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The structure of nuclei near ^{78}Ni from isomer and decay studies

R. Grzywacz[a]

University of Tennessee, Knoxville, TN 37996, USA and Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

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Abstract. Recent progress in experimental decay studies in the region of the doubly magic nucleus ^{78}Ni is discussed. In particular new data on low-energy excitations in nickel isotopes has been obtained in experiments employing fragmentation reactions. The experimental data are confronted with different shell-model calculations. The position of the 2^+ energy levels and behavior of 8^+ isomers in even-even $^{70-76}$Ni isotopes has been interpreted.

PACS. 21.60.Cs Shell model – 25.70.Mn Projectile and target fragmentation – 27.50.+e $59 \leq A \leq 89$ – 23.40.-s β decay; double β decay; electron and muon capture

1 Introduction

Understanding of nuclei with very large neutron excess requires development of increasingly complex many body models. The half-century old nuclear shell model, a very successful tool describing properties of nuclei, is undergoing a period of revival [1], enabled by the availability of computing power. The predictive power of the calculations has to be tested by experiments on nuclei with large proton-neutron asymmetry. Magic nuclei are the best benchmarks.

The shell-model structure of neutron-rich $Z = 28$ nuclei was investigated for the first time by the study of ^{68}Ni produced in a multi-nucleon transfer reaction [2]. Evidence for shell closure at $N = 40$ was found. The subject of the $N = 40$ magicity has been addressed in a number of papers, for example [3,4,5,6].

Since then, the use of fragmentation reactions made it possible to study more exotic nuclei toward ^{78}Ni and along $N = 40$. Several experiments on neutron-rich nuclei $Z \approx 28$ and $40 < N < 50$ have been performed using fragmentation reactions of ^{86}Kr beams at intermediate energies at GANIL [7,8,9,10,11] and NSCL [12,13,14] facilities using high-acceptance fragment separators to select nuclei of interest. Detection systems sensitive to beta and gamma radiation enabled spectroscopy of states populated in de-excitation of short-lived isomers and following beta decay. A variety of other gamma-spectroscopy methods have been applied to study the properties of these nuclei [4,15,16]. These sensitive measurements provided, among other results, such as observation of microsecond isomers, see fig. 1, the first observation of the energies of the lowest excited states in the even-even magic nickel nuclei from ^{70}Ni to ^{76}Ni, see fig. 2. Neutron-rich iron and cobalt nuclei studied, showed indications of the onset of deformation [11]. The shell-model framework applied in the case of ^{68}Ni [2,17,18] could not satisfactorily reproduce the measured properties of the more exotic nickel nuclei for example the disappearance of the 8^+ isomer in ^{72,74}Ni [18] and its reappearance in ^{76}Ni. These new observations resulted in a successful revision of the shell-model approach to the nickel isotopes [18,19].

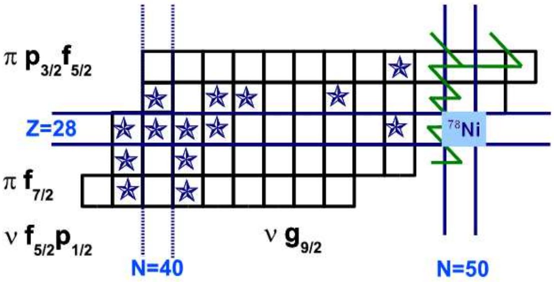

Fig. 1. Fragment of the chart of nuclei around ^{68}Ni and ^{78}Ni with selected known microsecond isomers observed using ^{86}Kr fragmentation [7,10,11,30].

2 Experimental technique

The experiments using the fragmentation of heavy ions to produce exotic nuclei rely on event-by-event identification of mass, charge and atomic number via measurements of their time of flight, magnetic rigidity, energy loss in detector material and of total kinetic energy [20]. The decay properties of each identified ion can be measured with a

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[a] Conference presenter;
e-mail: `grzywacz@mail.phy.ornl.gov`

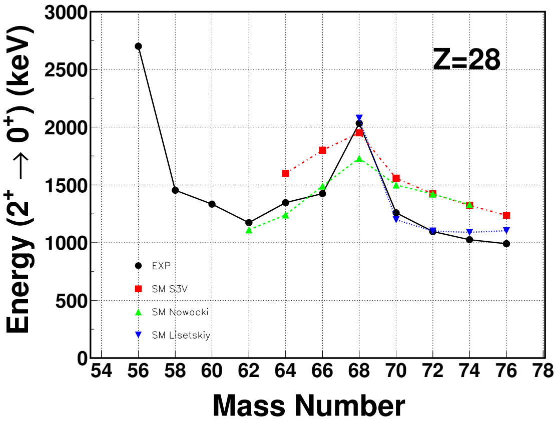

Fig. 2. Experimental energies of the first-excited 2^+ levels in magic even-even nickel isotopes (black dots). The most neutron-rich nuclei $^{70-76}$Ni has been measured using isomer and beta-decay spectroscopy methods using fragmentation of the ^{86}Kr beam [7,8,30]. Shown are also theoretical predictions using different shell-model approaches (SM-S3V [18], SM-Nowacki [4], and SM-Lisetskiy [19]).

radiation detection setup, consisting of beta detectors [8,9,12], gamma detectors [7,15,16] or conversion electron detectors [21]. The data described below has been obtained in experiments performed at GANIL using LISE2000 and at NSCL with the A1900 spectrometer. The beams of ^{86}Kr accelerated to energies of 58 A MeV (80 pnA) and 140 A MeV (16 pnA) have been used. Thick targets can be used thus maximizing the production rates. A 300 μm thick rotating tantalum target was used in the GANIL experiment and a 2226 μm thick fixed beryllium target at NSCL. The aim of the experiments was to measure gamma radiation emitted in the beta and isomeric decay of the exotic ions. State of the art detectors have been used for the decay radiation measurement. Gamma radiation was measured using an array of germanium detectors consisting of four clover detectors or twelve detectors of the SEGA array [22] array with similar detection efficiencies of about 6% and 4.6% at 1.3 MeV. To achieve high coincidence efficiency between gammas and beta decay electrons, thick (1 mm - GANIL, 1.5 mm - NSCL) double-sided silicon strip detectors (16×16 strips, 3 mm wide at GANIL and 40×40 strips, 1 mm wide at NSCL) have been used [8,23]. The beta detection efficiencies amounted to about 20% (GANIL) and 30% (NSCL). The earlier GANIL (100 h long) experiment aimed at search for 8^+ isomers in ^{72}Ni and ^{74}Ni and beta-decay studies of ^{72}Co and its neighbors. The NSCL experiment was aimed to improve on the measurement of the decay of ^{72}Co (27 h long) and to extend the information on ^{74}Ni via ^{74}Co decay (68 h long). Both experiment used the same experimental method [24] to detect microsecond isomers.

3 Low-energy states in neutron-rich nickel isotopes

Beta and electromagnetic decay of long-lived nuclear states can provide information on low-energy excitations in exotic nuclei. In several experiments the $J^\pi = 8^+$ isomers were sought in the even-even isotopes of nickel for $N > 40$. It was expected that using the very efficient and selective method of microsecond isomer detection [24] information about low level excited states, in particular first $J^\pi = 2^+$ excitations in ^{70,72,74,76}Ni isotopes, could be obtained in relatively uncomplicated experiments. The first of the expected isomers was discovered in ^{70}Ni [7]. The isomers in ^{72}Ni and ^{74}Ni could not be detected, even though a sufficient number of ions were measured. The lifetime limits have been deduced [25,8]. The lifetime limits are outside those expected from theory and this presented a challenge for the shell-model calculations.

These 8^+ excitations have very simple nature in these spherical nuclei. In the spherical shell-model picture for the $N > 40$, $Z = 28$ nuclei, the valence neutrons are starting to occupy the $g_{9/2}$ orbital. Two valence neutrons can be coupled to states with maximum available spin $J^\pi = 8^+$. The positive parity and the high angular orbital momentum $l = 4$ of the $g_{9/2}$ orbital prevents this state from being mixed with *fp*-shell ($l = 1, 3$, $\pi = -1$) states, hence the wave function of this state should in all cases be a rather pure two-neutron $(g_{9/2})^2$ excitation. The isomerism is caused predominantly by the yrast nature of this state and the low energy difference between the 8^+ and the nearest state available for electromagnetic transition $J^\pi = 6^+$. For ^{70}Ni this energy is 182 keV and results in a 230(3) ns lifetime [7,26] of the state decaying via $E2$ photon emission. The transition strength is about 0.7 W.u. indicating the non-collective nature of the states involved. For the ^{72}Ni and ^{74}Ni this transition will be slowed down due to the $B(E2)$ quenching in the mid-shell [18], but the isomerism was robustly predicted by various shell-model calculations. For the pure configurations the isomeric properties are linked to the values of interaction two-body matrix elements (TBME). The relevant values of these TBME are dominated by the short-range nature of nuclear interactions which leads to near degeneracy of the 6^+ and 8^+ states [27]. Such behavior is independent of j and the example of such isomers can be found across the nuclear chart. The arguments presented above advocate that the presence of the 8^+ isomers reflects a fundamental behavior of residual interactions and the anomalies may possibly uncover new nuclear structure effects.

Several hypotheses have been brought about to explain the absence of the isomerism in ^{72,74}Ni. One suggested very long lifetime of 8^+ states, into the milliseconds range, rendering them difficult to detect. Another idea called for the onset of deformation which would effectively introduce strong mixing and would deem the above single-particle picture invalid. The non-observation of the 8^+ isomers in ^{72}Ni and ^{74}Ni suggested a beta decay of ^{72}Co and ^{74}Co as a method to populate and investigate the levels in these nickel isotopes. The $Z = 27$ cobalt isotopes are rather difficult to describe within the shell model, because of the large model space needed to include the full *fpg* shell for neutrons and opening of the $Z = 28$ closed shell. But rather simple arguments are pointing to the fact that the beta decay of odd-odd cobalt isotopes will populate excited states

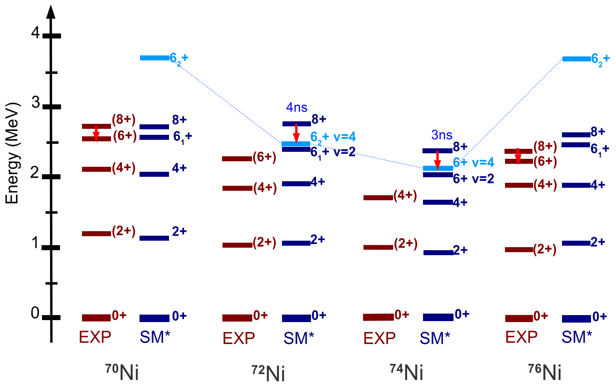

Fig. 3. The calculated and experimental level schemes for even-even nickel isotopes [19]. The migration of the seniority $\nu = 4$ $J^{\pi} = 6^{+}$ level is shown.

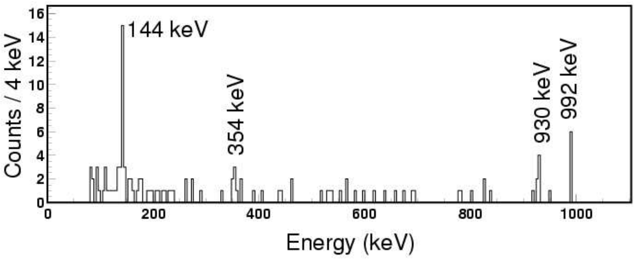

Fig. 4. The gamma rays observed in correlation with ^{76}Ni ions. Four lines belonging to the decay of the $T_{1/2} = 590^{+180}_{-110}$ ns 8^{+} isomer have been identified.

in even-even nickel isotopes. This is because of the coupling between the $f_{7/2}$ proton hole and $g_{9/2}$ neutron will generate only negative-parity states thus making the allowed Gamow-Teller transition to the 0^{+} ground state of even-even nickels impossible if any of the negative-parity and high-spin states becomes a ground state. The low-lying state with paired $g_{9/2}$ neutrons and vacancy in $p_{1/2}$ leads to the generation of 3^{+} and 4^{+} states at low energies. Again, in this case the ground-state beta decay will not be allowed by selection rules. Thus the decay of cobalt isotopes will be dominated by the Gamow-Teller transitions to either negative-parity states in nickel or to excited positive-parity states. The caveat of choosing beta decay to study excited states in nickel isotopes is that the cobalt isobars are much more difficult to produce and a penalty has to be paid not only in having more complicated experimental system, which have to be sensitive to beta-gamma coincidences, but also because production cross-sections are roughly a hundred times smaller. In addition, the beta-delayed neutron emission [28] competes with beta-delayed gamma decay, as observed experimentally [14]. Despite these difficulties the experiments have been successful. The experiment by Sawicka *et al.* [8] led among others to the measurement of excited states in ^{72}Ni. The strongest lines at 1096 keV and 845 keV have been interpreted as the $E2$ decays of the 2^{+} and 4^{+} states. It has been noticed that the adopted 2^{+} energy at 1096 keV is lower by about 330 keV than the SM calculations with S3V TBME [18], which have been working reasonably well for the $N < 40$ nickels [17]. The predicted energy was already lower for ^{70}Ni, but systematic observations proved it is not just a single case anomaly. It led Grawe [18] to link the energies of the 2^{+} states with disappearance of the 8^{+} isomers in the mid-shell. The "experimental" TBME elements has been extracted from ^{70}Ni choosing a very simple model space of two valence neutrons in the $g_{9/2}$ orbital and an inert ^{68}Ni core. These calculations for ^{72,74}Ni led to a new interpretation of the structure of the 8^{+} states. These calculations in a very restricted model space have been recently replaced by the full *fpg* model space shell model with a new set of TBME extracted from the experimental data [19]. The interpretation for the disappearance of the isomerism in refs. [18,19] is based on the existence of the second low-lying 6^{+} state which is a result of coupling four neutrons. The calculations for the series of even-even nickel isotopes for $40 < N < 50$ is shown in fig. 3. The position of the second 6^{+} state is sensitive to small changes of the TBME. The new calculations pushed the energy below the energy of the 8^{+} state opening up a new decay channel with large $B(E2)$. According to the calculations by Lisetskiy the lifetime of the 8^{+} level in ^{72}Ni is 6 ns with small strength ($B(E2) \sim 0.1$ W.u.) to the seniority $\nu = 2$ 6^{+} state and with much larger strength ($B(E2) \sim 3$ W.u.) to the $\nu = 4$ state. Isomers with such short lifetime are usually inaccessible by the standard detection method. The same modification of the TBME which leads to generation of the seniority $\nu = 4$ and spin 6^{+} state is also responsible for the lowering of the energies of the first 2^{+} excited states. This is done by introducing additional mixing to the 2^{+} and 0^{+} states. Not surprisingly, the new SM predicts robust isomerism for ^{70}Ni and ^{76}Ni, where the creation of $\nu = 4$ states would require promoting neutrons from the *fp* shell, or across $N = 50$ shell gap. The expected isomer in ^{76}Ni has indeed been observed for the first time in the GANIL experiment [11] and its full decay cascade and lifetime (fig. 4) have been determined in the NSCL experiment. The overall agreement between shell model and experiment is good. Particularly impressive is the good reproduction of the gap between 8^{+} and 6^{+} states (144 keV exp. *vs.* 135 keV th.), the $B(E2) \sim 0.7$ W.u.) values and the position of the 2^{+} state. In the NSCL experiment the first evidence for the 2^{+} and 4^{+} energies in ^{74}Ni has been obtained completing the lowest-level systematics for the isotopic chain of $40 < N < 50$ nickel isotopes. The energies of these states are close to the theoretical ones. The second 6^{+} states have not been observed in either experiment. thus the interpretation presented above is still not fully confirmed experimentally. Either an experiment with high statistics on ^{72}Co decay or an experiment sensitive to isomers with few nanosecond lifetimes with ^{72}Ni has to be performed. However, even assuming that this circumstantial evidence favors Grawe and Lisetskiy's calculations, we have to answer the question of what is the fundamental reason for such modification of the TBME. The other set of experimental data crucial in constraining the theories should come from odd-even nickel isotopes. Here

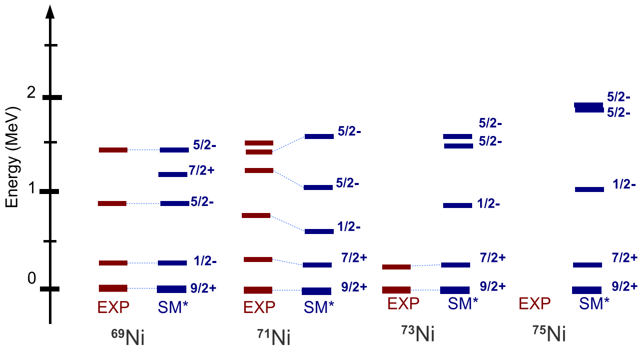

Fig. 5. The calculated and experimental level schemes for odd-mass nickel isotopes [19]. The correspondence between experimental and theoretical levels is tentative.

the long-lived $1/2^-$ and short-lived high-spin isomers were expected for the series ^{71,73,75,77}Ni [25]. The experimental data [29,30], however, are much more difficult to interpret. Very low statistics precludes reliable correlation between experiment and theory, the attempt is presented in fig. 5. No evidence for the short-lived isomers has been found yet and evidence for long-lived $1/2^-$ isomers is difficult to extract from the data.

4 Other experimental developments

In the time between the two ENAM conferences a number of other measurements have been performed which probe in detail the nature of excited states in the region of neutron rich nickel isotopes. These experiments require more statistics than the "discovery" experiments presented above and thus are concentrated around ^{70}Ni. A pioneering experiment on g-factor measurements of isomeric states was performed studying the structure of the wave function of the isotopes ^{69,71}Cu and ^{67}Ni [16] and more recently on ^{61}Fe [31]. Here the surprising result for the $J^\pi = 9/2^+$ isomer in ^{67}Ni was obtained, indicating strong mixing of the previously supposed pure $g_{9/2}$ state.

A very important study of level lifetimes below the isomers was performed using the delayed coincidence method with BaF$_2$ [15]. Nano- and subnanosecond lifetimes in ^{67,69,70}Ni and ^{72}Cu have been studied, and the $B(E2)$ values have been compared with S3V SM [18].

These experiments can be employed to study more exotic isotopes with only small investments into the experimental setup.

The attempts to study the structure of the 2^+ states via $B(E2)$ measurements using Coulomb excitation of the relativistic ion beams has been performed on ^{68}Ni [4].

5 Summary

In a series of experiments using fragmentation reactions and efficient beta and gamma ray detection systems, experimental evidence for the lowest excited states of nickel isotopes has been obtained. The shell-model approach which reproduces well the excitations of even-even isotopes has been developed. The calculation can explain the lower than previously expected positions of the 2^+ excited states and link it to the disappearance of the 8^+ isomerism. The data on odd-mass isotopes are still tentative and need improved measurements.

The evidence for the seniority $\nu = 4$ states at low energies still has to be found. One possible way is to search for the now predicted to be very short-lived isomers in ^{72,74}Ni. A short-lived 8^+ isomer was found in ^{68}Ni in a challenging experiment using a multi-nucleon transfer reactions [5] with a combination of stable beams and targets. This method can potentially be used with radioactive ion beams with sufficient intensity, to search for the isomers in ^{72,74}Ni.

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