EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the
ISOLDE and Neutron Time-of-Flight Experiments Committee
for experiments with HIE-ISOLDE

Single-Particle Evolution and Test of Shell Models

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Abstract

Experiments are proposed that makes use of the unique beams available at ISOLDE accelerated to the appropriate energies by the HIE-LINAC to investigate the evolution of single-particle states and make tests of large-scale shell model calculations using transfer reactions.

1. Introduction

One of the major motivations for studying exotic nuclei is the expectation that macroscopic alterations induced by weak binding will affect the microscopic structure of the atomic nucleus. Motivated by these expectations at the extremes, recent advances have revealed a quite surprising evolution in single-particle structure, even in near-stable and moderately neutron- or proton-rich systems where the effects due to weak binding are unlikely to be significant. In lighter nuclei changes have been observed that are sufficient to destroy magic numbers observed near stability. Drifts in single-particle states can open up new gaps in the single-particle spectra and create regions with associated relative stability. Similar trends in single-particle states have been observed in near-stable heavy nuclei, suggesting a ubiquitous phenomenon. Such changes have begun to be interpreted as arising from the effects of the tensor interaction between protons and neutrons [1]. The gradual filling of particular orbits with one type of nucleon has an increasing interaction with orbitals containing the other type, driving an evolution in single-particle states with nucleon number. The consequences of an evolving microscopic structure go beyond the quantum levels: single-particle structure influences other nuclear properties such as nuclear shapes and the modes of collective behaviour that are energetically favourable to the system.

2. Physics case

(i) Trends in the evolution of single-particle states

There are several regions of the nuclear landscape where important information is emerging concerning the nature of the interaction driving single-particle evolution. One of these is the region with *N=83*, where neutron-adding reactions on stable targets have been used to investigate the trends in high-*j* single-particle strengths [2]. There is fragmentation of $i_{13/2}$ and $h_{9/2}$ states due to coupling with vibrational excitations of the core, so measured spectroscopic factors are essential to disentangle the trends in single-particle energies as a function of proton number from the effect of this coupling. The separation of the resulting centroid energies of these single-neutron states monotonically decreases with increasing proton number, a variation that appears to be consistent with the effects of the tensor interaction between the neutrons in the $i_{13/2}$ and $h_{9/2}$ states and protons filling mainly the $g_{7/2}$ orbital with increasing *Z*. Away from stability, at even higher proton numbers, the proton Fermi surface should move from $g_{7/2}$ into $h_{11/2}$, with the expectation that the sense of the tensor interaction reverses, causing the difference in energy of the $i_{13/2}$ and $h_{9/2}$ neutron states to increase (see Fig.1). Indeed, the energies of the lowest $13/2^+$ and $9/2^-$ states do suggest such a turnaround, but there is no information on the spectroscopic factors away from stability. Such information is essential; it is expected that the coupling to octupole vibrations will be highest at Z=64, exactly where the trend reverses, so the energies of the lowest states are likely to be a poor indicator of the single-particle energies.

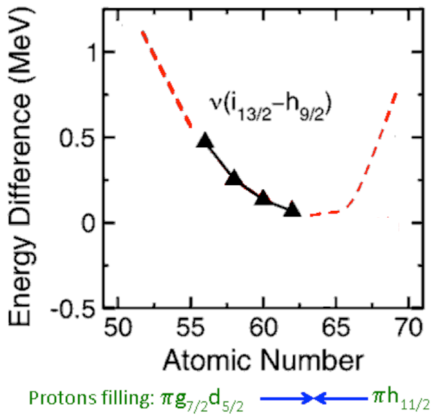

Figure 1: The measured energy difference between the centroids of neutron $i_{13/2}$ and $h_{9/2}$ strength as a function of proton number. The trend is expected to reverse after Z=64 once the proton $h_{11/2}$ orbital begins to fill, indicated schematically red dashed lines.

In order to resolve these issues, measurements are needed of spectroscopic factors with beams such as ^{146}Gd and heavier N=82 species, which are unique to ISOLDE. These are currently available with high yield, but the low energies at REX-ISOLDE make transfer measurements unviable as cross sections are very small. Such studies could begin using (d,p) reactions, but the improved matching for high *l* transfer in (α,^{3}He) studies would be an advantage. At 5 MeV/u there is sufficient yield for experiments to be done, but for states with known spins since at this energy the angular distributions are not sufficiently discriminating to make firm spin assignments. With increasing energy, diffraction-like patterns develop that can be used to assign *l* transfers at forward angles in the centre of mass. Increasing yield, and the development of distinct angular distributions, as the beam energy is increased from sub-barrier to tens of MeV/u are common features for many such direct reactions. But there are also more subtle improvements: the influence of non-direct reaction processes tends to decrease with beam energy, which leads to more robust extraction of spectroscopic factors at higher beam energies.

The availability of heavy radioactive beams at ISOLDE also provides a unique possibility to study the evolution of single-neutron states away from ^{208}Pb using neutron transfer on beams of ^{206}Hg, (^{210}Po), ^{212}Rn and ^{214}Ra. Single-particle states outside the ^{208}Pb core have been well studied, but experimental investigations elsewhere are restricted to some studies of direct reactions on a radioactive target of ^{210}Po. There are several high-*j* states in the shell above *N=126* that would be of particular interest, and nucleon addition and removal reactions could establish trends of single-particle states in *N=125* and *127* nuclei.

(ii) Shell gaps in neutron-rich systems

Calcium isotopes lie at the beginning of the *fp* shell where several novel shell closures have been observed and predicted. For example, a strong *N=32* sub-shell gap was first proposed to explain the surprisingly large excitation energy of the first 2^+ state in ^{52}Ca compared to the corresponding state in ^{50}Ca (see discussion in [3] and references therein). This shell effect gradually dies in higher *Z* nuclei;

the neutron $f_{5/2}$ is pushed down by interactions with increasing numbers of $f_{7/2}$ protons closing the gap at $N=32$. Full *fp* shell-model calculations have become possible over the past decade and new effective interactions have been developed that are able to accurately reproduce the $N=32$ gap in Ca, Ti and Cr isotopes [4]. In calcium isotopes, there are indications of a large separation between neutron $f_{5/2}$ and $p_{1/2}$ levels producing a sizeable $N=34$ gap. But this gap is somewhat controversial, arising with some effective interactions but not others due to different predicted single-particle evolution beyond ^{48}Ca, despite similar predictions for less exotic species. Discrimination between predictions would clearly benefit from a measurement of the energy of the first 2^+ state in ^{54}Ca, but such experiments are currently virtually impossible. However, measurements of the centroid of $f_{5/2}$ and $p_{1/2}$ single-particle strength would be a direct way of looking for the shifts predicted by the shell-model calculations, and give early indication of the validity of the predictions of the $N=34$ gap. Quantitative measurements of spectroscopic factors using transfer reactions are necessary as measurements of level energies and spins alone are not sufficiently discriminating. For example, an unambiguous statement concerning the presence of the $N=34$ gap in ^{54}Ca has been difficult to reach from studies of γ rays from states in ^{52}Ca populated using deep-inelastic collisions [3, 5].
There is potential for using two-nucleon transfer reactions in this region. The use of the (t,p) reaction would elucidate the development of neutron-pair correlations in these neutron-rich calcium isotopes. Moreover, with specific beam development, it may become possible to consider two-nucleon transfer reactions on ^{52}Ca. Although this increases the spectroscopic reach by only two neutrons, it could lead to direct spectroscopy of ^{54}Ca, allowing the existence of the $N=34$ gap to be tested directly by a measurement of the energy of the first-excited state via (t,p).

3. Experimental setup

Experiments could be performed with the existing T-Rex and Miniball system, but could also take advantage of a new spectrometer, should one become available in the future.

4. Beam requirements

In general, the minimum useful beam intensity is ~10^4 pps on target for an experiment of the order of 7-10 days. Some measurements can be done at 5.5 MeV/u, mainly Ca(d,p), but 10 MeV/u is preferable for heavy beams. Beam purity will be important. Note that the majority of the beam species are not available at other facilities.
Beams of interest: (i) Beams with $N=82$: ^{146}Gd, ^{148}Dy, ^{150}Er. Beams with $N=126$: ^{206}Hg, ^{212}Rn, and ^{214}Ra. The previously measured SC/PSB yields suggest that current intensities more than sufficient. Some investigation might be needed into beam purity. For higher Z beams, energies approaching 10 MeV/u will be needed to maximize yield, but some spectroscopy might be possible at lower energies. Beams of ^{210}Po are potentially interesting, but the long half-life may present issues. Other $N=126$ beams would be useful, but may require further development.
(ii)$^{49-51}$Ca previous yields suggest experiments are possible, although improvements in intensity would be advantageous. The current yield of ^{52}Ca is probably not useable, but would be a particularly interesting beam to develop. Beam purity is an issue, but developments of laser ionization and high work-function ion-source linings could improve the situation.
Quoted beam emittance for HIE-LINAC is sufficient.

5. Safety aspects

These experiments should not present any health and safety issues additional to the ones currently experienced in the ISOLDE Hall. Previous experiments have demonstrated the safe use of tritiated targets at ISOLDE (IS470). The long half-life of ^{210}Po may prohibit its use.

6. References

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