fascinating insights into many-particle correlations in heavy systems and the profound rôle of shell structures.

I would, however, like to mention in a little more detail a type of decay which takes us right out to the ridge of nuclear stability, the proton drip line [3], which is proving to be an extremely powerful spectroscopic tool [4].

Figure 1 The nuclear $N-Z$ plane, showing many new phenomena either under exploration or which may shortly become accessible with the advent of radioactive beams [1].

Fig. 1 indicates the position of the proton emitters and the inset their decay mechanism, tunneling through the Coulomb, and possibly centrifugal barriers.

By definition they lie on or near the proton drip line; a stiff hike up from the valley bottom to overlook the abyss of particle instability. Once past the drip line, the last proton in the nucleus finds no unoccupied state which lies below the top of the potential barrier and leaves the nucleus unimpeded in a time of around 10^{-22} s. The last proton in an emitter, however, although still having positive energy, must tunnel through the barrier and consequently the nucleus has a much longer lifetime. This can be of the order of milliseconds for a proton with high angular momentum l . Indeed a measurement of the proton energy and lifetime allows one to extract l and thus study the single-particle structure of these unbound levels.

An excellent example can be found in the review article of Woods and Davids [4]. Fig. 2 shows the ground-state-to-ground-state decay of ^{167}Ir to ^{166}Os via proton emission. Note, however, that a metastable state of ^{167}Ir can also decay to the ground state of ^{166}Os . The lifetimes for these two decays allow angular momentum assignments of $l = 0, 5$ respectively, permitting spin and parity assignments of the two states in the parent nucleus. Alongside this, however, ^{167}Ir (both ground state and isomer) can give rise to a chain of four α -decays down to the closed-neutron-shell nucleus ^{151}Tm ($N = 82$). Again lifetimes show that all these decays are $l = 0$, permitting spin assignments as well as the localisation of the ground states and isomers in all four daughter nuclei. Note especially the inversion between ^{159}Ta and ^{155}Lu .

Figure 2 The interplay of proton decay and α -decay in this single example leads to a mine of nuclear structure information [4].

Much work remains to be done in this region of the $N - Z$ plane using such techniques. In addition one is starting to resolve the kind of fine structure in proton emission (long-since observed in α -decay) where the proton may leave the daughter nucleus in excited states. The search for simultaneous 2-proton

emission is also underway with the interesting question as to whether the spatial correlations emerging from such experiments will allow us to talk of di-protons.

Moving down from the proton drip line, nuclei decay by β^+ emission or by electron capture. Fermi transitions, especially for $N = Z$ nuclei (see e.g. Ref. [5]), are of particular interest. In addition, due to the steepness of the valley wall, much energy may be available for the weak decay, to the extent that a considerable part of the strength of the Gamow-Teller resonance may fall into the β -decay window (see e.g. Ref. [6]). Measured distributions of this strength will provide a fierce challenge to theoretical calculations of nuclear structure in this region. The high decay energy also means that further decays (γ -decay and proton emission) may follow providing a wealth of nuclear structure information through the exploitation of new detectors designed for the appropriate coincidence measurements.

3.2 *The alchemists*

The Curies' search for unknown elements was certainly arduous and demanded outstanding dedication to their task. At least, however, these elements existed to be discovered. If we are interested in seeing more, we must set about making our own! Most of the recent progress has come from the SHIP at GSI, where the new elements $Z = 110, 111$ and 112 have been produced (see e.g. Ref. [7]).

An enormous effort is currently being put into taking one step further than this at the Joint Institute for Nuclear Research in Dubna, where particle-microamp beams of ^{48}Ca are being used to bombard a ^{244}Pu target and I am confident that the next superheavy element will be discovered in this way².

Of course future radioactive beams of sufficient intensity, especially those rich in neutrons, may open up new shipping lanes to the superheavy island of stability; lower intensities possibly being compensated by large enhancements of the fusion cross section [9] arising from strong coupling to neutron-transfer channels etc.

3.3 *How big and how heavy?*

Rutherford taught us that the nuclear radius varies according to $R = r_0 A^{1/3}$, with $r_0 \approx 1.1$ fm. The nuclear mass is approximately given by A ($= N + Z$) atomic mass units. This is powerful information but of course much more

²A week or so after this talk was given, the discovery of $Z = 114$ was officially announced in Dubna. The reaction was $^{48}\text{Ca} + ^{244}\text{Pu} \rightarrow ^{292}\text{X}^*$. A single event was registered apparently corresponding to the evaporation of three neutrons to form a ^{289}X residue. After 30.4 s, this nucleus emitted an α -particle of energy 9.71 MeV, followed by a second α -particle of energy 8.67 MeV 15.4 min later and a third α -particle of energy 8.83 MeV after 1.6 min. The final product ^{277}Hs spontaneously fissioned after 16.5 min. The very long lifetime of the $Z = 114$ isotope leads one to believe that the evaporation residue lies very close to the fabled island of stability [8].

The reader may wonder at the author's clairvoyance, or may suspect that he had a little inside information before his talk.

interesting is how these properties deviate from this apparent simplicity. The semi-empirical Bethe-Weizsäcker formula tells us that macroscopic properties play an important rôle in determining the nuclear binding energy and hence its mass. Of course pairing and shell effects are also crucial.

Figure 3 shows dramatically these latter two effects through the neutron separation energy S_n and the 2-neutron separation energy S_{2n} for the calcium isotopes. The curve for S_n shows clearly the effects of pairing and that for S_{2n} shows the effects of crossing the neutron shells at $N = 20$ and $N = 28$. Thus a single piece of information, the nuclear mass, recounts interesting stories of nuclear structure. This is just as well since for many exotic nuclei this may be the only information accessible in the relatively near future! Enormous leaps are, however, being made in providing such information. One might, for example, cite the Schottky Mass Spectrometer experiments at GSI, where vast swathes of the $N - Z$ plane have been tackled and mass measurements obtained [10].

Figure 3 The neutron separation energy S_n and the 2-neutron separation energy S_{2n} for the calcium isotopes show beautifully the effects of pairing and of shell closures.

One can go one stage further than separation energies and define the pairing energy directly through $P_N = |M_{A+1} - 3M_A + 3M_{A-1} - M_{A-2}|/4$. A study of this property shows that the pairing strength itself may change abruptly at shell closures, though a full analysis of the effect also requires [11] a detailed knowledge of the corresponding nuclear deformation. Again, fortunately, this is a quantity which can be obtained from experiments involving relatively few atoms using laser-spectroscopy techniques [12]. These give a measure of the nuclear rms charge radius which in turn depends on its deformation. Recent experiments at Jyväskylä [13] (the first to successfully handle refractory elements on-line) have even yielded information on the differences in radii between nuclei in their ground and meta-stable states.

The increasing sophistication of techniques involving trapped ions of exotic nuclei should allow us in the future to push such measurements further and further from the stability line.

3.4 *Breaking up is hard to do; the still-neutral neutron*

As commented early, the neutron remained a mystery for many years due to its lack of charge. This property still makes it difficult to detect but large modern arrays of efficient neutron detectors such as the franco-belgian DEMON array make possible experiments which would have left Chadwick breathless.

One could cite, for example, the use of this detector system as a nuclear clock and thermometer in the measurement of the multiplicity and energy spectrum of the neutrons from a fission event. This idea has recently been applied to the phenomenon of bi-modal fission [14] of ^{226}Th ($^{18}\text{O} + ^{208}\text{Pb}$ at the Strasbourg Vivitron) where the fission-fragment mass distribution displays two distinct components, one symmetric and the other asymmetric. This shows the existence of two separate valleys in the fragment-fragment potential energy and the associated neutrons give valuable information on the timescales relating to the propagation down these.

A real *tour de force*, however, is the exploitation of this multidetector to the measurement of the size of neutron halos (see Fig. 1). Here [15], two neutrons emitted from a halo during a break-up reaction are detected in coincidence so that the technique of interferometry (as used to measure the size of distant stars) can be employed to measure the size of the halo; and this despite the very low intensity beams of ^{11}Li and ^{14}Be etc. available.

4 GAMMA-RAY SPECTROSCOPY

The discovery of a superdeformed fission isomer by Polikanov in 1962 [16] suggested that maybe such states existed in other nuclei and that one should think of other means of populating them. This was eventually achieved using the EUROGAM detector in Daresbury in 1986 [17] by the creation of ^{152}Dy at very high angular momentum, an experiment in which John Sharpey-Schafer played an active part. Since then a plethora of superdeformed rotational bands have been discovered in many other nuclei in the same and different regions of mass. More importantly than this, some of these bands have been shown to have some remarkable properties; a C_4 or $\Delta I = 4$ staggering, identity of bands [18] in different nuclei etc.

One obstacle which remained for many years was to establish how these bands decay to the known ground-state bands. Without this information, these structures were left "hanging in the air" with no firm assignments of their spins and with no absolute measure of their energies. The breakthrough of finding the linking transitions was made in 1996 [19, 20] in ^{194}Hg and ^{194}Pb . This opened up many new possibilities for the future; a genuine spectroscopy of the second potential well, an experimental determination of the pairing strength in the bands if links are found in adjacent nuclei etc.

Of course high-spin physics is not simply concerned with superdeformations and other topics of interest can be found in the splendid GAMMASPHERE booklet [21] for which we should congratulate Mark Riley and his colleagues. Figure 4, taken from this booklet, highlights a number of the phenomena in question. Of course much of the physics shown on this figure also stems from EUROGAM (both in Daresbury and in Strasbourg) and from earlier arrays such as TESSA as well as work pursued with EUROBALL III in Legnaro and to be further developed with EUROBALL IV, again in Strasbourg. While some of this physics is well established, much is still in its infancy. Problems for the future will almost certainly include the coupling of charged-particle devices to such γ -ray arrays, not simply to provide a gate by which to clean up the spectra of particular residues but to explore the details of reaction mechanisms, molecular resonances and fission etc. The coupling of appropriate recoil devices will also permit the observation of the excited states of very heavy nuclei produced weakly in fusion-evaporation experiments such as those on ^{254}No at the Argonne Laboratory and in Jyväskylä [24, 25].

Figure 4 The angular momentum world of the nucleus [21].

The future will also almost certainly have surprises up its sleeve, like the totally unexpected proton decay of the highly deformed band in ^{58}Cu [22] or the curious “shears” bands corresponding to “magnetic rotations” [23]. It may even herald the arrival of the ultimate γ -ray devices exploiting “tracking” techniques.

I will say no more about γ -ray physics, since I suspect that we will hear much more about it from other (more qualified) speakers at this conference. I just leave you with the thought that on a board at the poster session I noticed a copy of a recent paper on fission isomers "Experimental Evidence for *Hyperdeformed* States in U Isotopes [26]" which transports us neatly back to the beginning of this section...

5 EPILOGUE: DOES SIZE MATTER?

The future of nuclear physics seems bright, though we have hinted at the dominance of fearsome arrays of detectors and radioactive beams. Do laboratories which do not possess such capabilities have a rôle to play in this future?

I think that the answer is clearly yes and would like to give two examples to support this. The first is the relatively modest GAREL+ array which we have exploited in Strasbourg to partially fill the breach left by EUROGAM before the return of EUROBALL. By coupling its 14 large-volume Ge detectors to the Recoil Filter Detector (Berlin/Krakow/Strasbourg) and the Betatronic conversion-electron spectrometer (CSNSM Orsay/ ISN Grenoble), much interesting physics became accessible. Indeed you will hear a couple of contributions on GAREL+ during this meeting.

My second example comes from the southern hemisphere. The Nuclear Physics Laboratory at the Australian National University in Canberra has similarly exploited its small CESAR array to become world leaders in the study of high- K isomeric states through the application of imaginative timing techniques. Also, in the field of my own theoretical work, the use of a relatively simple velocity filter has allowed the group to lead in the field of "fusion barrier distributions" [9].

I am, therefore, confident that the new AFRODITE array at the National Accelerator Centre here in Faure, coupled to its ancillary detectors but more importantly, coupled to the great enthusiasm and experience of John Sharpey-Schafer, can also play an important rôle in the future of nuclear physics research.

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