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

Spectroscopy of neutron-rich Ni, Cu and Zn isotopes near ^{68}Ni and ^{78}Ni using transfer reactions in inverse kinematics

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Abstract

This Letter sets forth the intent to study single-particle properties in neutron-rich Ni, Cu and Zn isotopes near N=40 and N=50. These nuclei will be investigated by performing single- and two-nucleon transfer reactions in inverse kinematics, using some of the most neutron-rich beams made available by HIE-ISOLDE. These measurements will yield spectroscopic knowledge on low-lying states in the key nuclei ^{68}Ni and ^{78}Ni, and will lead to a more accurate determination of proton and neutron single-particle strengths as a function of the filling of the $g_{9/2}$ neutron orbital.

1. Introduction

One of the most important avenues of research permitted by radioactive ion beams is the study of the considerable reorganization of nuclear shell structure occurring away from the line of beta stability (cf. [Sorlin08] and references therein). For bound nuclei, a significant step forward in the description of the evolution of shells was taken with the inclusion of the monopole component of the tensor interaction in the effective Hamiltonian [Otsuka05]. Recently, an additional central component was added to the interaction, which seems to yield better agreement with experimental data [Otsuka10], and which differs, among other things, in the prediction of empirical single particle energies (SPEs) of bound neutron and proton states. SPEs offer, in fact, a privileged viewpoint to discriminate between distinct theoretical pictures, thanks to their marked sensitivity to the properties and interplay of the various components of the nucleon-nucleon interaction. Hence measured values of SPEs are critically important to understand and to accurately describe shell evolution. The aim of this Letter of intent is to exploit the unique possibilities offered by the HIE-ISOLDE project to investigate, by means of transfer reactions, the properties of low-lying states in neutron-rich isotopes near and including ^{68}Ni and ^{78}Ni, key nuclei situated at the harmonic oscillator shell closure N=40 and the shell closure N=50.

2. Physics case

Nuclei neighbouring the isotopic Ni chain between ^{68}Ni and ^{78}Ni are of great interest since they permit the study of the effects of the filling of the neutron $g_{9/2}$ orbital on the Z=28 shell gap. For instance, there is controversial evidence on the nature of the N=40 harmonic-oscillator sub-shell closure in ^{68}Ni [Diriken10], leading to conflicting descriptions of this nucleus and its neighbours: the neighbours of ^{68}Ni can be described as proton/neutron particles and holes coupled to a rigid core, while Coulomb excitation and decay measurements around ^{68}Ni point out the importance of neutron pair scattering across N=40 and proton excitation across Z=28. The extent of the persistence or erosion of the Z=28 and the N=40 and N=50 shell gaps bear furthermore very relevant consequences for the astrophysical r-path. In addition, detailed knowledge of neutron and proton SPEs neighbouring the ^{78}Ni doubly-magic shell closure will serve as a fundamental benchmark for modelling the nuclear structure of regions with even larger N/Z ratios [Grawe07]. Direct single-nucleon transfer experiments, which identify the distribution of single-particle strengths in nuclei, are the only tool to determine SPEs accurately. At times, SPEs have been inferred without real justification from the energies of low-lying nuclear excitations, often with reliance on systematic trends for spin assignments. HIE-ISOLDE will offer neutron-rich Ni and Zn beams of sufficient intensity and excitation energy to permit an accurate determination of proton and neutron SPEs from single-nucleon transfer experiments, eventually allowing access to spectroscopic knowledge on low-lying states in ^{78}Ni.

The Z=28 shell gap emerges from the splitting of the proton $1f_{7/2}$ and $1f_{5/2}$ orbits, caused by the addition of the nucleon spin-orbit interaction to the central mean field. The evidence gathered so far suggests that the filling of the neutron $g_{9/2}$ orbital reduces the gap between the $1f_{7/2}$ and $1f_{5/2}$ orbits, and may even lead to an eroded proton gap at ^{78}Ni. These changes are attributed to the combined action of the attractive (repulsive) potential between protons in the $1f_{5/2}$ ($1f_{7/2}$) and neutrons in the $1g_{9/2}$ orbits. In support of this hypothesis, the sudden lowering of the $5/2^-$ state in ^{73}Cu was attributed to the lowering of the $f_{5/2}$ orbit, which results in its inversion with the $2p_{3/2}$ orbit in the ground state of ^{75}Cu. This inversion as indicated by a recent *g*-factor measurement performed at ISOLDE [Flanagan09] which established its proton $f_{5/2}$ character. Furthermore, the core polarization required to explain the B(E2; $0^+ \rightarrow 2^+$) values of neutron-rich Zn isotopes was attributed to a decrease in the binding of the $1f_{7/2}$ proton shell [VandeWalle07]. It is dangerous to equate the behaviour of the energies of the low-lying states to the SPEs, which are identified instead by the centroid of the single-particle strengths of all the states of the same single-particle character. It is worth noting, for example, that reduced transition probabilities of low-lying states (which are known up to N=46 [Daugas10]) indicate a significant amount of collectivity. Unfortunately, measurements of single-particle strengths obtained via single-nucleon transfer reactions are available for Cu isotopes only up to N=42, and for Ni isotopes only up to N=37. Promising data on neutron single-particle states in ^{67}Ni (N=39) were recently obtained at Isolde using the ^{66}Ni(d,p) reaction (IS469) [Diriken10]. The results will determine to what extent ^{67}Ni can be described as the coupling of a neutron hole to a ^{68}Ni core.

The spin of the populated states will be inferred from the orbital angular momentum quantum number of the transferred nucleon(s), which in turn affects the shape of the differential cross-section. The upgrade from 3MeV/u to 5.5MeV/u beam energy, and subsequently 10MeV/u will result in much more distinguishable angular distributions and in confident spin assignments. Examples of experiments which will be proposed are the following:

- (d,p) transfer reactions on Ni and Zn isotopes between N=40 and N=50, and notably on ^{68}Ni and ^{80}Zn, to populate neutron single-particle states for N=41 and 51, i.e. the $g_{9/2}$, $d_{5/2}$ $s_{1/2}$ $d_{3/2}$ and $g_{7/2}$; these experiments will determine the single-particle character of the low-lying states and the behaviour of the neutron SPEs;
- (t,α) transfer experiments in inverse kinematics to selectively populate single-proton states in odd-A $^{75-79}$Cu isotopes, using the 5.5MeV/u beams of neutron-rich zinc isotopes provided by the HIE-ISOLDE upgrade. Proton removal from the ground states of neighbouring even-even Zn isotopes will give access to $2p_{3/2}$, $1f_{5/2}$ and $1f_{7/2}$ states in Cu isotopes, and will identify the ground-state proton occupation of even Zn isotopes;
- (t,p) transfer reactions on e.g. ^{68}Ni, in particular to study the 0^+ excited states configuration; two-neutron transfer reactions will in fact selectively populate excited states possessing a large overlap with the 0^+ ground state of the radioactive ion beam;
- two-proton stripping reaction (^{10}Be,^{12}C) on ^{80}Zn, to populate states in ^{78}Ni. This somewhat exotic reaction, because of the low statistics, will probably not provide angular distributions, however it may represent a unique way to access to extremely important spectroscopic information in ^{78}Ni. This reaction will employ a 50% enriched ^{10}Be target.

3. Experimental setup

The experimental setup will consist of the MINIBALL HPGe spectrometer and the T-REX array for particle detection. The set-up will not differ much to the one used in previous transfer experiments. In the reactions envisaged, with the exception of (^{10}Be,^{12}C), fusion-evaporation channels are expected to decay mainly via neutron emission and not to present a major problem. For the experiments, commercially-available tritium- loaded targets are needed. One such target has already been successfully employed in a transfer experiment performed at ISOLDE [Wimmer09]. For (^{10}Be,^{12}C) reactions the use of a spectrometer would help identifying the reaction channel.
The gamma-rays detected with the Miniball array in coincidence with the light particles, will be essential to precisely measure the energy of the populated states.

4. Beam requirements

The isotopes of interest are ^{68,70}Ni and ^{76,78,80}Zn. For (d,p) and (d,t) transfer experiments, beam intensities of 10^5 pps are required in the reaction chamber at MINIBALL. For (t,α) experiments, the needed Zn beam rates are of the order of 10^5-10^6 pps. An increase in beam intensity is therefore necessary for all the beams. The required intensities would lead to experiments lasting between 5 and 10 days. Beam purity needs to be as high as possible, and at least >60%, and a beam-spot size of 3mm diameter. An EBIS release time as long as flat as possible is required.

5. Safety aspects

It has been demonstrated in experiment IS470 that the radioactive ^{3}H target can be operated via an approved radiation-safety protocol without any hazards. A similar safety procedure is envisaged for the ^{10}Be target too. There are no further safety concerns.

6. References

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