Physics Letters B 736 (2014) 533–538

Contents lists available at ScienceDirect

Physics Letters B

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

J. Diriken [a,b,*], N. Patronis [a,c], A.N. Andreyev [a,d,e], S. Antalic [f], V. Bildstein [g], A. Blazhev [h], I.G. Darby [a], H. De Witte [a], J. Eberth [h], J. Elseviers [a], V.N. Fedosseev [i], F. Flavigny [a], Ch. Fransen [h], G. Georgiev [j], R. Gernhauser [g], H. Hess [h], M. Huyse [a], J. Jolie [h], Th. Kröll [g], R. Krücken [g], R. Lutter [k], B.A. Marsh [i], T. Mertzimekis [l], D. Muecher [g], F. Nowacki [m,n], R. Orlandi [a,o,p], A. Pakou [c], R. Raabe [a], G. Randisi [a], P. Reiter [h], T. Roger [a], M. Seidlitz [h], M. Seliverstov [a,i], K. Sieja [m,n], C. Sotty [j], H. Tornqvist [q], J. Van De Walle [q], P. Van Duppen [a], D. Voulot [i], N. Warr [h], F. Wenander [i], K. Wimmer [g,r]

[a] KU Leuven, Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200D, 3001 Leuven, Belgium
[b] Belgian Nuclear Research Centre SCK·CEN, Boeretang 200, B-2400 Mol, Belgium
[c] Department of Physics and HINP, The University of Ioannina, 45110 Ioannina, Greece
[d] Department of Physics, University of York, YO10 5DD, United Kingdom
[e] Advanced Science Research Center, Japan Atomic Energy Agency (JAEA), Tokai-mura, 319-1195, Japan
[f] Department of Nuclear Physics and Biophysics, Comenius University, 84248 Bratislava, Slovakia
[g] Physik Department E12, Technische Universität München, D-85748 Garching, Germany
[h] IKP, University of Cologne, D-50937 Cologne, Germany
[i] AB Department, CERN 1211, Geneva 23, Switzerland
[j] CSNSM, CNRS/IN2P3, Universite Paris-Sud 11, UMR8609, F-91405 ORSAY Campus, France
[k] Fakultät für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany
[l] INP, NCSR "Demokritos", GR-15310, Ag. Paraskevi/Athens, Greece
[m] Université de Strasbourg, IPHC, 23 rue du Loess, 67037 Strasbourg, France
[n] CNRS, UMR7178, 67037 Strasbourg, France
[o] School of Engineering, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom
[p] The Scottish Universities Physics Alliance (SUPA), United Kingdom
[q] PH Department, CERN 1211, Geneva 23, Switzerland
[r] Department of Physics, Central Michigan University, Mount Pleasant, MI 48859, USA

ARTICLE INFO

Article history:
Received 5 May 2014
Received in revised form 21 July 2014
Accepted 2 August 2014
Available online 7 August 2014
Editor: V. Metag

Keywords:
Nuclear physics
One-nucleon transfer reactions
RIBs
Nuclear structure

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.

* Corresponding author.
E-mail address: jandiriken@gmail.com (J. Diriken).

http://dx.doi.org/10.1016/j.physletb.2014.08.004

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 $9/2^+ \rightarrow 5/2^- \rightarrow 1/2^-$ 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.

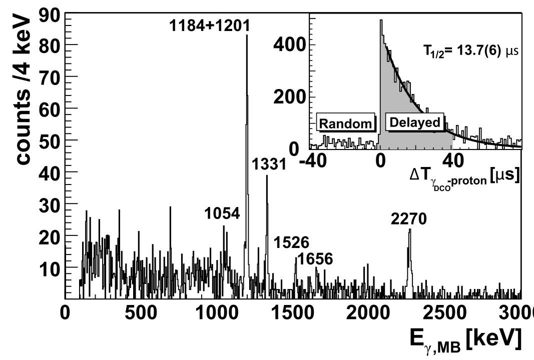

Fig. 1. Miniball γ-ray spectrum, in prompt coincidence with a proton detected in T-REX and in delayed coincidence (120-μs time window) with either a 313 or 694 keV γ-ray transition. The inset shows the time difference between a prompt proton–MB γ-ray event and a delayed 313 keV γ-ray transition. The 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

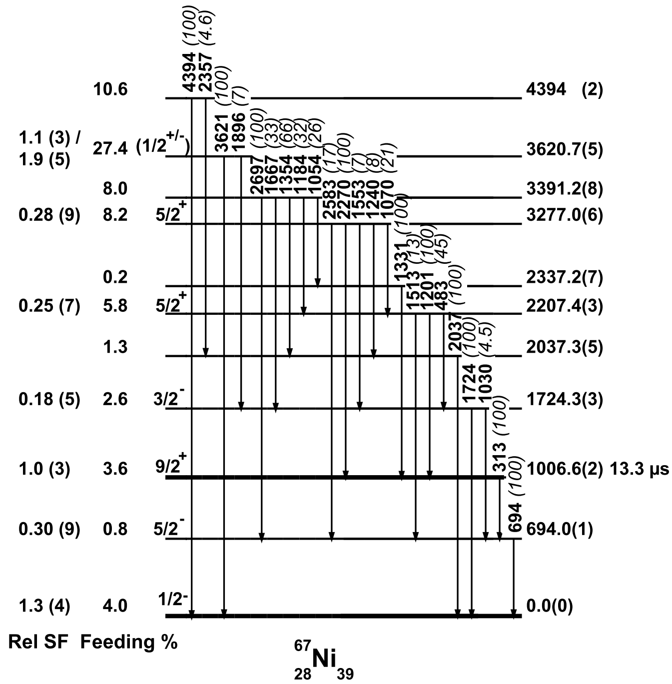

Fig. 2. Partial level scheme of ^{67}Ni. All levels below 2 MeV observed in this study are shown. Above 2 MeV the partial level scheme includes the levels with a feeding probability larger than 5% and the levels involved in their γ decay. Relative spectroscopic factors (Rel SF) with respect to the $9/2^+$ state are also given. The remaining (d, p)-strength is distributed among other states up to 5.7 MeV in excitation energy and will be discussed in a forthcoming publication. In total 17 levels of which 7 are shown between 2.0 and 5.8 MeV were identified and characterized by their γ decay.

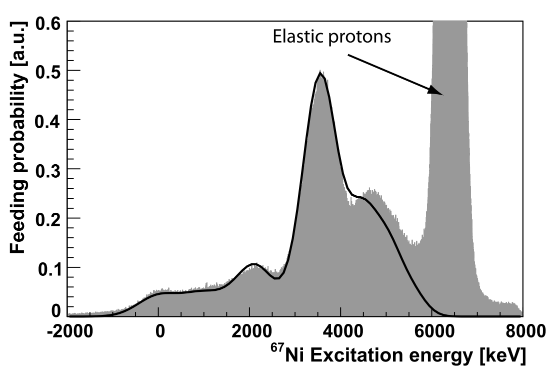

Fig. 3. Excitation energy in ^{67}Ni deduced from proton kinematics with respect to coincident Doppler-corrected γ rays in Miniball. Events on the solid, diagonal line indicate the population of an excited state followed by a ground-state transition (examples are indicated with the γ-ray energy in keV). The events above 6 MeV excitation energy are random coincidences with elastically scattered protons. Inset: grey area: Experimental feeding probability of ^{67}Ni, deduced from the detected proton kinematics and intensities. Black line: Excitation curve reconstructed from efficiency-corrected γ-ray intensities, their position in the level scheme and folded with the experimental energy resolution (see Fig. 2). An additional 4% feeding probability to the ground state was included to match the low-energy part of the spectrum with the grey area.

need for proton–γ coincidences to extract proton angular distributions of the direct population of individual excited states.

Angular distributions of the detected protons could be extracted for various states by requiring strict conditions on proton kinematics (and thus the excitation energy in ^{67}Ni within ±300 keV) and coincident γ rays. The obtained angular distributions were compared with DWBA calculations from FRESCO [30] by using global optical model potentials from Refs. [31,32]. Examples of fits with

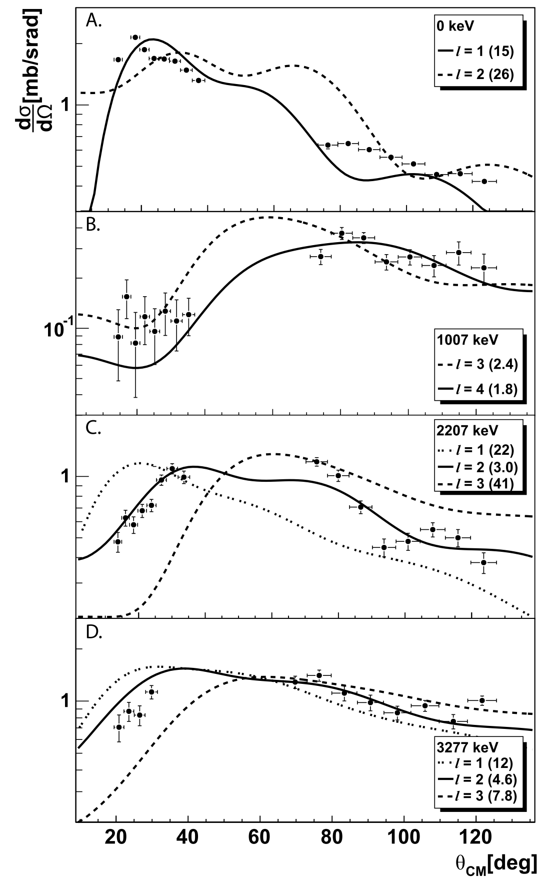

Fig. 4. Angular distributions and DWBA calculations (best fits only) for states with energies of 0, 1007, 2207 and 3277 keV. The reduced χ^2 values of the fits are quoted between parentheses.

different ℓ transfers for states at 0, 1007, 2207 and 3277 keV are presented in Fig. 4. The data generally allow to identify a preferred value for the value of ℓ, mostly thanks to the data points at forward angles for which the calculated cross sections are less dependent on the details of the interaction potentials. For a given state i, relative spectroscopic factors with respect to the 1007-keV $9/2^+$ isomer (Rel SF in Fig. 2) were deduced from the ratio R of experimental and DWBA cross sections according to: Rel SF $= [R/(2J+1)]_i/[R/(2J+1)]_{9/2^+}$.

From our DWBA analysis of the ground-state feeding (Fig. 4.A) a $\ell = 1$ assignment is favoured, in agreement with the $1/2^-$ spin assignment and $\nu p_{1/2}^{-1}$ shell model interpretation. The high relative spectroscopic factor hints at a pure configuration compatible with the magnetic-moment measurement [17].

Transfer to the $9/2^+$ state at 1007 keV was determined with the delayed-coincidence technique and is compatible with $\ell = 3$ or 4 transfer (Fig. 4.B), the latter one in agreement with the adopted $9/2^+$ spin and parity.

The proton angular distribution of the 1724 keV level is in agreement with an $\ell = 1$ transfer. A spin and parity assignment of $3/2^-$ is favoured due to the small γ branch to the $5/2^-$ state at 694 keV and the strong top-feeding from the $5/2^+$ level at 2207 keV (see below).

The proton angular distribution of the excited state at 2207 keV agrees with $\ell = 2$ as the χ^2 of the other fits assuming different ℓ-values are substantially higher (Fig. 4.C). Note that $\ell = 1$ is anyway excluded because of the strong, prompt γ-ray transition towards the $9/2^+$ state at 1007 keV. The absence of direct γ decay

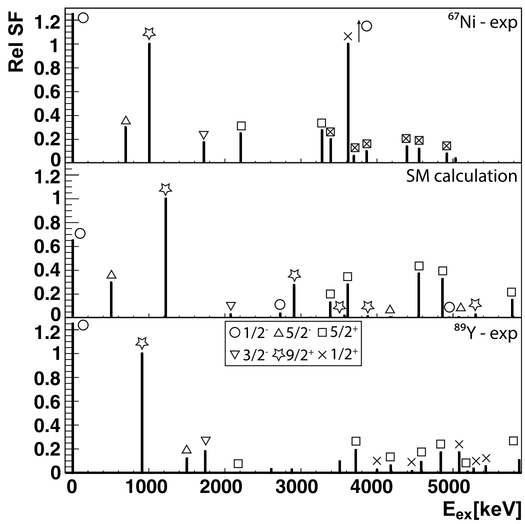

Fig. 5. Distribution of single-particle strength in ^{67}Ni as deduced from the present study (top) are compared to shell-model calculations (middle) and the strength deduced from the ^{88}Sr(^{3}He, d)^{89}Y reaction [35] (bottom). Relative SF with respect to $9/2^+_1$ are shown. States that could not be characterized in ^{67}Ni have a double label ($1/2^+$ and $5/2^+$).

to the $1/2^-$ ground state further supports this $5/2^+$ spin assignment.

Similar arguments hold for the 3277-keV state (Fig. 4.D), where the proton angular distribution is best described by $\ell = 2$ transfer. The combination with the specific γ-decay pattern leads again to a $5/2^+$ assignment.

As θ_{CM} angles close to 0° are not covered, $\ell = 0$ states cannot be identified unambiguously. The angular distribution for the state at 3621 keV only excludes $\ell \geq 3$. From the γ-decay pattern a low-spin assignment is preferred due to the strong branch to the $1/2^-$ ground state and $3/2^-$ 1724-keV state. A $1/2^+$ spin assignment is perhaps favoured considering the strength observed for the corresponding transfer reactions in lighter Ni isotopes [33,34], and the fact that a $1/2^-$ assignment would correspond to an unphysically large relative spectroscopic factor of 1.9(5).

The other observed states were weakly populated and no information on the spin could be extracted. Based on the observations in the lighter nickel isotopes [33,34] we assume that feeding to states above 3277 keV is of $\ell = 0$ or 2 character.

With the exception of the $1/2^-$ ground state that receives similar strength as the $9/2^+$ state (see Fig. 5), the relative spectroscopic factors of the negative-parity $p_{3/2}$ and $f_{5/2}$ neutron orbitals are further reduced, a trend which is observed in the lighter Ni nuclei when going heavier [36]. Concerning the positive-parity states, however, one notices that half of the $\nu d_{5/2}$ strength (relative to the $\nu g_{9/2}$ strength) is divided over the first two $5/2^+$ states at 2207 keV and 3277 keV. A similar phenomenon is observed in the lighter nickel isotopes albeit with lower strength: 31%, 27%, 23% and 34% in ^{59,61,63,65}Ni respectively [33,34]. The difference between the weighted average energy (by using the Rel SF's as individual weights) of the $5/2^+$ relative to the $9/2^+$ levels in $^{59-65}$Ni has a rather constant value around 2.6 MeV. The same value is obtained for ^{67}Ni assuming that all levels not characterized by spin above 3 MeV are $\ell = 2$ transfer. As the influence of the $N = 40$ shell gap swiftly disappears when moving towards lower Z values, one expects a strong influence of quadrupole correlations in the (s)dg orbitals as observed through the enhanced collectivity in the Fe and Cr nuclei at $N = 40$ [13,37,38]. The weighted average of the energy of the $\nu s_{1/2}$ configuration follows closely the one of the $\nu d_{5/2}$ orbital. However, the $1/2^+$ assignment to the 3621-keV state, favoured by our data, would lead to a different distribution of the strength in ^{67}Ni with respect to the lighter isotopes. State-of-the-art shell model calculations for this region [13,15] include at most the $d_{5/2}$ orbital above $N = 50$ but not the $s_{1/2}$ orbital. An interpretation of this strength distribution in terms of the shell model is thus still out of reach.

Recently, the low-energy structure of ^{68}Ni and ^{90}Zr has been compared in order to evaluate the effect of the $Z, N = 40$ subshell closure in these singly-closed nuclei [39]. It was concluded there that neutron pair scattering across $N = 40$ around ^{68}Ni is far more important than proton pair scattering across $Z = 40$ around ^{90}Zr. Similarly, it is now possible to compare ^{67}Ni, a neutron hole coupled to ^{68}Ni, with ^{89}Y, a proton hole coupled to ^{90}Zr. This can be seen in Fig. 5 where our one-neutron transfer data is plotted against the one-proton transfer data from ^{88}Sr(^{3}He, d)^{89}Y [35]. Despite the agreement for the $1/2^-$, $3/2^-$, and $9/2^+$ states below 2 MeV, the structure of the positive-parity (s)d-states is very different as the $\ell = 0$, 2 strength resides at higher energy in ^{89}Y. A low-lying $5/2^+$ state at 2222 keV in ^{89}Y has been identified [40] but it is only very weakly observed in the available (^{3}He, d) data [35]. This comparison indicates a much more pronounced $Z = 50$ gap in ^{90}Zr compared to the $N = 50$ gap near ^{68}Ni and stresses the difference in the structure of these singly-closed shell nuclei in spite of their similar excitation spectrum.

The experimental findings have also been compared with shell model calculations, in a valence space composed of the pf shell for protons and $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ in addition to the $g_{9/2}$ and $d_{5/2}$ orbitals for neutrons. The Hamiltonian is the LNPS from Refs. [13,41] with minor revisions [42]. The calculated theoretical spectroscopic strength functions for the valence neutron orbitals are shown in the middle part of Fig. 5. As reflected in the experimental situation, the calculated distributions appear to depend strongly on the involved orbital. The low-lying profiles corresponding to the $p_{1/2}$, $f_{5/2}$ and $g_{9/2}$ are essentially concentrated in the single lowest peak revealing the single-particle character of these states. The spectroscopic amplitude corresponding to the $f_{5/2}$ orbital is indeed small since this orbital is already partially filled for neutron number $N = 38, 39$. On the other hand, the profile corresponding to the $d_{5/2}$ orbital appears to be much more fragmented in agreement with the experimental findings. The actual value of the effective single-particle energy gap in ^{68}Ni from the Hamiltonian [42] at $N = 40$ is in agreement with the one extracted experimentally and the one extracted in the recent d(^{68}Ni, p)^{69}Ni reaction study [43], although the calculated strengths appear to be shifted to higher energies by 1 MeV. The missing correlation mechanism to lower these strengths is still not identified and further theoretical investigations need to be implemented in order to understand this trend. The $N = 38$–40 region appear to be a place where single particle behavior coexists with very complex regimes and where highly correlated intruders are present in the low-lying spectrum as in ^{67}Co [41,44].

In conclusion, the ^{66}Ni(d, p)^{67}Ni one-neutron transfer reaction has been studied for the first time by using a post-accelerated RIB to investigate positive-parity states beyond the $N = 40$ and 50 gaps close to ^{68}Ni. The combination of efficient particle and γ-ray detection arrays formed a key ingredient for this experiment. Compared to the $\nu g_{9/2}$ strength, more than 50% of the $\nu d_{5/2}$ strength is concentrated in two relatively low-lying states while the relative $\nu s_{1/2}$ strength appears to be situated in one state only. The weighted average of the energy of the $\nu d_{5/2}$ configuration relative to the $g_{9/2}$ configuration is similar to recent shell-model calculations. The position of the g–d strengths, somewhat lower than predicted by calculations, should allow enhanced quadrupole collectivity from the $g_{9/2}$–ds neutron orbitals to play a key role in the heavy chromium isotopes around $N = 40$. It will be important to extend these studies by using the higher beam energies available from HIE-ISOLDE to investigate the strength distribution of the neutron sdg orbitals when moving towards ^{78}Ni.

Acknowledgements

This work has been funded by FWO-Vlaanderen (Belgium, grants G.0706.08 "Big Science", ASP/08-SCK and G.0626.09), by KU Leuven (BOF grant GOA/10/10), by the Belgian Science Policy Office (Interuniversity Attraction Poles Programme, grants P6/23-C and P7/12-C "BriX network"), by the European Commission within the Seventh Framework Programme through I3-ENSAR (contract No. RII3-CT-2010-262010), by a grant from the European Research Council (ERC-2011-AdG-291561-HELIOS), by the Slovak Research and Development Agency (No. APVV-0105-10), by BMBF under contracts 06KY9136I, 05P12PKFNE, 06MT7178 and 06MT9156 and the Maier-Leibnitz-Laboratorium, Garching.

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