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Direct lifetime measurements of the excited states in ^{72}Ni

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The lifetimes of the first excited 2^+ and 4^+ states in ^{72}Ni were measured at the National Superconducting Cyclotron Laboratory with the recoil-distance Doppler-shift method (RDDS), a model-independent probe to obtain the reduced transition probability. Excited states in ^{72}Ni were populated by the one-proton knockout reaction of an intermediate energy ^{73}Cu beam. γ-ray-recoil coincidences were detected with the γ-ray tracking array GRETINA and the S800 spectrograph. Our results provide evidence of enhanced transition probability $B(E2; 2^+ \to 0^+)$ as compared to ^{68}Ni, but do not confirm the trend of large B(E2) values reported in the neighboring isotope ^{70}Ni obtained from Coulomb excitation measurement. The results are compared to shell model calculations. The lifetime obtained for the excited 4_1^+ state is consistent with models showing decay of a seniority $\nu = 4$, 4^+ state, which is consistent with the disappearance of the 8^+ isomer in ^{72}Ni.

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With the advances in rare isotope production facilities, a broad swath of nickel isotopes are now experimentally accessible covering both isospin symmetric as well as highly asymmetric systems. Particular to the nickel isotopes is the presence of three accessible doubly magic systems: ^{48}Ni, ^{56}Ni, and ^{78}Ni. This allows for a systematic investigation of the shell effects. Furthermore, these systems are tractable theoretically for recently developed state-of-the-art shell model approches which provide extensive and detailed predictions. Key observables can serve to discriminate between these models. In this work, we will focus on the properties of the $N = 44$ nucleus ^{72}Ni, an isotope midway between the $N = 40$ and $N = 50$ subshell closures. We utilize the properties of the first excited 2^+ state, traditionally considered as a measure of the contribution of collective effects. Several unexpected effects have been observed in neutron-rich nickel isotopes. One of them was the measurement of reduced transition probability $B(E2; 2^+ \to 0^+)$ in ^{70}Ni ($N = 42$) obtained in a Coulomb excitation at $60A$ MeV [1]. It was determined to be high as compared to ^{68}Ni. That phenomenon was explained as due to a strong core polarization effect beyond $N = 40$ which has its origin in the $\pi f_{5/2} - \nu g_{9/2}$ proton-neutron interaction. This experimental result was later interpreted with a theoretical shell model calculation [2]. The enhanced collectivity in nickel isotopes for $N > 40$ was also reported in ^{74}Ni ($N = 46$) [3] where a large transition strength was deduced from the deformation parameter measured in the 2^+ inelastic scattering cross-section measurement. This value, however, was not confirmed in a recent Coulomb excitation measurement at $95.8A$ MeV where the reduced probability was found to be lower, posing a question about the degree of enhanced collectivity in this region [4].

The non-observation of 8^+ isomers in ^{72}Ni and ^{74}Ni [5, 6] remains to be an unsolved problem in this region. The explanation for missing isomers was suggested by Grawe et al. [7], who linked the increased collectivity of high spin states to the unusually low excitation energy of the first 2^+ states in the $N > 40$ series of isotopes (see Fig.4 (top)). According to Grawe's hypothesis, the excitations of the high seniority ($\nu = 4$) 4^+ and 6^+ states are depressed with respect to their simpler $\nu = 2$ counterparts due to strong two-body matrix elements (TBME), which also influences the excitation energy of the first 2^+ states.

To further investigate the open question of collective behavior in the nickel isotopes above $N = 40$ we measured the lifetimes of the first 2^+ and 4^+ excited states in ^{72}Ni. To eliminate the model-dependence we used the

Recoil Distance Doppler-Shift (RDDS) method ([8], and references therein). RDDS is a well-established technique for measuring lifetimes of nuclear levels to obtain reduced transition probabilities in a non-intrusive and model-independent way. The measurement was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A 140 MeV/nucleon ^{82}Se primary beam was accelerated by the coupled K500 and K1200 cyclotrons. The beam impinged upon a 423 mg/cm^2 ^{9}Be production target. The secondary cocktail beam was selected by the A1900 fragement separator [9] with a momentum acceptance of 1%. The resulting purity of the desired secondary component, ^{73}Cu, was 15%. The remaining contaminants ($^{75-74}$Zn, $^{77-76}$Ga and ^{72}Cu) were distinguished from ^{73}Cu by their time of flight measured between 1 mm thick plastic scintillators located at the A1900 focal plane and the object position of the S800 spectrograph [10] . The secondary beam was delivered to a new plunger device, the TRIple PLunger for EXotic beams (TRIPLEX) [8, 11, 12], at the S800 target position with an energy of 102 MeV/nucleon and an average intensity of 8400 pps. Excited states in ^{72}Ni were populated by one-proton knockout reactions from ^{73}Cu on a 55.5 mg/cm^2 ^{9}Be plunger target. The velocity distribution of nuclei emerging from the target was centered at $\beta_{\mathrm{target}} = v/c = 0.43$. These nuclei were further slowed down by the 482.8 mg/cm^2 ^{197}Au plunger degrader to a final velocity distribution cenetered at $\beta_{\mathrm{degrader}} = 0.38$. De-excitation γ-rays were measured with the Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA) [13] in coincidence with the reaction residues. In this experiment, seven GRETINA detector modules, which consist of 28 Ge crystals in total, were used. Using the digitally recorded signal, the decomposition described in Ref. [13] reconstructed the interaction position and improved the Doppler-shift corrections for γ-rays emitted from recoils. Knockout reaction residues were identified on an event-by-event basis by their energy loss in the S800 and their time-of-flight. To achieve a good balance between the detection efficiency and Doppler-shift due to the recoil velocity changes caused by energy loss through the foil, the plunger-target was placed 12 cm upstream of the nominal center of GRETINA. ^{72}Ni gated γ-ray spectra were collected at different target-degrader separations: 0.3, 0.6, 1.0, 2.0, 3.0 and 10.0 mm. Each separation leads to a unique γ-ray spectral line shape which depends on the lifetime of the state of interest and the observation angle. Decays happen before or after the degrader and contribute to peaks corresponding to a fast or slow velocity, respectively. To maximize the sensitivity to the lifetimes the γ-ray spectra were constructed from the four forward GRETINA detectors covering the laboratory angles of $20° - 50°$ with respect to the beam axis.

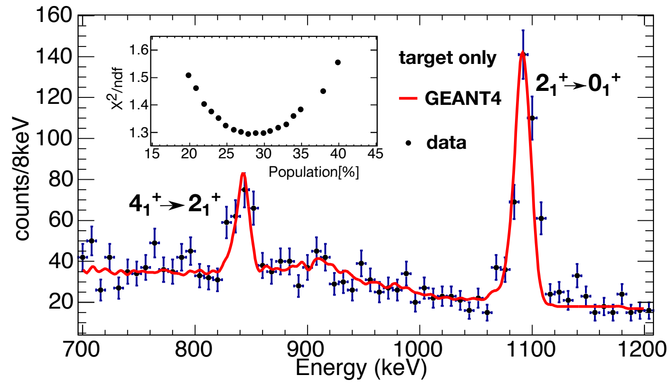

FIG. 1. (Color online) Experimental Doppler-shift corrected γ-ray spectrum of ^{72}Ni with statistical error bars for the target only measurment compared to best-fit GEANT4 simulations (red solid line). The inset shows a distribution of reduced χ^2 values from the fit for the population ratio of the excited 4^+ state.

Lifetimes of the excited states in ^{72}Ni were determined by comparing the measured and simulated spectra. The simulation was performed using a program utilizing the GEANT4 toolkit [14, 15] which included modifications to incorporate GRETINA in the configuration used in our experiment. To extract the lifetime, the least-squares method was employed, using lifetimes of the excited states, an exponential function was chosen to describe the background in the region of the fit, and an overall normalization factor as parameters of the fit. The population ratio of the excited states 2_1^+ and 4_1^+ with 69(6)% and 31(6)%, respectively, was determined from the target only data as shown in Fig.1. The degrader-to-target yield ratio, which represents the fraction of proton-knockout reactions on ^{73}Cu that occurred in the degrader compared to the target, was estimated using 10 mm data set, as any slow component left is attributed to reactions on the degrader, and was found to be 20(2)%. The Doppler-reconstructed energy spectrum had two clearly visible peaks. These peaks were found to correspond to the $2_1^+ \rightarrow 0^+$ (γ-ray energy 1096(2)keV [5]) and $4_1^+ \rightarrow 2_1^+$ (γ-ray energy 845(2)keV [5]) transitions in ^{72}Ni see Fig.1. No gamma-ray signatures of feeding from the 6_1^+ (454.5(3)keV [5, 16]) or 4_2^+ (1069.2(3)keV [17]) states were observed The lifetime of the first 2^+ state was obtained using all distances data (0.3 - 10.0 mm separation) and by taking into account the feeding from the 4_1^+ state, see Fig. 2 and Fig. 3 The lifetime of this state was determined to be $\tau(2_1^+) = 7(1)$ ps which corresponds to a reduced transition probability $B(E2; 2^+ \rightarrow 0^+) = 74(10)[e^2 fm^4]$. In the simulation the lifetime of the first 4^+ state was varied from 0 to 100 ps in steps of 1 ps. This effective lifetime accounts for any small feeding contribution of the second excited 4^+ state and the first 6^+ state in ^{72}Ni. The lifetime of the 4_1^+ state was determined mainly from the 2 mm, 3 mm and 10 mm target-degrader distance (data shown

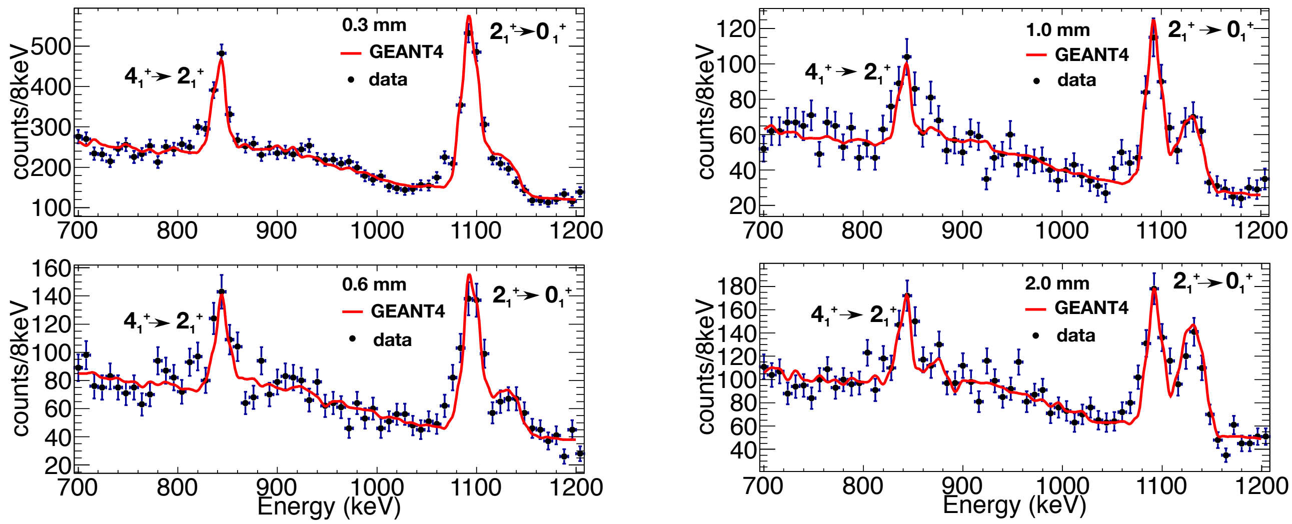

FIG. 2. (Color online) Experimental Doppler-shift corrected γ-ray spectra for ^{72}Ni with statistical error bars compared to best-fit GEANT4 simulations (red solid line).

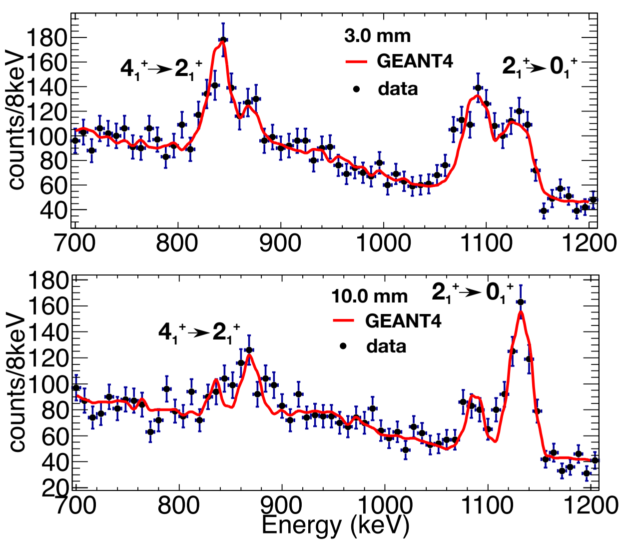

FIG. 3. (Color online) Experimental Doppler-shift corrected γ-ray spectra for ^{72}Ni with statistical error bars compared to best-fit GEANT4 simulations (red solid line). Using these two largest target-degrader distances the lifetimes of the excited 2^+ and 4^+ states were deduced.

in Fig. 2 and Fig. 3). The slow component of the 4_1^+ transition emerges only in these two experimental energy spectra indicating a long lifetime. Indeed, the lifetime was found to be $\tau(4_1^+) = 38(9)$ ps, corresponding to $B(E2; 4_1^+ \to 2_1^+) = 50(9)[e^2 fm^4]$.

In Fig. 4 (top) we present the systematics of 2^+ excitation energies and compare them with different theoretical models: GXPF1A [18] ($N = 32 - 38$), LIS [19], JUN45 [20], LNPS [21, 22] and the chiral N3LO interaction [23] (referred later in the text and in the figures as Monte Carlo Shell Model (MCSM) [24] [25]). The 2_1^+ energy systematics in nickel isotopes between $N = 40$ and $N = 50$ established in the isomer and beta decay studies [16, 26, 27] demonstrate a decreasing trend when approaching ^{78}Ni. The experimental energies are well reproduced with almost all theoretical models presented here, except for JUN45 [20] which overestimates them. This discrepancy was explained as coming from the missing $f_{7/2}$ orbital in the $f_{5/2}pg_{9/2}$ model space [20]. Within the shell model picture, starting with ^{69}Ni ($N > 40$) valence neutrons start occupying the $\nu g_{9/2}$ orbital that determines the properties of the nuclei (or isotopes) in this region, for example, the influence of the $\nu g_{9/2}$ on the size of the $Z = 28$ proton shell gap, which is formed between the $\pi f_{7/2}$ and the $\pi p_{3/2}$ (or $\pi f_{5/2}$) orbitals. Lisetskiy et al. quantified this trend of the lowering of the 2^+ energies with modification of the pairing two-body matrix element related to the $\nu g_{9/2}$ orbital, which could mimic the effect of $Z = 28$ core excitations [16, 19]. He developed a set of residual interactions which explained not only the 2^+ energies trend but also the properties and disappearance of the 8^+ isomers [16] in ^{70,72,74,76}Ni. While Lisetskiy's model provided compelling arguments to explain the experimental systematics, it used phenomenological methods by selectively modifying key matrix elements to fit the experimental data. As a result, its predictive power could be limited to the stems used in the fit. Large-scale shell models such as LNPS [21, 22] and MCSM [24] [25] calculations also are in good agreement with the data of the 2_1^+ energies while also predicting well the doubly-magic nature of ^{78}Ni.

The systematics of the reduced transition probabilities for the nickel isotopes with $N = 32 - 50$ are pre-

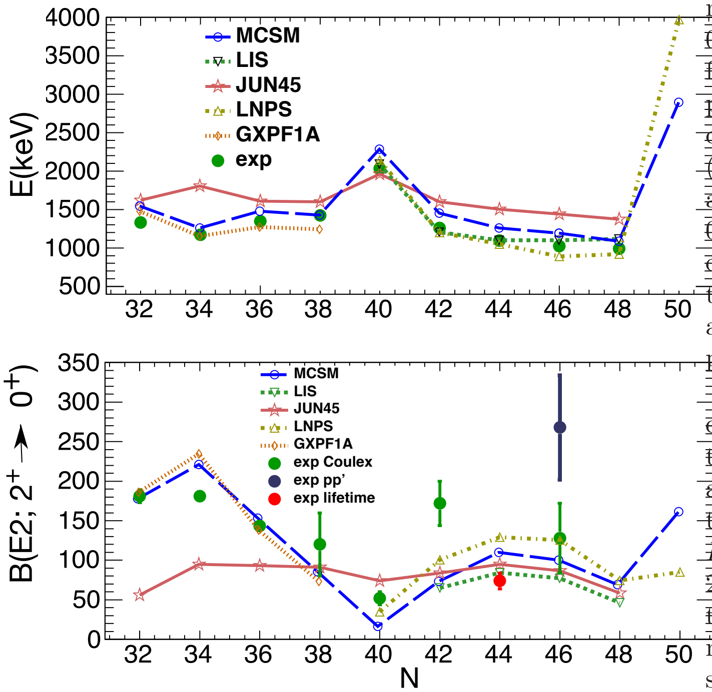

FIG. 4. (Color online) Top: Experimental 2^+ excitation energies in the nickel isotopes ($^{60-78}$Ni) compared to different theoretical models [18–21, 25]. Bottom: Experimental reduced transition probabilities $B(E2;2^+ \to 0^+)[e^2fm^4]$ [1, 3, 4, 28] in the nickel isotopes compared to theoretical values from different models [18–21, 25].

sented in Fig.4 (bottom). In red we show the result for ^{72}Ni obtained from this experiment. This result is much lower than the previously indicated trend measured with Coulomb excitation for ^{70}Ni [1] and the $(p,p^{'})$ experiment for ^{74}Ni [3]. It is, however, closer (within the error bars) to the new result from Coulomb excitation measurement of ^{74}Ni [4], confirming the indication of normal rather than enhanced (as reported in [1]) core-polarization picture in neutron-rich nickel isotopes. We compare our result with shell model calculations. The best agreement is achieved when comparing our result with the LIS interaction. However, one has to take into consideration the empirical modification made and higher effective charges $(e_p,e_n)=(2.0,1.0)e$ [19] used in this interaction to account for the reduced valence space. The calculations of the JUN45 ($(e_p,e_n)=(1.5,0.5)e$) interaction are in a good agreement with the data at $N>40$ but fail to reproduce transition probabilities at lower masses. The LNPS effective interaction($(e_p,e_n)=(1.31,0.46)e$) predicts slightly higher values of the reduced transition probability but not high enough to indicate a strong core polarization in ^{68}Ni. None of those interactions, however, account for the excitations related to the $\nu f_{7/2}$ orbital which is not included in the model space. Those possible excitations were accounted for only in the newest MCSM calculations [24] [25] performed in the full $0f_{7/2}0f_{5/2}1p_{5/2}1p_{3/2}g_{9/2}d_{5/2}$ space using conventional effective charges $(e_p,e_n)=(1.5,0.5)e$, giving in this case possibly the most quantitative overall agreement with the data. In this interaction, the two-body matrix elements (TBMEs) of the pf shell are those of the GXPF1A interaction and the TBMEs of the f_5pg_9 shell related to the $0g_{9/2}$ orbit were taken from the JUN45 interaction. The other TBMEs are from the G-matrix effective interaction calculated from the chiral N3LO interaction [23]. In addition, no strong evidence of influence from ^{68}Ni core polarization was indicated, in agreement with our result.

Given the observed lifetime of the 4_1^+ state and its excitation energy we compare our result with the LIS theoretical calculations as a follow-up on the discussion about the seniority-changing and non-changing transitions (see [17, 19]). The theoretical transition strengths $B(E2;4^+_{\nu=4} \to 2^+_{\nu=2}) = 93e^2fm^4$ and $B(E2;4^+_{\nu=2} \to 2^+_{\nu=2}) = 2.4e^2fm^4$ differ by a factor of 40. Considering the possibility of an inverted energy ordering of the seniority states the data, while not in excellent agreement, support a $\nu=4$ assignment. The nonobservation of the excited 4_2^+ state could indicate that its lifetime was too long to be detected in our experimental conditions. The specroscopic factors to populate both 4_1^+ and 4_2^+ states calculated for the knockout reaction using $jj44bpn$ interaction [29] are similar in magnitude ($C^2S \sim 0.02$) and lead to very similar cross sections [30] calculated using eikonal approximation. These interactions produce similar $B(E2)$ values to that of Listetskiy ($90e^2fm^4$ and $0.6e^2fm^4$ for 4_1^+ and 4_2^+ states, respectively). Considering the momentum of the outgoing beam and the experimental setup, the limit for the observation of the decay of an excited state was about 75 ps. Using the de-excitation energy of the experimental level postulated to be the 4_2^+ in the β-decay experiment [17] the experimental half-life for the present observed 4^+ state, and incorporating a theoretical hindrance factor of 40 for seniority-conserving transitions, we would expect a lifetime on the order of 400 ps. Thus, the unobserved excited 4_2^+ state could be of seniority $\nu=2$ decaying to the first excited $2^+_{\nu=2}$ state outside the view of the experimental apparatus. Assuming this analysis is correct, the $\nu=4$ 6^+ state is also posited to have a lower excitation energy which is a possible reason for the disappearance of the 8^+ isomer in both ^{72}Ni and ^{74}Ni isotopes.

We measured the electromagnetic observables for the first two excited states in neutron-rich ^{72}Ni with the recoil distance method following a one-proton knockout of ^{73}Cu. The lifetime of the excited 2_1^+ state was determined to be $\tau(2_1^+)=7(1)$ ps while for the excited 4_1^+ state $\tau(4_1^+)=38(9)$ ps. Calculated reduced transition probabilities for the transitions $0_1^+ \to 2_1^+$ and $2_1^+ \to 4_1^+$ were compared to various shell model predictions. In the former case, we observe no evidence of a polarization of the proton core (as suggested in [1]) which is also supported by the recent study of the quadrupole transition strength in ^{74}Ni [4].

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