Neutron knockout from ^{68,70}Ni ground and isomeric states.

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Abstract.
    Neutron-rich isotopes are an important source of new information on nuclear physics. Specifically, the spin-isospin components in the nucleon-nucleon (NN) interaction, e.g., the proton-neutron tensor force, are expected to modify shell structure in exotic nuclei. These potential changes in the intrinsic shell structure are of fundamental interest. The study of the excitation energy of states corresponding to specific configurations in even-even isotopes, together with the single-particle character of the first excited states of odd-A, neutron-rich Ni isotopes, probes the evolution of the neutron orbitals around the Fermi surface as a function of the neutron number a step forward in the understanding of the region and the nature of the NN interaction at large N/Z ratios.
    In an experiment carried out at the National Superconducting Cyclotron Laboratory [1], new spectroscopic information was obtained for ^{68}Ni and the distribution of single-particle strengths in ^{67,69}Ni was characterized by means of single-neutron knockout from ^{68,70}Ni secondary beams. The spectroscopic strengths, deduced from the measured partial cross sections to the individual states tagged by their de-exciting gamma rays, is used to identify and quantify configurations that involve neutron excitations across the $N = 40$ harmonic oscillator shell closure. The de-excitation γ rays were measured with the GRETINA tracking array [2].

The results challenge the validity of the most current shell-model Hamiltonians and effective interactions, highlighting shortcomings that cannot yet be explained. These results suggest that our understanding of the low-energy states in such nuclei is not complete and requires further investigation.

1. Introduction

Nuclear physics aims to understand the properties of nuclei, complex highly-correlated quantum systems, in terms of theoretical models of their structure. The most important degrees of freedom need to be sensed and highlighted by means of experimental measurements. Among these are the trends and notable changes in between nuclei in the same mass-isospin region that shed light on the relevant aspects of the underlying nuclear interactions.

Sophisticated nuclear models have been developed in order to account for the large variety of nuclear phenomena observed in nuclear systems under different conditions of excitation and isospin. The shell model is indeed one of the most successful efforts to reproduce basic features in a wide range of nuclei: many nuclear properties can be explained by means of bunching of nuclear orbitals, separated by energy gaps corresponding to stabilizing number of protons and neutrons. As nucleons are added to a closed-shell configuration, strong correlations in between them drive the shape of the nucleus from a spherical shape to either an oblate or a prolate one, with a substantial modification of the structure that is better understood by means of collective models. The exploration of the Segré chart by means of rare isotopes has made possible to track several changes in the shell-model structure of nuclei having an unbalanced number of protons and neutrons.

Spin-isospin parts in the nucleon-nucleon interaction, e.g., the proton-neutron tensor force, are expected to modify shell structure in exotic nuclei [3–5]. Potential changes in the intrinsic shell structure are of fundamental interest, and also have implications for nucleosynthesis. For example, they could directly affect the role of ^{78}Ni as a waiting point nucleus in the r-process [6, 7].

Shell evolution has been shown to imply that nuclei expected to show closed-shell features instead display an open-shell behavior as a consequence of the breakdown of magic numbers [8, 9]. And in some cases, new unexpected magic numbers appear. New regions of deformation appear typically to be related with the promotion of pairs of quasi-particles to high-j orbitals located near the shell closure [10]. Recently, the way this mechanism can be at play within a single nucleus was highlighted. Deformation driving particle-hole pair configurations can compete with spherical ones, resulting in two different structures coexisting at low excitation in the same nucleus.

Of particular interest is the ^{68}Ni region where a shell closure occurs at Z=28 and the harmonic-oscillator shell gap separates the fp and $g_{9/2}$ neutron orbitals. A systematic study of the region shows that, in ^{68}Ni, there is a maximum of the excitation energy of the 2_1^+ state [11] and a minimum of the $B(E2; 0_1^+ \rightarrow 2_1^+)$ [12] transition probability.

For decades, the excitation energy $E_x = 1770(30)$ keV of the 0_2^+ isomer, obtained by Bernas et al. [13] using particle-spectroscopy techniques with the ^{70}Zn(^{14}C, ^{16}O) transfer reaction, was the only direct measurement for this state. Although the uncertainty was quoted to be 30 keV, comparisons of early transfer-reaction data for ^{67,68}Ni [13, 14] with subsequent, higher-precision γ-ray spectroscopy (e.g., Refs. [11, 15, 16]) reveal a systematic 100- to 200-keV offset in the excitation spectrum from which one may infer the 0_2^+ isomer to be lower in energy than originally reported. However, only recently did Suchyta et al. [17] directly measure the electrons produced in the E0 decay. A parallel work by Recchia et al. [18] provided not only an improved value for the energy of the 0_2^+ state [1603.5(3) keV], but also indicated the presence of prompt

1138- and 2420-keV transitions preceding the $E0$ decay [17]. In addition to the 0_1^+ and 0_2^+ states, a 2511-keV 0_3^+ level was tentatively proposed following β decay [19]. This assignment was later firmly established in a deep-inelastic-scattering (DIS) experiment [20].

The investigation of the excitation energy of low spin states of nuclei in the ^{68}Ni region is particularly interesting because they are often associated with rather simple configurations interpreted in terms of excitations of protons and neutrons across the gaps at $Z=28$ and $N=40$. A number of recent examples has been reported [17, 21–32] together with several theoretical works [33–38] .

2. Experiment, results and discussion

How sharply does the neutron occupancy change when the Fermi surface moves from the fp to the $g_{9/2}$ orbitals near ^{68}Ni? To what extent does the ground state of ^{68}Ni have a configuration corresponding to a spherical shape dominated by a completely filled fp shell? What is the configuration of the ^{70}Ni ground state (g.s.)?

In order to answer these questions, an experiment was performed in which we used exclusive one-neutron knockout cross sections, measured using γ-ray tagged neutron removal reactions from ^{68,70}Ni [39]. This technique allowed us to identify and quantify configurations that involve neutron excitations across the $N=40$ gap. Specifically, the partial cross sections to the lowest-lying $1/2^-$, $5/2^-$, $3/2^-$ and $9/2^+$ levels are measured and compared to calculations using shell-model spectroscopic strengths and eikonal reaction theory for both ^{68,70}Ni. Partial cross sections were measured as well for higher-lying states populated by neutron knockout from a long-lived isomer present along with the g.s. of ^{68}Ni.

The experiment was performed at the Coupled Cyclotron Facility (CCF) at the National Superconducting Cyclotron Laboratory (NSCL) [1]. Secondary beams of ^{68,70}Ni were produced by fragmentation of a 140 MeV/u ^{82}Se primary beam on a 423-mg/cm^2 ^{9}Be production target located at the entrance of the A1900 separator [40]. The secondary beams, selected and purified with the separator, were delivered at momentum acceptances of 1% for ^{68}Ni and 3% for ^{70}Ni, respectively. The ^{68}Ni and ^{70}Ni beams impinged on ^{9}Be reaction targets (100- and 281-mg/cm^2 thick, respectively) with mid-target energies of 85 and 74 MeV/u. The measurements described below were carried out with GRETINA [2] surrounding the target and the S800 spectrograph [41].

The projectile-like reaction residues, after traversing the trigger plastic scintillator at the back of the S800 focal plane, were implanted into an aluminum plate placed in front of a CsI(Na) detector array [42]. The delayed γ-ray detection with the scintillator array in this IsoTagger configuration [43] enabled measurements of transitions from isomers in the knockout residues.

With the ∼50-ns flight time for ^{68}Ni ions through the S800 spectrograph, it was possible to correlate isomeric decays measured using the CsI(Na) detectors at the focal plane (see below) with prompt γ rays at the target position. The coincidence relationships observed between prompt 1139- and delayed 511-keV γ rays (see fig.1), as well as the relative intensities of the 663- and 1139-keV lines, indicate that the latter should be placed above the 0_2^+ isomer, likely depopulating the known 2743-keV, 2_2^+ level and, thus, fixing the 0_2^+ energy at 1604(1) keV, in agreement with Suchyta et al. [17]. The placement described above is further supported by determination of the half-life of the 511-keV isomeric decay line. The measured $t_{1/2}$ values are reasonably consistent with the 0.270(5)-s half-life reported for the 0_2^+ state in Ref. [13].

The position of the 0_2^+ isomer at 1603.5(3) keV was measured and the comparisons with shell-model (SM) calculations reveal the importance of mixing to account for the observed decay patterns, as reported in [18], but quantification of the amount of mixing requires further experimental data.

The ^{68}Ni nucleus has two known isomeric states, the 0_2^+ ($\tau = 390$ ns) and the 5^- ($\tau = 1.24$ ms) levels that, if produced in the fragmentation process, survive sufficiently long to be transmitted
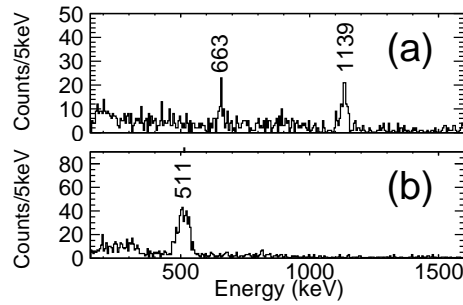
Figure 1. (a) Prompt GRETINA spectrum coincident with the identification of a ^{68}Ni recoil and the detection of a delayed 511-keV γ ray in the CsI(Na) focal plane detectors. (b) Delayed γ-ray spectrum recorded in the CsI(Na) scintillators in coincidence with implanted ^{68}Ni ions [18].

to the reaction target. ^{70}Ni has only one known isomeric state, the 2861-keV 8^+ ($\tau = 335$ ns) level that, if populated, will survive to the experimental end station as well. Accordingly, to interpret the cross sections for the population of individual final states, the isomeric ratio had to be determined for each projectile. For this purpose, a stopper was placed in the center of the GRETINA array and the γ-decay radiation from the implanted nuclei was measured over several microseconds. To determine the ^{68}Ni 5^- and ^{70}Ni 8^+ isomeric contents, the number of implanted ions was counted with a plastic scintillator upstream of the stopper. The efficiency-corrected yields of the γ-ray cascades depopulating the two isomers were then used to determine the isomeric ratios. These were 39(4)% for the 5^- level in ^{68}Ni and 8(1)% for the 8^+ one in ^{70}Ni, respectively. For the ^{68}Ni 0_2^+ state, the isomeric ratio was determined by the measurement of the 511-keV γ rays following positron annihilation associated with the internal pair formation, the main decay mode of this level. Including corrections for internal conversion, this ^{68}Ni 0_2^+ isomeric ratio was determined to be less than 1%.

The ^{67}Ni and ^{69}Ni one-neutron knockout residues, produced upon collision with the ^{9}Be reaction target, were detected and identified on an event-by-event basis using the time-of-flight and energy-loss information measured with the beam line timing detectors and the S800 spectrograph focal-plane detector system [41]. Prompt γ rays, emitted in-flight from the de-excitation of the knockout residues, were detected with the GRETINA array [2] surrounding the target at the entrance of the S800 spectrograph. The γ-ray energies were Doppler corrected on an event-by-event basis using the reconstructed momentum vector provided by the S800 spectrograph for each reaction residue [41].

The measured inclusive cross sections for the ^{9}Be(^{68}Ni,^{67}Ni)X and ^{9}Be(^{70}Ni,^{69}Ni)X one-neutron removal reactions, $\sigma_{inc}^{-1n} = 133(10)$ and 168(13) mb, respectively, were derived from the yield of the ^{67,69}Ni reaction residues relative to the number of incoming ^{68,70}Ni projectiles and the number density of the reaction target [39].

The theoretical partial and inclusive cross section calculations follow Refs. [44, 45]. The cross section for neutron removal from an initial state i of the A-body projectile – here its ground state or isomer – to a given residue final state f is given by

$$\sigma_\alpha^{fi} = \left(\frac{A}{A-1}\right)^N C^2 S \, \sigma_\alpha^{sp}, \tag{1}$$

where $C^2 S$ is the shell-model spectroscopic factor and σ_α^{sp} the single-particle cross section. Here, α labels the quantum numbers n, ℓ, j of the removed nucleon. The A-dependent multiplicative term is a center-of-mass correction factor to the shell-model $C^2 S$ value for removal from an

orbital with N oscillator quanta [46]. The single-particle cross section σ_α^{sp} is obtained with the eikonal approach [44], assuming a normalized single-particle overlap form factor for the removed nucleon and complex residue- and nucleon-target optical potentials.

Usually, the shell- plus eikonal models overestimate the cross section (and the total spectroscopic strength) leading to bound final states. This reduction is not observed here. However, this might be expected considering the shell-model orbitals used here, which, so far, neglect any possible neutron $f_{7/2}$ single-particle strength. Furthermore, for the ^{68}Ni→^{67}Ni reaction, the following applies as reported in [39]: (i) a systematic over-prediction of the cross sections to the low-spin, negative-parity states ($1/2^-$ - $5/2^-$), populated in removal from the ground state of ^{68}Ni, and (ii) a systematic underestimation of the cross sections to high-spin states ($9/2^+$ - $15/2^+$) populated by the removal from the 5^- isomer in ^{68}Ni. One may speculate that the discrepancy reported here points to an opportunity to improve the neutron configurations in the shell-model framework. However, any improvement to the Hamiltonians in this region would have to preserve the good description of the spectroscopic strength distribution that is found in the knockout to ^{69}Ni [39].

3. Conclusion

With this experiment, it was possible to obtain the precise excitation energy for the 0_2^+ state in ^{68}Ni, that was correctly predicted by the state-of-the-art shell-model calculations. Moreover, the new data enabled the identification of a number of new states in both ^{67}Ni and ^{69}Ni, in particular, levels that carry the largest part of the single-particle strength of the neutron orbitals lying at the Fermi surface. In comparison to shell-model calculations, the high measured inclusive cross sections hint at significant bound $f_{7/2}$ neutron strength, which is outside the shell-model space considered here. In contrast, the relative single-particle strength distribution for the knockout to ^{69}Ni is described well by the shell-model calculations if we consider the tentative ^{69}Ni level scheme proposed from this work. The results for the neutron removal to ^{67}Ni challenge the validity of one of the most current shell-model Hamiltonians, highlighting its shortcomings and providing benchmarks for future interactions developed for this neutron-rich region of the nuclear chart. The results suggest that our understanding of the low-energy states in these interesting nuclei is not yet complete and requires further investigation.

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