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Study of the deformation-driving $\nu d_{5/2}$ orbital in $^{67}_{28}Ni_{39}$ using one-neutron transfer reactions

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ABSTRACT

The $\nu g_{9/2}, d_{5/2}, s_{1/2}$ orbitals are assumed to be responsible for the swift onset of collectivity observed in the region below ^{68}Ni. Especially the single-particle energies and strengths of these orbitals are of importance. We studied such properties in the nearby ^{67}Ni nucleus, by performing a (d, p)-experiment in inverse kinematics employing a post-accelerated radioactive ion beam (RIB) at the REX-ISOLDE facility. The experiment was performed at an energy of 2.95 MeV/u using a combination of the T-REX particle detectors, the Miniball γ-detection array and a newly-developed delayed-correlation technique as to investigate μs-isomers. Angular distributions of the ground state and multiple excited states in ^{67}Ni were obtained and compared with DWBA cross-section calculations, leading to the identification of positive-parity states with substantial $\nu g_{9/2}$ (1007 keV) and $\nu d_{5/2}$ (2207 keV and 3277 keV) single-particle strengths up to an excitation energy of 5.8 MeV. 50% of the $\nu d_{5/2}$ single-particle strength relative to the $\nu g_{9/2}$-orbital is concentrated in and shared between the first two observed $5/2^+$ levels. A comparison with extended Shell Model calculations and equivalent $(^3He, d)$ studies in the region around $^{90}_{40}Zr_{50}$ highlights similarities for the strength of the negative-parity pf and positive-parity $g_{9/2}$ state, but differences are observed for the $d_{5/2}$ single-particle strength.

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It is well-established that atomic nuclei with a magic proton and neutron number have a spherical character while nuclei situated far away from these so-called doubly-closed shell nuclei are deformed. In singly-closed shell nuclei, the description in terms of spherical or deformed configurations is strongly dependent on the number of valence nucleons determined by the shell closures and on the specific single-particle orbitals occupied. However the general validity of the traditional magic numbers, established in regions in the nuclear chart close to stability, are now more and more questioned as experimental and theoretical studies indicate that the effective single-particle gaps are altered [1–5]. Furthermore the stabilizing effect of closed shells and subshells can be overturned by residual interactions between proton and neutrons with as result the coexistence of different shapes and even in some cases the inversion of the coexisting structures as a function of the nucleon number leading to sudden changes in the ground-state properties [6]. An illustrious example is the so-called "island of inversion" discovered around the magic number $N = 20$ where, unexpectedly, semi-magic nuclei appear to be deformed in their ground state due to strong quadrupole correlations between $\Delta j = 2$ orbitals, in this case within the pf-shell [7–9].

The recently intensively-studied region of the nuclear chart below ^{68}Ni, with its protons filling up the $Z = 28$ spin–orbit shell and neutrons filling up the $N = 40$ Harmonic Oscillator subshell, is also characterized by a swift onset of collectivity [10–12]. This is suggested to arise from the combination of the small size of the $N = 40$ shell gap and of the presence of the $\nu g_{9/2}, d_{5/2}, s_{1/2}$ sequence of orbitals above this gap which should strongly enhance quadrupole collectivity [13]. Large-scale shell model calculations have shown that the inclusion of the $\nu d_{5/2}$ orbital in the model space is indeed necessary to reproduce the collective features of nuclei in this region [13–15]. The contribution of the $\nu g_{9/2}$–$d_{5/2}$ quadrupole collectivity depends on the single-particle energies and occupancies of these orbitals (sensitive to three-body monopole forces [16], see also Fig. 3 in Ref. [3]). From this perspective, the distribution of the positive-parity $\nu g_{9/2}, d_{5/2}, s_{1/2}$ single-particle strength at $N = 40$ (^{68}Ni) serves as an anchor point to validate shell-model calculations and the proposed collectivity-driving mechanism.

One-neutron transfer reactions into the direct neighbours of ^{68}Ni should be an excellent tool to probe the size of shell gaps and test the single-particle character of the neutron orbitals. Due to the lack of stable isotopes in this mass region, the use of energetic radioactive ion beams (RIBs) is needed to perform these studies. In this Letter we report on the one-neutron transfer reaction in inverse kinematics ^{66}Ni$(d, p)^{67}$Ni (Q-value = 3.58 MeV), performed with a post-accelerated RIB (^{66}Ni, $T_{1/2} = 54.6$ h). The problem of using low-intensity RIBs in inverse kinematics lies in the conflict between optimizing the reaction yield and keeping the resolution of the ejectiles (here the protons). This has been circumvented by combining a highly-segmented silicon detector for the identification of the exit channel with an efficient γ-ray detector array providing a precise state selection at the keV level. Additionally the $\Delta\ell$-transfer information combined with the γ-decay pattern can lead to firm spin identification.

Spectroscopic information on ^{67}Ni is available from a range of different experiments [17–25]. A $1/2^-$ spin has been attributed to the ground state of ^{67}Ni on the basis of a nuclear moment measurement [17] while a g-factor measurement of the 13.3-μs isomeric level at 1007 keV [18] calls for a $9/2^+$ assignment even though the g-factor is twice smaller than expected for a pure $1g_{9/2}$ configuration [19]. The isomeric 313–694 keV decay sequence of the 1007-keV state has been shown to have a stretched quadrupole character [20]. The half life of the 313 keV line calls then for a M2 transition while the short life time (150(4) ps) [21] fixes the 694 keV transition as E2. All this combined leads to a $9/2^+ \to 5/2^- \to 1/2^-$ spin sequence for the levels at 1007 keV, 694 keV and the ground state respectively. Further information on higher-lying levels comes from deep-inelastic reactions [23] but these yrast states were not populated in the present study.

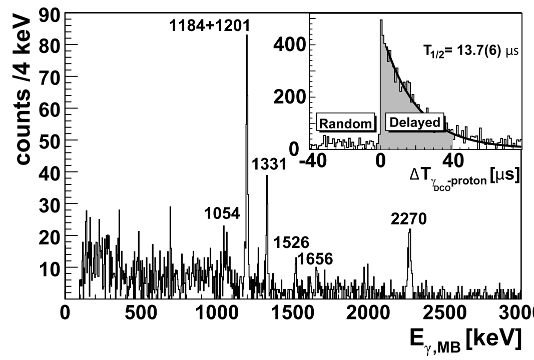

Fig. 1. Miniball γ-ray spectrum, in prompt coincidence with a proton detected in T-REX and in delayed coincidence (120-μs time window) with either a 313 or 694 keV γ-ray transition. The inset shows the time difference between a prompt proton–MB γ-ray event and a delayed 313 keV γ-ray transition. The half life deduced from an exponential fit is 13.7(6) μs, in agreement with the previously observed values of 13.3(2) μs [18] and 13(1) μs [19] for the 1007-keV isomer in ^{67}Ni.

The 99%-pure ^{66}Ni beam was produced at the REX-ISOLDE facility by using the RILIS ion source [26], post-accelerated to 2.95 MeV/nucleon by REX [27] and directed onto a deuterated polyethylene target, resulting in a center-of-mass (CM) energy of 5.67 MeV and average intensity of 4.1×10^6 particles per second. A combination of the T-REX position-sensitive particle detection array [28] and Miniball (MB) γ-ray detectors [29] was used to register the reaction products and coincident γ radiation. Although the protons were detected in the T-REX array with a total energy resolution of the order of 1.3 MeV (FWHM), still the feeding of individual states in ^{67}Ni could be determined from the coincident γ rays.

In order to investigate the 13.3-μs $9/2^+$ isomeric state (1007 keV) in ^{67}Ni, a delayed-coincidence setup was developed. The reaction products and the beam were stopped in a thick aluminium foil 2 meters downstream of the target. The characteristic 313 and 694 keV transitions depopulating the isomer were detected in a germanium detector positioned in close geometry to the beam stopper. Delayed correlations in a 120-μs time window between prompt proton–γ coincidences in the arrays surrounding the target and the isomeric transitions detected in the beam-stopper-detector could be studied in this way despite the strong radioactive decay background (Fig. 1).

By using the available information from prompt γ–γ coincidences, detected proton position and energy, and delayed coincidence data, an improved level scheme was constructed. Part of the deduced level scheme is shown in Fig. 2. An illustrative figure depicting the quality of the data is shown in Fig. 3. The inset of Fig. 3 shows the feeding pattern of ^{67}Ni based on measured proton intensities and kinematics (grey area) and on the measured γ-ray intensities and their position in the level scheme (black line). Both curves have been integral-normalized up to 5.4 MeV excitation energy to exclude the influence of the elastically-scattered protons visible at 6.4 MeV. An additional 4(1)% feeding probability to the ground state was added to the γ-ray intensities, estimated by fitting the γ-ray feeding to the particle feeding through an iterative procedure. This ground-state feeding does not influence the relative spectroscopic factors of the excited states. The good agreement between the feeding pattern in ^{67}Ni deduced from the proton kinematics from T-REX and the γ-ray spectra from Miniball supports the reliability of the used analysis method and demonstrates the