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RECENT EXPERIMENTS TOUCHING NUCLEON DRIP LINES AND NEW REGIONS OF DEFORMATION

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Abstract - Important nuclear structure information already gained from experiments in the intermediate energy regime is summarised. The direction and likely success of future studies of exotic nuclei are also discussed, especially for the nucleon drip lines and new regions of deformation.

I - INTRODUCTION

Most of our semi-empirical nuclear structure theory arises from stable nuclei, which all have rather similar A/Z ratios and generally low spin and excitation. We must therefore expect to see rather similar physics down in the valley of stability \(/1/\). Those who prefer to clamber up the sides seek to find some rarity or to reach the plateau above for a rather different and more global view. There are some dangers to this approach, for example in particle physics where the struggle towards the top (quark?) necessary to achieve the unification of the 100GeV intermediate vector bosons with the massless photon may have revealed a 'desert' \(/2/\). By contrast the uprising efforts around the Fermi domain in Normandy provide a real 'dessert' for us all .... even the English \(/3/\)!

The recent discoveries of light 'exotic' beta decaying nuclei \(/4,5/\), of slow direct proton emission from the rare earth nuclei \(/6/\) and of \(^{14}\)C emission from actinides \(/7/\) serve to emphasize the delicate balance between nuclear, Coulomb and centrifugal forces in nuclei, and the phenomena of nuclear deformation, pairing, superfluidity and quantum tunnelling. By using the copious production rates available at new intermediate energy heavy ion accelerators, several groups of physicists have extended the first generation experiments to more detailed studies of 'exotic' nuclei. While Daniel Guerreau has discussed \(/8/\) the reaction

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mechanisms responsible for this welcome bounty, I shall present some of the more important nuclear structure results and the future understanding that is anticipated from the exploration of the Fermi energy regime at GANIL and similar laboratories.

II - NUCLEON DRIP LINES.

Adding many neutrons to a light isotope, and studying the evolution of the resultant level spectra, is one classic approach to extending our knowledge of nuclear forces and their symmetries. The single particle shell model for spherical nuclei predicts $N = 20$ is a magic number, but in the light elements around sodium there is evidence that the nuclear ground states are quite highly deformed. An examination of the nuclear masses, lifetimes and energy spectra of such light 'exotics' is of especial interest.

In order to know the range of beta-decaying nuclei that might be available for such studies, the limits of nuclear stability against nucleon(s) emission need to be established. This has been one aim of the first generation work by the Orsay-GANIL PE46 collaboration over the last 2 years. With the end-products of heavy ion bombardment of various targets analyzed at 0 degrees with LISE observations of both neutron-rich and neutron-deficient nuclei have been made for the first time. Reasonable criteria for particle instability can be formulated and applied to establish the non-existence of isotopes too /4/, and it seems that the so-called 'nucleon drip lines' are now reached for proton rich nuclei up to calcium ($T^n_z = -5/2$ series) and for neutron rich nuclei up to nitrogen ($^{23}N$).

III - PROPERTIES OF EXOTIC NUCLEI

In the interesting $N = 20$ region, several experiments have searched for $^{26}\alpha$, $^{29}F$ and $^{32}Ne$ but so far without success. This may reflect both the reaction mechanisms and the beam energy ceiling imposed by the 3.2Tm rigidity limit of LISE for such massive low Z 'exotics' rather than the nuclear structure. A mass measurement $^{29,30}Ne$ would be well worthwhile and would complement very recent /9/ work done elsewhere at lower energies on the $N = 20$ isotones $^{35}F$, $^{34}Si$ and $^{33}Al$ and the $N = 21$ nucleus $^{35}Si$.

For beta-decaying exotic nuclei produced at Fermi energies it is possible to determine their inertial mass by measurement of their velocity and momentum. The overall mass measurement accuracy required to test the predicted 'drip lines' is less than 0.5MeV, which is quite difficult to achieve for particles with about 1GeV kinetic energy. Despite this, some very elegant studies using the SPEG magnetic spectrometer at GANIL have recently emerged for nuclei very close to the
Fig. 1 Evidence for observation of the $T_z = -5/2$ series: $^{35}\text{Ca}$, $^{31}\text{Ar}$, $^{27}\text{S}$ and $^{23}\text{Si}$. (Langevin et al /4/, Nuclear Physics A (1986) to be published.)

Fig. 2 Evidence for stability of $^{22}\text{C}$ and $^{19}\text{B}$ against nucleon emission. (Pougheon et al /4/.)
limit of stability: $^{20}\text{N}$, $^{23}\text{O}$, $^{24},^{25}\text{F}$ so far (Bianchi et al to be published).

Mass determinations of proton rich exotics could be used to examine the $T=2$ isospin multiplets in light nuclei, but would be better constructed experimentally via decay energetics. Progress towards the equally difficult identification of analogues at $20\text{MeV}$ excitation in the valley itself has been achieved for the $A=23$ system /10/, and should prompt further efforts on the exotics.

Beta decay lifetimes and preferably level schemes would be most useful checks on nuclear structure because they give more direct tests on the wavefunctions and overlaps between initial and final states. This has recently been achieved by workers at MSU as reported at this conference for the lighter exotic nuclei $^{14}\text{Be}$ and $^{17}\text{B}$ /11/. Unfortunately 'exotic' level schemes will be only measurable for daughters of radioactive 'exotic' parent nuclei: the spectroscopy of the most accessible nuclei has recently been determined on LISE at GANIL using techniques (e.g. /12/) of enhanced isotope selection provided by energy degraders. Results will be reported to this conference for $^{40}\text{S}$, $^{37},^{38}\text{P}$, $^{35},^{36}\text{Si}$, $^{26}\text{Ne}$, $^{24}\text{F}$, $^{22}\text{O}$ and $^{17}\text{C}$ /13/.

Further work to get to the parent level schemes must rely on high flux secondary beams /14/ using inelastic scattering techniques or the application of gamma ray shrouds (e.g. the UK Daresbury Laboratory's POLYTESSA array /15/) in multiple coincidence with intermediate energy beamlines like LISE. Both these options are very hard experimental challenges as shown by some crude rate calculations.

IV - FUTURE OUTLOOK

As there is more interest in the levels of for example $^{22}\text{C}$ and $^{24}\text{O}$ than $^{22}\text{N}$ and $^{24}\text{F}$, because the tests of nuclear deformation are simpler to unravel for the even-even isotopes, there will be continued pressure to make these parents as efficiently as possible. This encourages us to take care that the excitation energy put into the primary nuclei at Fermi energies does not get so large that the detected residuals are rather less exotic than expected /8/.

The reward for careful preparations of our experimental exotics production line will be to chart deformations in the lightest nuclei. Calculations based on Hartree-Foch-Bogliubov theory have been made recently at Orsay /16/ for exotic neon and oxygen isotopes.

In contrast there are already published shell model predictions from the Utrecht group /17/ explicitly for 1-p shell exotics, and also the universal s-d shell interaction of Wildenthal can be applied for heavier systems.
Neutron number

Fig. 3 Touching nucleon drip lines in the light nuclei: parts of the Segre chart are shown following the recent GANIL experiments /4/.

Intense beams from ECR ion sources for gaseous and metallic elements can be exploited by choosing the accelerated isotope to optimise the rates of exotic species at the final detectors. The use of $N = Z$ beams rather than enriched isotopes may be warranted on cost grounds too, and especially for the production of proton-rich exotics. For $2p$ radioactivity searches, for example from $^{31}$Ar, a beam of $^{36}$Ar could be easier than the $^{40}$Ca used initially at GANIL.

The region of deformation around $N = 20$ has yet to yield up all its secrets. Information from exotic transfer reactions (Chapman et al, to be published, and Fifield et al, to be published) at lower energies is consistent with a good shell closure at $N = 20$ for groundstate nuclei with $Z = 14$ to 16. Thus until the lower $Z$s are probed at Fermi energies, which will be difficult as remaining isotopes to search for are $^{33}$Al and the $A/Z$ 3 nuclei $^{26,28}$O, $^{29}$F and $^{32}$Ne, the known region of deformation remains just $^{31}$Na and $^{32}$Mg in a sea of near-sphericity.

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