Physics of N~Z Nuclei with Fast Beams at RISING

Letter-of-intent for Rising fast beam campaign at GSI

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This paper documents some of the possible physics programmes relating to N~Z systems that might be addressed through use of fast fragmentation beams at GSI coupled to the proposed Rising gamma-ray spectrometer. The proposal focuses on the techniques of Coulomb excitation and secondary fragmentation, and falls into three broad categories as follows.

1. Coulomb excitation of semi-magic nuclei near ^{100}Sn

The B(E2;$2^+\rightarrow0^+$) values in semi-magic nuclei provide a sensitive test for changing (sub)shell structure, E2 polarisability, and shape response of the magic core. Their measurement in unstable nuclei by standard Doppler methods is often hampered by the existence of higher lying isomeric states, whereas due to the high transition energies electronic lifetime measurements are beyond the possibility of present techniques. Therefore, Coulomb excitation is the only way to obtain the structure information needed to investigate the evolution of shell structure. Also the single-particle structures of low-spin states, key ingredients to any nuclear mean-field model, are difficult, if not impossible, to reach by means of other well established reaction mechanisms and techniques.

We propose therefore to investigate nuclei near ^{100}Sn, produced by means of projectile fragmentation at relativistic energies. The primary aim is to Coulomb excite the reaction products on a secondary target, either from their ground states or from isomeric states. The reaction products will be traced from the primary target to the secondary target placed at the focal plane S4 of the Fragment Mass Separator, FRS. The scattered reaction products will be detected and the gamma rays following the Coulomb excitation process will be measured in the Rising composite Ge detectors.

The nuclei of interest are the tin isotopes ^{102}Sn, ^{103}Sn, ^{104}Sn, ^{106}Sn, ^{108}Sn and ^{110}Sn and the N=50 nuclei ^{94}Ru, ^{96}Pd and ^{98}Cd. These nuclei will be created in projectile fragmentation of ^{112}Sn. The production cross sections have been estimated using the EPAX code. They suggest that all nuclei, except ^{102}Sn, are within reach. The gamma-ray rates following relativistic Coulomb excitation of the first excited states are estimated, in for example ^{108}Sn, to be 750 gamma rays per minute, and in ^{98}Cd, the most difficult case, to be 0.1 gamma rays per minute, i.e., of the order of 100 gamma rays per day.

Recently, the splitting of the $\nu d_{5/2}$ and $\nu g_{7/2}$ single-particle levels has been deduced from excited states in ^{103}Sn. The single-particle levels of the low-spin $\nu s_{1/2}$ and $\nu d_{3/2}$ orbits, however, are basically unknown. We propose to excite them in Coulomb excitation of ^{103}Sn. The B(E2;$2^+\rightarrow0^+$) values will be measured in the even Sn isotopes. This value is known experimentally in ^{112}Sn, which thus can be used for calibration. The nuclei ^{94}Ru, ^{96}Pd and ^{98}Cd all have μs isomeric 8^+ states. Here we will Coulomb excite either the 2^+ state from the ground state or the 10^+ state from the isomeric 8^+ state, or both, depending on the isomeric ratio, and it will be possible to measure both the B(E2;$2^+\rightarrow0^+$) and B(E2;$10^+\rightarrow8^+$) values. Another consistency check is provided by the known B(E2;$2^+\rightarrow0^+$) value in ^{92}Mo. These B(E2) values are sensitive to the E2 core excitation in ^{100}Sn.

2. Isobaric analogue states in light proton-rich nuclei.

The investigation and understanding of fundamental symmetries is one of the principal goals of nuclear structure physics. One of the most basic of these is neutron-proton exchange symmetry which can be studied through detailed spectroscopy of isobaric analogue states. The excitation energies of the excited isobaric analogue states will show slight differences associated with the subtle influence on the Coulomb force of the changing nucleon orbitals which contribute to the wave functions of the excited states – Coulomb energy differences (CED). The study of this phenomenon, whilst in its infancy, has shown some remarkable results and the investigation of the CED has been proved to be a highly sensitive probe of changes in structure as a function of spin and excitation energy.

To date, studies of this kind have been restricted, due to low production cross-sections, to the lowest possible values of isospin (i.e. close to N=Z). Recently, advances in experimental techniques have allowed T=1/2 mirror-pairs to be studied up to the highest accessible spins in the $f_{7/2}$ shell. In addition, high spin structures in N=Z-2 nuclei in this shell have recently been identified, allowing full comparison of analogue states at high spin in T=1 isobaric triplets. The CED between these analogue states has been measured, and the trends of the CED as a function of spin and energy have been understood *quantitatively* and in detail in terms of specific nuclear structure effects. These include rotational alignments of specific nucleon pairs, non-collective multi-particle alignments at high spin, changes in deformation and the effect of the coriolis force on specific nucleon orbitals. These results have been compared with predictions of the latest large-scale *pf*-shell model calculations, which can calculate the CED directly. This yields a *uniquely* stringent test of the model on a state-by-state basis, and has resulted in new refinements to the model.

Population of the proton-rich members of these multiplets is hampered by very low cross-sections when using fusion evaporation techniques and, as a result, the T=1 systems mentioned above represent the current limit (in isospin) for detailed spectroscopy of isobaric analogue states. Very little is known about high spin isobaric analogue states of larger isospin, e.g. T=3/2 quadruplets. It is clearly important to apply the experience gained in analysis of Coulomb energies to larger isospin multiplets, and such systems may be accessible through fragmentation techniques. Detailed spectroscopy of mirror states where the difference in T_z is ≥ 3 has never been undertaken. Indeed, the degree to which isospin symmetry holds as the proton drip-line is approached (with the concomitant increase in the effect of the Coulomb potential) is completely unknown. Examples of nuclei that might be accessible via fragmentation include ^{49}Fe and ^{45}Cr – the proton rich members of the A=49 and A=45 T=3/2 quadruplets. For example, nothing is known about the excited structures of ^{45}Cr, whilst the mirror nucleus ^{45}Sc has been extensively studied. Lying away from the mid-shell deformed region, ^{45}Sc has a non-collective yrast structure, but which coexists with a positive parity deformed rotational structure built on the excitation of a $d_{3/2}$ proton. The band head for this structure lies very low, at an excitation energy of 13keV. We would seek to identify the mirror structures in ^{45}Cr to address the points raised above.

Study of the prompt gamma-rays emitted in the fragmentation of ^{58}Ni directly to ^{45}Cr is not possible due the large atomic background from the fragmentation target. Additionally, due to the small cross-section the contribution to the background from the competing channels would be too great. However, these difficulties can be circumvented using secondary fragmentation. Nuclei close to ^{45}Cr are produced through the fragmentation of the primary ^{58}Ni beam, and selected using the FRS. These primary fragments are then used to cause a second fragmentation reaction in cave C, with the Rising array used to detect the prompts gammas from the secondary fragmentation. The final (secondary) fragment is then identified in cave C downstream of the second target. With a primary beam intensity of 3×10^8 ^{58}Ni particles per second, a rate of 25 ^{46}Cr nuclei per second is predicted in cave C (assuming EPAX cross-sections, 4gcm^{-2} Be target, a 20% FRS efficiency and 10% transmission to cave C). This would yield around 0.025 ^{45}Cr nuclei per second via a second fragmentation event. Assuming 5 prompt gamma-rays emitted per event, this corresponds to around 2000 gamma rays in a "singles" spectrum in a 7-day run. Of course, the final nucleus can be produced by a number of secondary fragmentation reactions, and if one assumes that a range of ±1 in N and Z of the primary fragment can be transmitted to cave C, then this number increases to around 6000 gamma-rays. With clean final selection, this would be sufficient to identify the main structures in the level scheme of ^{45}Cr. As the mirror nucleus is well known, mirror symmetry arguments can be used to gain information on the level scheme based on a clean singles spectrum alone. Of course, these numbers are at the limit of feasibility and there are, at present, many uncertainties in the parameters that affect the final production rate of the nucleus of interest. However, for lighter exotic systems (such as the N=Z-3 nucleus ^{25}Si) produced using an N=Z primary beam such as ^{40}Ca, the production rates would be typically 100 times larger, and many of the above physics questions can be addressed successfully.

In addition, it is proposed to use relativistic Coulomb excitation (see sections 1 and 3) to study mirror symmetry in ^{54}Ni, the mirror partner to ^{54}Fe, and in ^{36}Ca, the mirror partner to ^{36}S. The ^{54}Ni and ^{36}Ca nuclei will be produced in projectile fragmentation of ^{58}Ni and ^{40}Ca, respectively. The ^{36}S nucleus, for example, has magic features, i.e., a large 2^+ energy and a small $B(E2;2^+\rightarrow0^+)$ value. The aim is to measure these values in ^{54}Ni and

^{36}Ca. Does, for example, the magicity remain in ^{36}Ca? These studies will give information on the isovector part of the mean field.

3. Coulomb excitation of N=Z nuclei in the A=70-80 region.

One of the most active areas of current research in nuclear physics centres on the structure of heavier nuclei with roughly equal numbers of neutrons and protons and, specifically, nuclei in the $pfg_{9/2}$ shell with $20 \le N{\sim}Z \le 50$. Above this, the N=Z nuclei rapidly become unbound by virtue of the large excess of protons relative to stable nuclei. Experiments to elucidate the structure of the $20 \le N{\sim}Z \le 50$ nuclei come up against the limits of current experimental sensitivity and represent a notable challenge for the new generation of radioactive beam facilities. The combination of two features renders these nuclei of special interest: they have neutrons and protons in the same valence shell and the 28-50 shell is large enough for the nuclei to exhibit all aspects of nuclear collective behaviour. These characteristics imply that the role of the neutron-proton exchange symmetry should be taken into account in describing the collective structure in this region, and particularly for N=Z nuclei. We also now know that deformed shell gaps play a vital role in stabilising nuclear shapes at particular values of Z, N and angular momentum. When these shell gaps are approached, one observes sudden abrupt changes in nuclear shape due to the polarising influence of high angular momentum nuclear orbits. The special nature of N=Z nuclei means that these effects are particularly dramatic and gives their study particular significance in developing and testing models which predict equilibrium nuclear shapes. This is because the neutrons and protons are filling the same orbits which exaggerates the collectivity induced by the neutron-proton interaction because of the coincident shell structure and the consequently enhanced neutron-proton overlap. In this situation, small changes in the Fermi surface resulting from the addition or removal of one or a few nucleons can lead to very rapid changes in the ground state nuclear shape.

It is predicted that as one progresses along the N=Z line from 28 to 50 the nuclei change from spherical to triaxial, then through oblate shapes to extremely prolate at mid-shell before returning through triaxial to spherical at ^{100}Sn. In recent years it has been possible to populate the even-even N=Z nuclei of medium mass from ^{64}Ge to ^{84}Mo. However, these experiments are at the limits of experimental sensitivity, and the amount of information that can be obtained decreases steadily with mass, such that, for ^{84}Mo, only the first excited (2^+) state is known. Moreover, no experimental measurements of electromagnetic transition probabilities have been made above A=60. Thus comparisons with theoretical predictions have, of necessity, been based on approximate semi-empirical relationships between 2^+ energies and deformation.

Recent experiments at GSI and GANIL have shown that N=Z nuclei are particle-bound up to ^{100}Sn. After this, the N=Z line crosses the proton drip line in the neighbourhood of the Ba and Ce isotopes but, as explained above, the current limit of any detailed spectroscopic study with stable beams lies at ^{64}Ge. This stems from the fact that, with low energy stable beams, the 2n channel of the fusion evaporation reaction has so far been used to reach the heavier even-even nuclei on the N=Z line in this region. As a result, the cross sections decrease rapidly with increasing mass, ranging from around 600 μb for ^{64}Ge down to ≤10 μb for ^{84}Mo, which is the heaviest N=Z nucleus yet reached in spectroscopic studies. As will be shown below, it seems likely that the technique of relativistic Coulomb excitation (RCE) with radioactive beams produced by projectile fragmentation reactions should in fact offer a more promising way of studying these nuclei. Moreover, it will provide, for the first time, a direct measurement of the size of the quadrupole matrix elements in these nuclei. It is proposed, therefore, to investigate the structure of the N=Z nuclei in the mass 50-80 region. We intend to measure the $B(E2;0^+_{g.s.} \rightarrow 2^+_1)$ values for these nuclei in order to study the ground state shape evolution with increasing N=Z. We also hope to populate higher lying structure in some of these nuclei. To what extent this is possible will, of course, depend on the structure itself and, in particular, the E2 strength connecting it to the ground state. Initially, the heaviest N=Z nucleus we intend to investigate is ^{72}Kr, and this is used as the example quoted below.

The ^{72}Kr ions will be produced following the projectile fragmentation of a ^{78}Kr or ^{92}Mo primary beam. The secondary beam will be selected using the FRS separator and will be incident on the Coulomb excitation target. The gamma rays following the Coulomb excitation will be measured using the RISING array. The beam will be accurately tracked onto and off of the Coulomb excitation target, with the secondary ions of interest identified before and after the interaction in the target. These measurements will allow some Doppler corrections to be made and will allow discrimination between Coulomb excitations of the projectile and nuclear excitations.

In February 2000, an experiment was performed at GSI to Coulomb excite nuclei in the N=Z region and measure their B(E2) values. This experiment has demonstrated what is necessary to perform such experiments in the future, and the rate estimates are based on this experience. ^{72}Kr was produced by a primary beam of ^{92}Mo at 500 MeV/nucleon. The primary beam intensity from SIS was, on average, 1×10^7 pps which gave a yield of ^{72}Kr of 1 pps at the excitation target. This resulted in approximately 1 gamma ray per day from the $2^+\rightarrow0^+$ transition of interest. Clearly this count rate was insufficient to measure the B(E2) value. For a statistical accuracy of 10% and assuming a running period of 2 days for each ion of interest, we require a count rate of ~ 2 gamma rays from the transition of interest per hour. To achieve this rate given an efficiency of RISING of 2.5%, a target thickness of 150 mg/cm^2 and a Coulomb excitation cross section of 100 mb, requires 500 pps of ^{72}Kr incident on the target. This can be achieved with a primary beam intensity of 5×10^9 pps.