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Phys. Rev. C **84**, 037304 — Published 19 September 2011
DOI: 10.1103/PhysRevC.84.037304

Seniority, collectivity, and $B(E2)$ enhancement in ^{72}Ni

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Gamma rays assigned to $^{72}_{28}$Ni$_{44}$ have been identified with Gammasphere in deep-inelastic reactions involving a 450-MeV ^{76}Ge beam and a ^{198}Pt target. Using a combination of spectra produced by double gates on the known 454-, 843-, and 1095-keV members of the ground-state cascade, a coincident line at 199 keV has been identified and is tentatively assigned as the $8^+ \rightarrow 6^+$ transition. These γ-ray coincidences were observed only in prompt events, indicating an 8^+ half-life below 20 ns and requiring a large $B(E2)$ enhancement compared to that expected from a seniority scheme. This value is consistent with models showing decay to a seniority $\nu = 4$, 6^+ level that is depressed by the same two-body interaction responsible for the rather low 1095-keV 2^+_1 energy, as compared to the valence-symmetry counterpart $^{94}_{44}$Ru$_{50}$.

PACS numbers: 23.20.Lv, 27.50.+e

The structure of ^{72}Ni has proven to be both an experimental and theoretical challenge for over a decade. Following the identification of a 232(1)-ns 8^+ isomer in ^{70}Ni$_{42}$, model calculations were confidently put forth with the expectation that similar isomers would be found in ^{72,74,76}Ni$_{44,46,48}$ [1–3]. These *seniority isomers* arise due to the hindrance of $E2$ decays between states of the same seniority ν, particularly as the subshell containing the n valence nucleons is approximately half-filled [4]. This has been observed in the $N = 50$ isotones, for example, where the protons occupy the $g_{9/2}$ subshell; analogously, the 8^+ isomers in neutron-rich Ni isotopes would involve neutron $g^n_{9/2}$ configurations with seniority $\nu = 2$.

Contrary to expectations, no evidence was found in subsequent fragmentation experiments for the presence of isomers in ^{72,74}Ni similar to that in ^{70}Ni. Sawicka *et al.* [5] placed limits on the half-life, ruling out isomers between about 20 ns and 3 ms. One theoretical explanation put forth to account for a possibly short half-life of the 8^+ level in ^{72}Ni indicated that the presence of a $6^+_{\nu=4}$ level at about the same energy as the $6^+_{\nu=2}$ level would provide a fast decay path with a $B(E2)$ value $\sim$50 times larger than that expected from a pure $\nu = 2$ configuration [6].

Another mechanism that would result in a shorter half-life for the 8^+ level in ^{72}Ni would be a significant reduction in the energy of one or more 6^+ levels that would arise from enhanced collectivity for the lower-spin levels. Such a situation is well established for ^{86}Zr$_{46}$, isotone of ^{74}Ni$_{46}$. Unlike the expected quenching of the $B(E2)$ values for the $8^+ \rightarrow 6^+$ transition for the Ni isotopes, the $B(E2)$ values for ^{86,88,90}Zr are almost identical within the uncertainties [7]. Although calculations reported by Galindo *et al.* [8] showed an expected gap of $\sim$100 keV between the 8^+ and 6^+ states in ^{86}Zr, the energy of the observed transition was found to be 629 keV. The significantly shorter $t_{1/2} = 46$-ps half-life for the 8^+ level in ^{86}Zr relative to that of ^{88}Zr is a consequence of the lowering of the energy of the 2^+, 4^+, and 6^+ levels, creating a 629-keV energy gap between the 8^+ and 6^+ levels, in contrast with a 77-keV gap in ^{88}Zr that results in a 1.7-μs half-life. The $B(E2)$ values for the $2^+ \rightarrow 0^+$ transitions for ^{70,74}Ni and ^{74}Zn, even-even neighbors of ^{72}Ni, have been measured and found to exhibit larger collectivity than expected from the simplest shell-model calculations [9, 10] . The enhanced $B(E2)$ values have been attributed to increased interactions between the neutron and proton particle-hole states, where the latter are usually not included in shell-model calculations owing to the large valence-nucleon spaces that would be required.

The expected 8^+ isomer in ^{76}Ni was identified in Ref. [11], with a measured $t_{1/2} = 590^{+180}_{-110}$ ns, as were lower-spin levels in ^{72}Ni following the β decay of 59(2)-ms ^{72}Co. The methods used for these studies at the NSCL have high sensitivity to microsecond-level isomers, permitting confirmation of a 20-ns upper limit for the half-life of any possible 8^+ isomer in ^{72}Ni. In a subsequent experiment, the possible presence of a second β-decaying isomer in ^{72}Co, populating a proposed (4^+_2) level at 2164 keV in ^{72}Ni, was identified [12]. More precise energies of 454.3(2), 842.7(3), and 1095.1(3) keV were reported for the main yrast cascade from the proposed 6^+ level at 2396 keV.

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In an effort to identify the 8^+ level in ^{72}Ni, the Gammasphere array of 100 Compton-suppressed HPGe detectors [13] was used to study γ rays following deep-inelastic-scattering (DIS) reactions of a ^{76}Ge beam with three different heavy, neutron-rich targets. Beams were provided by ATLAS at Argonne National Laboratory. In these reactions, ^{72}Ni is produced via the removal of four protons from the beam ions ($-4p$ channel). This choice was motivated by successful previous studies: in a reaction with a 430-MeV ^{64}Ni beam and a ^{238}U target [14–17], the previously proposed structure for ^{60}Cr, populated in the $-4p$ reaction channel, could be observed [18]. Subsequently, Fioretto *et al.* also reported population of ^{66}Fe levels via $4p$ removal in the reaction of a 460-MeV ^{70}Zn beam with a ^{238}U target [19].

The first experiment attempted in this work utilized a 530-MeV ^{76}Ge beam directed onto a 55-mg/cm^2 ^{238}U target. Standard ATLAS beam timing was used, namely, pulses of approximately 1-ns duration at 82.5-ns intervals. The experimental details have been reported previously [20], and a description of the use of both prompt and delayed coincidences to associate γ rays and isomeric levels was given in Refs. [15, 21]. The data were unfolded into triple-γ coincidences and sorted into separate prompt (PPP) and delayed (DDD) three-dimensional histograms (*cubes*). The PPP cube consisted of events in which three γ rays were required to fall within a 50-ns window centered at the time of the beam pulse, whereas for the DDD cube the three γ rays were detected within about 40 ns of each other in the time region between beam bursts. All cubes were analyzed using the code LEVIT8R [22]. Although it was possible to observe population of known levels in the $-3p$ channel ^{73}Cu in the PPP cube, no evidence could be found for the mutual coincidence of the 454-, 843-, and 1095-keV ^{72}Ni γ rays in double gates set in either the PPP or DDD cube.

In a second experiment, a ^{76}Ge beam was directed onto a 56-mg/cm^2 ^{208}Pb target. In addition, reasoning that the cross section for the four-proton transfer out of ^{76}Ge might be enhanced by transferring them into a nucleus that is four protons below a closed shell, a third reaction was investigated with a 31-mg/cm^2 ^{198}Pt target. In both cases, a 450-MeV beam was delivered by ATLAS with a 1-in-5 timing structure; that is, beam pulses were delivered to target every 412 ns. PPP and DDD cubes were created for both targets as described above, except the width of the delayed time window was about 310 ns. PPD (PDD) cubes with two (one) prompt and one (two) delayed γ rays were also sorted. The delayed γ rays were further constrained to fall within $\sim$50 ns of each other inside the delayed time gate, in order to reduce contributions from random coincidences. Finally, a delayed cube was sorted (SSS, for the ^{198}Pt data only) using a 50-ns-wide "short delay" time window offset by about 25 ns from the prompt time window, intended to enhance isomeric decays that occur within a few tens of nanoseconds of the reaction.

As with the reactions using the ^{238}U target, double gates on the known ^{72}Ni lines in the data taken with the ^{208}Pb target did not reveal any evidence of the 454-843-1095-keV coincidence in prompt or delayed γ-ray triples. In the ^{198}Pt data set, however, double gates in the PPP cube on each pair of these ^{72}Ni lines reveals the third, as is evident in Fig. 1. Energies of 453.6(10), 843.0(10), and 1095.2(5) keV are obtained from these data, consistent with the earlier β-decay work [12]. No conclusive evidence for the 1194.7- or 1069.2-keV transitions reported in Ref. [12] could be identified. However, these may originate from lower-spin (non-yrast) states that are not strongly populated in DIS reactions. Also, since our analysis relies on triple-γ coincidences, firmly associating a 1069.2-keV line with ^{72}Ni when it is coincident with only one known line would be difficult without additional supporting evidence. The presence of the ^{72}Ni lines in only the data taken with the $Z = 78$ ^{198}Pt target supports the hypothesis that this reaction favors removal of four protons from the beam to reach the proton closed shell at $Z = 82$.

With the complexity of the spectra in DIS experiments such as those discussed here, where a very broad range of nuclei are produced and the identification of nuclei relies solely on the observed γ-ray coincidences (e.g., there is no direct Z or A determination with a spectrometer), the possibility of contaminant channels with similar coincident γ-ray energies must be investigated. To this end, the NuDat2 database [23] was searched for nuclei having γ rays within 2 keV of 453.6, 843.0, and 1095.2 keV in mutual coincidence. There were three candidates (none if only ± 1.5 keV is permitted), each of which can be rejected by searching for other lines in those nuclei that would be expected if they were present in our data. In other words, there are no known nuclei with these γ rays that could be a likely contaminant, and they are thus assigned to ^{72}Ni. Additional support of this assignment comes from examining the yields of nuclei produced in this reaction: The intensities of the γ rays feeding the 4^+ state of each even-A Ni and Zn nucleus, measured in spectra double gated on the $4^+ \to 2^+$ and $2^+ \to 0^+$ transitions and corrected for efficiencies, were summed to give a relative yield. These yields peak at $A = 66$ ($-4p6n$ channel) and 72 ($-2p2n$) for the Ni and Zn isotopes, respectively, and fall off dramatically as N increases; the results for the γ rays associated with ^{72}Ni are consistent with this yield curve.

It is important to note that the three coincident transitions were observed only in the PPP cube, not in any other combination involving delayed γ rays, including the "short delayed" SSS cube. These experiments are sensitive to decays occurring at all time scales. Even if an isomer γ decayed with a >1-ms half-life, it would be visible in our spectra. (A β-decaying 8^+ state would populate an unknown high-spin sequence in ^{72}Cu which we would have no means to identify from our data, but this scenario is not supported by earlier experimental efforts [24].) The decays of the isomeric 8^+ states in ^{68,70}Ni ($t_{1/2} = 23$ and 232 ns, respectively) were observed in this data set, with contributions in both the SSS and DDD cubes as well as, for ^{68}Ni, in the PPP cube. The absence of the ^{72}Ni coincidences in these delayed cubes indicates that the decay paths populated in this reaction do not pass through any isomeric state with a half-life of more than ∼20 ns, consistent with earlier upper limits for the half-life of the 8^+ state in ^{72}Ni.

To search for candidates for the $8^+ \to 6^+$ transition in ^{72}Ni, the spectra double gated on each pair of transitions at 453.6, 843.0, and 1095.2 keV in the ^{198}Pt PPP cube were compared for peaks common to all three gates. The only candidate found is at 198.5(5) keV, shown in Figs. 2(a,b,c) amid considerable background. The sum of those three spectra is given in Fig. 2(d), where this peak begins to stand out compared to neighboring lines. A NuDat2 search [23] for each of the triple-γ coincidences involving the 198.5-keV line again revealed no viable candidates for contaminants. (A 197-keV peak, originating from ^{19}F in the Ge detectors themselves, is sufficiently separated from 198.5 keV to not interfere.) We, therefore, tentatively assign the 198.5-keV γ ray as the $8^+ \to 6^+$ transition in ^{72}Ni. Although there is no direct experimental evidence of an 8^+ assignment for the parent state, it is a plausible assumption based on the expected population of yrast levels in this reaction. The intensity of this transition is roughly half that of the 453.6-keV $6^+ \to 4^+$, though with rather large uncertainties.

The proposed level scheme for ^{72}Ni is shown in Fig. 3 and includes the tentative assignment of the 198.5-keV $8^+ \to 6^+$ transition, fixing the position of the 8^+ level at 2590 keV. Included in the plot are the results of several theoretical approaches to the description of the even-even Ni nuclei, for which the $g_{9/2}$ neutrons are the valence nucleons, as well as the experimentally established levels of ^{70,76}Ni [2, 3, 5, 11]. The position of the proposed 8^+ level in ^{72}Ni fits smoothly between those of the 8^+ levels at 2860 keV in ^{70}Ni and 2420 keV in ^{76}Ni.

The levels calculated using the S3V approach are taken from Grawe *et al.* [5, 6]. The NR78 levels are from Mazzocchi *et al.* [11], based on calculations by Lisetskiy *et al.* [25] and Horoi *et al.* [26]. The latter paper presented an analysis of levels in nuclei with valence $g_{9/2}$ nucleons and noted the differences between the $Z = 28$ Ni isotopes and $N = 50$ isotones. In particular, their analysis shows the strong correlation between the position of the $4^+_{\nu=4}$ level and the energy of the first 2^+ level. For the $N = 50$ isotones with 2^+ energies near 1.5 MeV, the $4^+_{\nu=4}$ level lies well above the $4^+_{\nu=2}$ level. In contrast, for the even-even Ni isotopes with 2^+ energies near 1.1 MeV, the $4^+_{\nu=4}$ level comes down in energy and becomes yrast. Comparison of the models and the experimental levels shows that the S3V approach places the 8^+ level low enough in energy, at 2616 keV, to be near the proposed position at 2590 keV, while placing the $6^+_{\nu=4}$ level ∼200 keV above it. The high position of the latter is correlated with the high position of the calculated 2^+_1 level. In the NR78 calculations, the $2^+_{\nu=2}$ and $4^+_{\nu=4}$ levels are in good agreement with the observed ^{72}Ni ground-state band. This model places both $6^+_{\nu=2,4}$ states below the $8^+_{\nu=2}$; the one with $\nu = 2$ is yrast, but the $\nu = 4$ has similar energy and provides a fast (predicted 35-ns) decay path for the 8^+ state.

Recently, Van Isacker has shown that a purely algebraic analysis of levels in nuclei with four identical valence $g_{9/2}$ nucleons (either neutrons or protons) leads to a structure for ^{72}Ni quite similar to those described above that exhibit both $\nu = 2$ and $\nu = 4$ levels [27]. The unique feature of this description is the lowering of the $\nu = 4$, 4^+ and 6^+ levels to positions below their $\nu = 2$ counterparts, coupled with large $B(E2)$ values for both the $8^+_{\nu=2} \to 6^+_{\nu=4}$ and $6^+_{\nu=4} \to 4^+_{\nu=4}$ transitions. This approach had been applied to the odd-Z, $N = 50$ isotones with $g_{9/2}$ valence protons by Escuderos and Zamick to describe seniority conservation and seniority breaking [28]. Subsequently, Van Isacker and Heinze demonstrated the significant effects of the algebraic approach for $B(E2)$ values for the even-even $N = 50$ isotones ^{94}Ru and ^{96}Pd, each of which has four valence $g_{9/2}$ protons, particles or holes [29]. Owing to the relatively high ∼1.5-MeV energies for the 2^+_1 levels in both of these nuclei, the $\nu = 4$, 4^+ and 6^+ levels lie above their $\nu = 2$ counterparts. For ^{72,74}Ni, the lower ∼1.1-MeV energies of the 2^+_1 levels bring down the $\nu = 4$ levels such that the relative positions are reversed. The spectrum of states for ^{72}Ni from these pairing, seniority, and quasi-spin-algebra calculations (PSQ) have been estimated from Fig. 2 of Ref. [27] and are included here in Fig. 3. The $2^+_{\nu=2}$ and $4^+_{\nu=4}$ levels in the PSQ calculations are similar to NR78 in their agreement with data. Unlike in NR78, here the $6^+_{\nu=4}$ level is yrast; both it and the 8^+ state are lower in energy than in the NR78 calculations, and are in better agreement with the experimental results. Not shown in Fig. 3 is a 2164-keV (4^+) level identified in β decay [12], which matches nicely with the calculated 2173-keV $4^+_{\nu=2}$ state. Overall, PSQ reproduces the observed level scheme rather well.

Following a pure seniority scheme for the $B(E2; 8^+ \to 6^+)$ values in the Ni isotopes and scaling from the energies and half-lives in ^{70,76}Ni (see Fig. 3), the proposed 198.5-keV transition in ^{72}Ni would be expected to have $t_{1/2} \sim 1$ μs [4]. In order for the observed half-life to be less than 20 ns, a significant increase of the $B(E2)$ by ∼50 or more is required. Such enhancement is consistent with those proposed by the models that also show a lowered energy for the $6^+_{\nu=4}$ level, with predicted half-lives typically on the order of several nanoseconds.

In summary, a new transition at 198.5 keV has been identified in ^{72}Ni that is tentatively placed as the transition from an 8^+ level at 2590 keV to the previously proposed 6^+ level at 2392 keV. The transition energy and half-life limit are consistent with an increased $B(E2)$ value for the $8^+ \to 6^+$ transition that was suggested in a number of model calculations. Alternative experimental approaches are currently being considered in order to investigate the structural properties of ^{72}Ni further.

The authors would like to thank J. P. Greene (ANL) for preparing the targets and A. Lipski and R. S. Lefferts (SUNY at Stony Brook) for arranging availability of the ^{198}Pt material. This work was supported in part by the

U.S. Department of Energy, Office of Nuclear Physics, under Grant No. DE-FG02-94ER40834 and Contract No. DE-AC02-06CH11357, and the Polish Ministry of Science under Contract No. NN202103333.

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Figures

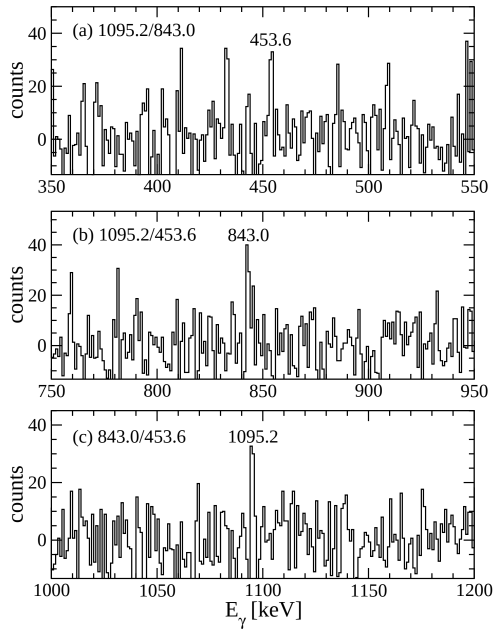

FIG. 1: Background-subtracted spectra double gated in the PPP cube on the known γ rays of the ^{72}Ni ground-state band. The gating transitions and labels for the known coincident ^{72}Ni peaks are given in keV on each panel. The dispersion is 1 keV/channel.

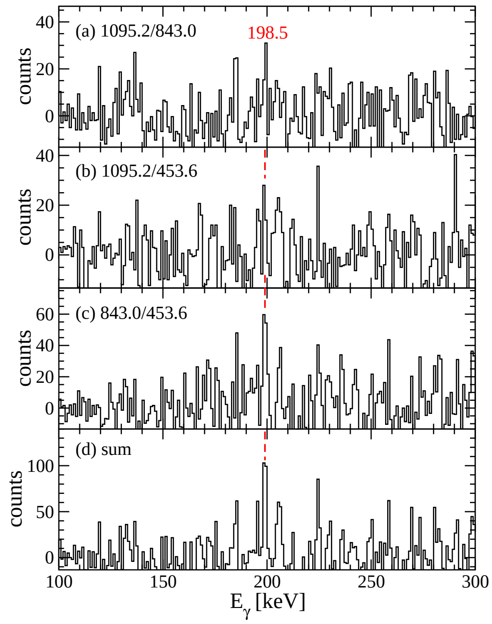

FIG. 2: (Color online) (a-c) Low energy portions of the spectra from Fig. 1. (d) Sum of the spectra in panels (a-c).

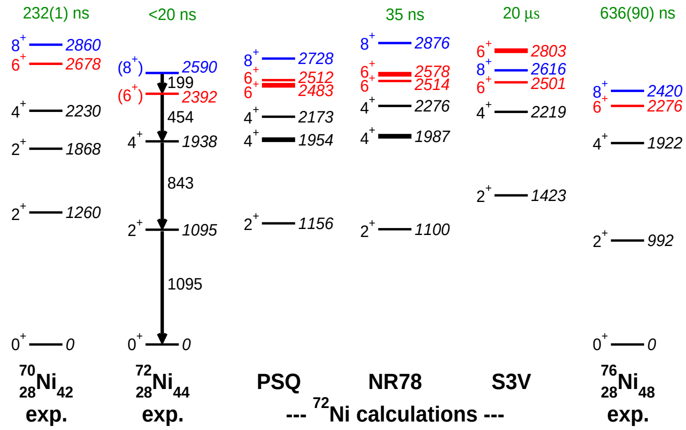

FIG. 3: (Color online) Measured and calculated level systematics for the neutron-rich Ni isotopes, including the proposed assignment of the 199-keV transition observed in this measurement as the $8^+ \rightarrow 6^+$ transition. Calculated $\nu = 4$ states are represented by thick lines. The measured or calculated 8^+ half-life is indicated above each sequence. The details of the calculations are discussed in the references contained in the text. Online, 6^+ and 8^+ levels are shown in red and blue, respectively, to guide the eye.