Charged particle studies with Radioactive Nuclear Beams at SPIRAL - a letter of intent

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1 Background

In this letter of intent we outline our plans for a series of charged particle studies at SPIRAL. These would involve the measurement of elastic scattering, transfer reactions and breakup reactions to obtain spectroscopic information on exotic nuclei, which will provide details of the single particle structure, deformation, and clustering aspects of exotic nuclei. The experiments will be carried out using a multiple detector array developed from a detector setup already in use for radioactive beam experiments at GANIL

The present understanding of the structure of nuclear matter is underpinned, to a large extent, by the extensive studies using charged particle spectroscopy techniques performed during the 1960's and 1970's. Transfer type reaction measurements can yield detailed information on not only the excitation energies and spins of states, but also the associated single-particle structure. For instance, spectroscopic factors and the spatial extents of wave-functions may be determined. Such measurements have provided a stringent test of the nuclear shell model, which forms the basis of our understanding of the single-particle nature of nuclei. The deformed shell model predicts that as the potential is deformed the ordering of the single-particle orbits changes giving rise to new shell structures, and hence the magic numbers associated with the spherical shell model disappear and are superceded by alternative magic numbers. This feature may be linked with the appearance of superdeformation in heavy nuclei and clustering in light nuclei.

Recent studies of the neutron rich nuclei in the vicinity of the neutron magic numbers N=8, N=20 and N=28, indicate that with increasing ratios of neutrons to protons, these neutron magic numbers cease to be important. For example, studies of Coulomb excitation of the nuclei ^{38,40,42}S indicate the presence of moderate deformation near N=28[1]. β-decay studies also confirm the existence of this new region of deformation near N=28 in S and P isotopes [2] and further suggest deformation in Na and Mg nuclei near the N=20 shell closure[3]. Recent Coulomb excitation measurements also confirm that the ^{32}Mg nucleus is deformed[4]. This indicates that in these regions that there is a quenching of the spherical shell closures and that higher single-particle orbits are contributing to the structure in these nuclei, e.g., in the case of N=20 orbits, from the f-p shell. In the case of the N=7 nuclei ^{11}Be and ^{13}C, where the spectroscopy is determined largely by the orbit of the last unpaired neutron there are unexpected differences. In the case of ^{13}C, the ground state has spin and parity $1/2^-$ and the 3.1 MeV first excited state is $1/2^+$ corresponding to ($0P_{1/2}$) and ($1S_{1/2}$) neutron occupancies respectively. For ^{11}Be the order is reversed with the ground state and 0.3 MeV excited state possessing spin and parity $1/2^+$ and $1/2^-$ respectively, indicating that the ordering of the single-particle orbits is changing with increasing neutron to proton ratios, with particular intruder orbits playing a key role.

Such behaviour can lead to new features of nuclei. The appearance of halo structures in the ground states of, for example, the nuclei ^{11}Be and ^{11}Li is closely linked to the importance of the ($1S_{1/2}$) intruder orbit. In order to understand not only the changing single-particle structure, but also the effects that result, detailed spectroscopic measurements are required. In the instance of halo states, fragmentation or breakup type reactions in which the halo nucleons are separated from the core may be used as a crude measurement of the spatial properties of the halo wave-function, via measurements of the momenta distributions of the breakup products. Also more generally, β-decay studies provide information on the single-particle occupancies of shell model orbits. Spectroscopic factors determined from transfer reactions provide complementary information on the single-particle structure of nuclei to that available from these two types of experimental studies.

Multinucleon transfer type reactions can also be used to probe nucleon-nucleon correlations, for example in the study of halos composed of more than one particle, or to probe highly clustered states. Recent calculations using the Antisymmeterised Molecular Dynamic model (AMD) [5] reveal that clustering may play an important role in the structure of light nuclei away from the N=Z region where clustering is intimately linked to the stability of the alpha particle and the symmetries which exist for equal numbers of protons and neutrons. In the instance of neutron rich nuclei these new cluster structures must be composed of exotic subunits, e.g. ^{6}He clusters, and as such may adopt new and unusual nuclear forms. As an example, it has been speculated [6, 7, 8] that structures composed of chains and rings of alpha particles "covalently" bonded by the valence nucleons (predominantly neutrons) might exist. The stability of cluster structures is intimately linked to the behaviour of the underlying single-particle structure, with the appearance of shell gaps providing the important stabilizing influence [9, 10]. Hence, the detailed understanding of the single-particle structure both as a function of the isospin and shape degrees of freedom, determined from transfer reactions, will have an important impact on the understanding of clustering in this new nuclear environment.

Breakup type reactions have recently been employed with great effect to study the role of clustering in stable nuclei[11]. There are particular advantages in such a technique, for example in reducing experimental backgrounds in the study of highly excited states, and the extraction of spin information, often in a model independent fashion. But more importantly, breakup measurements provide the possibility of measuring partial decay widths of states, which is crucial in the determination of the cluster content of the associated wave-function. The application of this technique to the study of the properties of both neutron and proton rich nuclei will provide spectroscopic information which complements that from singles transfer reaction measurements.

The advent of SPIRAL will present the opportunity for the extension of the experimental programme of transfer and breakup measurements which has been initiated using the fragmentation beams from GANIL. In this letter we outline a series of experiments which we wish to perform with the beams which will be available from SPIRAL (section 2). We also identify some beams which we would like to see developed, these include carbon, oxygen, silicon, phosphorus, scandium and potassium isotopes. The developments to the design of the detection system required to improve the sensitivity to reactions at SPIRAL energies are described in section 3.

2 Experiments

2.1 Transfer reactions

Studies of the spectroscopy of the nuclei near the neutron shell closure N=8 have already been initiated using the fragmentation beams from GANIL, and involve the study of the N=8 isotone chain ^{11}Li, ^{12}Be, ^{13}B, ^{14}C .... The initial beams from SPIRAL will be exploited to explore the structure and spectroscopy of nuclei close to the N=20 and N=28 neutron magic numbers.

One and two nucleon transfer reactions using the intense Ne beams as neutron rich as ^{26}Ne will permit the study of the spectroscopy of nuclei up to and including ^{27}Na and ^{28}Mg (N=16) using reactions such as (^{10}B,^{9}Be), (^{15}N,^{14}C) and (^{16}O,^{14}C). Also oxygen and fluorine isotopes can be studied up to ^{25}F and ^{24}O (N=16) using the (d,^{3}He), (^{12}C,^{13}N) and (^{12}C,^{14}O) reactions. The variety of possible of Ne beams and transfer reactions should permit a detailed picture of the role of the intruder single-particle orbits in this region and the onset of deformation towards N=20. The Ar beams provide the possibility of probing the region towards the neutron magic number N=28. Some of the most promising measurements are the study of ^{42}S and ^{43}Cl (N=26) using the ^{44}Ar beam in conjunction with the reactions (^{12}C,^{13}N) and (^{12}C,^{14}O) respectively, and ^{44}S and ^{45}Cl (N=28) using the ^{46}Ar beam. These studies will begin to provide a picture of the changing order of the single-particle energy levels as a function of the neutron to proton ratio, and thus an important test for shell model calculations. Furthermore, in order to model the transfer angular distributions it will be necessary to perform measurements of the elastic scattering yields for optical model analysis. These measurements and the energy level systematics from the transfer reactions may also reveal shape and deformation trends along the isotope and isotone chains. Deformation has also been predicted to exist near the nucleus ^{52}Ca[12], the development of neutron rich scandium and phosphorus beams would permit this region to be studied.

The ability of transfer reactions to identify the fractions of various possible single-particle configurations associated with the wave-functions of ground and excited states of nuclei may be exploited to study the structure of candidate halo nuclei. For example, it has been speculated that ^{17}Ne might be a 2 proton halo nucleus (S_{2p}=0.96 MeV) if the last two protons have a significant 1s component in their wave-function. A measurement of the ^{17}Ne(d,^{3}He)^{16}F reaction can probe the parentage of proton s- and d-wave states in the ^{17}Ne ground state. Indeed, a systematic study of the contribution of the $1s_{1/2}$ proton orbit to the ground state wave-functions of nuclei in this proton rich region would also provide an indication for the possibility of the formation of other proton halo states. Also, the development of silicon and phosphorus beams would permit studies of proton halo candidates in the phosphorus isotopes [13].

All of these measurements will be performed using inverse type kinematics, with the detection of either the ejectile or the recoil-like particles to reconstruct the reaction kinematics and Q-values. For the light targets the recoils are scattered over a wide laboratory angular range and hence a large area detection system is required, with the ability of detecting low energy particles and measuring their scattering angles. A large area array of gas-silicon-scintillator telescopes is being constructed for this purpose (section 3). This array will be used in conjunction with the SPEG spectrometer, which will detect the heavy ejectiles which are predominantly emitted into a cone, centred on the beam direction with opening angle of a few degrees. The two detection systems provide complementary angular coverage, as for very forward centre of mass scattering angles the recoil particles can be too low in energy to be detected with the telescopes, and for larger scattering angles the ejectiles lie outside the SPEG acceptance. The combination of SPEG with the charged particle array also permits coincidence detection of the ejectile and recoil a technique which may be used to remove background contributions from projectile breakup type reactions. The SPEG spectrometer also compensates for the beam energy spread.

Further, for reactions involving targets of similar mass to the beam, the array will allow the coincident detection of the recoils and ejectiles without the use of additional spectrometers. The coincidence technique has the added advantage that the resolution with which the reaction Q-values can be reconstructed can be improved. The over determination of the reaction kinematics allows, to a first order, the effects of the intrinsic energy resolution of the beam and its energy straggling in the target to be removed from the reconstructed Q-value spectrum and hence improving the quality of the measurements. This technique could be an important development, especially with the use of weak beams, where thick targets will be required to enhance the reaction yields. This type of measurement will require a detection system with a wide dynamic range in energy and particle types, with the ability to measure angles and provide particle identification. Such an array is described in section 3. The array will also require a dedicated target chamber.

The lower energy beams from SPIRAL, as opposed to the high energy beams produced from the fragmentation process will result in a decrease of the linear momentum transfer, and hence the reaction cross sections being pushed out to large centre of mass angles. This has the advantage that the experimental angular resolution which is required is reduced, and hence the quality of the measurements which are possible is improved.

It has been estimated [14] that for a study of the $^{12}\mathrm{Be(p,d)}$ reaction, useful spectroscopic information can be determined with a target thickness of 3 mgcm^{-2} (limited by energy and angular straggling) and a ^{12}Be beam intensity of 2×10^4 pps, assuming a transfer cross section of 2 mb/sr. Correspondingly, the experiments outlined above should also produce useful results with the predicted SPIRAL intensities.

2.2 Breakup reactions

Breakup reactions may also be used to deduce much about the structure of nuclear states. For instance, the reconstruction of the invariant mass of the decaying system, following the coincidence detection of the decay products, may be used to deduce the excitation energy of the decaying states. Importantly, the resolution with which the excitation energy may be reconstructed is, to a large extent, independent of the beam properties such as energy resolution, spot size and divergence. Hence, under favourable circumstances the widths of states may be measured. Furthermore, by measuring the excitation probability in the reaction process the partial decay widths of the states may also be determined, providing key information on the components of the wave-function describing the state, and hence their cluster nature. Studies of the angular correlations of the breakup products can also yield information on the spins of the states, and if all the initial and final state particles are in spin zero states, then a model independent analysis may be performed.

These type of measurements are not only useful from the perspective of cluster studies, but provide a powerful technique for the characterisation of the spectroscopy of excited states, above particle decay thresholds. For example, it is proposed to study the breakup reactions $^{17}\mathrm{Ne} \rightarrow ^{15}\mathrm{O} + 2\mathrm{p}$ and $^{18}\mathrm{Ne} \rightarrow ^{16}\mathrm{O} + 2\mathrm{p}$. The detection of the three decay products, or the two protons and the target recoil would permit a full reconstruction of the reaction kinematics, and hence the relative angular momentum of the two protons and their angular momentum with respect to the core, and thus information on the 2p decay processes and the proton single-particle orbits in these nuclei.

From the perspective of nuclear clustering ^{20}Ne has been described as the archetypical cluster nucleus. The ^{20}Ne nucleus possesses states which have a strong association with both the $^{16}O+\alpha$ and $^{12}C+^{8}Be$ cluster structures. The dominance of these cluster components is in part a reflection of their stability and the underlying single-particle structure. For example, the ground state of ^{20}Ne is prolate deformed and corresponds to a shell gap at N=Z=10 in the energy level scheme of the deformed shell model. Interestingly, this deformed magic number can be decomposed into two spherical magic numbers, 10=8+2, which in turn may be associated with the spherical nuclei $^{16}O+\alpha$. This feature can be related to particular SU(3) symmetries possessed by the deformed shell model[15], and much of the cluster behaviour of light N=Z nuclei can be understood on this basis.

The removal of neutrons to form, for example, ^{18}Ne might be expected to thus diminish the cluster components in the wave-function. However, the reordering of the single-particle orbits as a function of the neutron to proton ratio may enhance different cluster components. The AMD calculations, which are based upon a nuclear system described by a Slater determinant of single-nucleon Gaussian wave packets, indicates that in many instances cluster structures indeed exist at disproportionate ratios of neutrons and protons. An investigation into this region would provide a new insight into the nature of the processes which result in the formation of clusters.

Studies of ^{18}Ne states decaying into $^{14}O+\alpha$ (Q_{bu}=-5.1 MeV), $^{16}O+2p$ (Q_{bu}=+10.1 MeV) and $^{17}F+p$ (Q_{bu}=-3.92 MeV) using breakup reactions, would provide new structural and spectroscopic information on excited states in the region $5 < E_x < 10$ MeV. In particular, if the stability of the ^{4}He or ^{16}O nuclei have a continuing influence on the cluster structure in this nucleus. The $^{14}O(\alpha,p)^{17}F$ reaction is also important in the hot CNO cycle[16], and hence the breakup measurement would also provide further information as to the contribution of ^{18}Ne resonant states to the reaction process.

The predicted existence of exotic cluster structures composed of chains of α-particles linked, or bound together by neutrons is an extremely exciting possibility. There is presently some evidence for such structures in the nuclei ^{9}Be and ^{10}Be, and an extension to heavier systems and longer chains would be interesting. Possible chain structures in the Ne isotopes lie too far from the valley of stability to be available for study (^{28}Ne and ^{30}Ne). However, in lighter elements this is not the case, and such structures might appear in the nuclei ^{12}Be, ^{16}C, ^{18}C and ^{22}O. A study of the spectroscopy of ^{12}Be has been initiated in a search for helium cluster states using the GANIL fragmentation beams, and the development of intense beams of carbon and oxygen isotopes would permit an extension of these studies to longer chains. These beams would also allow a systematic study of the evolution of clustering in an environment in which the single-particle contributions are also evolving.

Previous breakup studies [17] indicate that in order to perform statistically significant measurements that thick targets (10 $mgcm^{-2}$) and beam intensities of $> 10^5$ pps are required. Thus, the above measurements should also be within the limits of experimental possibility with the proposed SPIRAL intensities. With higher beam intensities thinner targets can be used in order to reduce the effects of angular straggling of the beam and reaction products in the target, and thus improving the experimental resolutions. This becomes increasingly important as measurements of breakup to heavier products are considered.

3 Detector array

In order to perform many of the measurements outlined in the preceding sections an extremely versatile detection system is required, with a wide dynamic range in particle types and energies. The array should also be able to accommodate both the transfer and breakup measurements without compromise to either. The detection system which is employed in the present transfer and breakup measurements is an array of 10 silicon-scintillator telescopes. The silicon elements of these telescopes are 5×5 cm^2 two dimensional position sensitive detectors, and the scintillators are 5.5 cm deep CsI crystals. The geometrical arrangement of the detectors can be selected for each individual experiment. The array presents a very large solid angle coverage ($\sim$1 sr) and can provide detection efficiencies, for example, of 40 to 50% for breakup measurements. The detector telescopes record the energy, emission angle, charge and in some instances mass of each incident particle, permitting detailed reconstruction of the reaction kinematics.

For the lower energy beams which will be produced by SPIRAL it will be necessary to augment the existing telescopes with a gas element, resulting in three element telescopes. This will permit the detection of light and heavy ions, with a wide range of energies, within the same detector telescope, thus maximizing the effectiveness of the array. These new hybrid detectors will be based upon the detectors constructed for the MEGHA array presently sited at ANU in Canberra.

For events in which the reaction products are spatially correlated, e.g. as in the case of the proposed $^{17}Ne \rightarrow ^{15}O + 2p$ and $^{18}Ne \rightarrow ^{16}O + 2p$ decay studies it is possible to replace the silicon elements in the hybrid telescopes with 16-strip, silicon strip detectors. This will then allow multiple particles to be detected within the volume of a single hybridised detector. The gas-silicon-scintillator array is presently under design and will be constructed so as to provide a flexible geometry for use in a number of types of different experiments and in conjunction with many of the GANIL spectrometers. As discussed in section 2.1, we propose to construct a dedicated target chamber in which to house the gas-silicon-scintillator

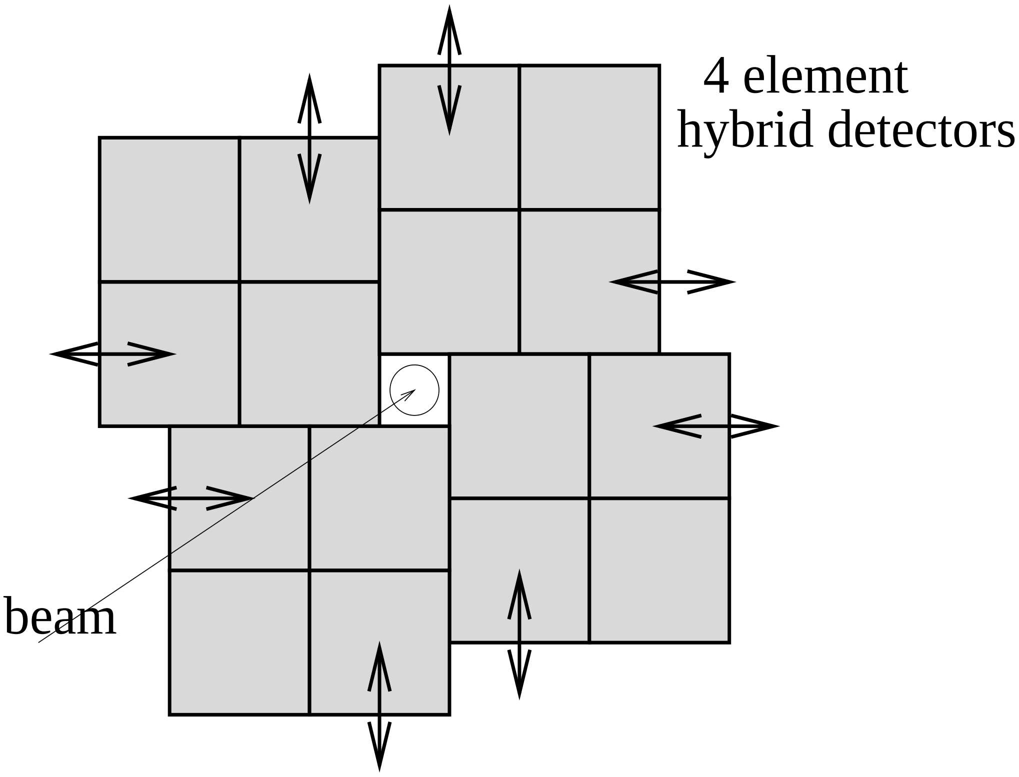

Figure 1: A proposed detector configuration for the hybrid telescopes. Each of the four hybrid detectors contains 4 telescopes. The telescopes are comprised of gas, silicon and scintillator elements. The mounting of the detectors is designed to give an adjustable geometry around the beam spot.

hybrid detector array. This will allow the “coincidence transfer” and breakup measurements to be performed without the use of spectrometers. This new target chamber would thus need to be sited at the end of a dedicated beam line. We would like to raise the possibility for finding such a site for the target chamber and array within one of the experimental halls.

Figure 1 shows a schematic drawing of the anticipated configuration of the new array. We already have experience of operating such a hybrid telescope which provides the energy and position resolution required, as well as the range of particle identification and dynamic energy range necessary for the proposed measurements

The electronic processing of the detector signals will be performed by dedicated electronics. Preamplifiers and amplifiers have been custom built to match the particular requirements of the hybrid detectors, and these will be coupled to a dedicated 256 channel data acquisition system, recording time and energy information for each channel.

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