Shell Evolution towards ^{78}Ni: Low-Lying States in ^{77}Cu

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The level structure of the neutron-rich ^{77}Cu nucleus was investigated through β-delayed γ-ray spectroscopy at the Radioactive Isotope Beam Factory (RIBF) of the RIKEN Nishina Center. Ions of ^{77}Ni were produced by in-flight fission, separated and identified in the BigRIPS fragment separator, and implanted in the WAS3ABi silicon detector array, surrounded by Ge Cluster detectors of the EURICA array. A large number of excited states in ^{77}Cu were identified for the first time by correlating γ rays with the β decay of ^{77}Ni, and a level scheme was constructed by utilizing their coincidence relationships. The good agreement between large-scale Monte Carlo Shell Model calculations and experimental results allowed the evaluation of the single-particle structure near ^{78}Ni and suggests a single-particle nature for both the $5/2^-_1$ and $3/2^-_1$ states in ^{77}Cu, leading to doubly-magic ^{78}Ni.

The evolution of the shell structure is one of the key motivations to study atomic nuclei with large neutron excess. The goal is to understand effects due to this excess of neutrons that are responsible for deviations from the conventional harmonic oscillator description with a strong, attractive spin-orbit coupling, which characterizes the shell structure and properties of nuclei near the line of β stability. Such deviations are related to the monopole components of the effective nucleon-nucleon interaction and their strong effects on the single-particle energies (SPE). The spin-dependent central component influences the energies of all single-particle orbitals, while the tensor interaction alters the spin-orbit splitting when specific orbits are filled by neutrons or protons [1–8].

For the chain of Ni ($Z = 28$) isotopes between $N = 40$ and $N = 50$ theoretical models predict significant changes in the proton SPE as the $\nu 1g_{9/2}$ shell is filled by neutrons [3, 4, 9–12]. Here, the tensor force responsible for SPE shifts becomes strongly attractive between two orbits with spins $j_> = l + 1/2$ and $j'_< = l' - 1/2$ (or $j_< = l - 1/2$ and $j'_> = l' + 1/2$) (l and l' denote orbital angular momentum of protons and neutrons, respectively) and repulsive between those with spins $j_>$ and $j'_>$ (or $j_<$ and $j'_<$) [3]. Accordingly, the modification of the $\pi 1f_{5/2}$ and $\pi 2p_{3/2}$ orbitals with increasing neutron number causes an inversion of these orbitals around the middle of the shell and thus the evolution of the Z=28 gap towards ^{78}Ni will be tightly bound to the questions as to what extent and where the mentioned inversion will occur between the two shell closures. Experimental information on the shell structure in the vicinity of ^{78}Ni is very sparse due to the large neutron excess and the resulting difficulty to perform spectroscopy in this region. The neutron-rich Cu nuclei with protons lying in the pf shell ($1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$) and neutrons occupying the $1g_{9/2}$ orbital are of crucial importance. Their excited levels provide the experimental basis to search for changes of the shell structure around ^{78}Ni and to test the predictive power of shell model (SM) calculations and their effective interactions.

Earlier β-decay, Coulomb excitation, and multi-nucleon transfer reaction studies showed rather complicated level sequences in the neutron-rich $^{69-73}$Cu isotopes, caused by different excitation modes [13–18]. The low-lying $5/2^-$ and $7/2^-$ states were identified to be of predominantly single-particle character, based on $\pi 1f_{5/2}$ particle and $\pi 1f_{7/2}^{-1}$ hole excitations, respectively, while the lowest-lying $1/2^-$ state was found to be of more collective nature rather than having a dominant $\pi 2p_{1/2}$ single-particle contribution. In addition to $7/2^-$ states with single-particle character, other $7/2^-$ states were observed and explained by the coupling of $\pi 1f_{5/2}$ or $\pi 2p_{3/2}$ protons to the 2_1^+ state of the corresponding Ni core. It was shown that the level energies and $B(E2)$ transition probabilities of these particle-core excitations in the $^{A+1}$Cu isotopes closely follow the trends observed for the ^{A}Ni cores [15].

Experimental data for heavy Cu isotopes are very limited. In addition to the experimental determination of the $5/2^-$ ground-state spin-parity [19], two low-lying microsecond isomeric states were observed in ^{75}Cu [20–22]. No information on excited states in the Cu isotopes beyond ^{75}Cu is available in the literature. For ^{77}Cu only the half-life of the ground state is known from β-decay experiments [23–26]. The 5/2 ground-state spin of ^{77}Cu was measured in an in-source laser spectroscopy experiment [27]. Identifying excited states in ^{77}Cu permits the evaluation of the single-particle structure near doubly magic ^{78}Ni and to investigate the effects of the proton-neutron tensor interaction. In this Letter, we report on the first measurement of excited states in neutron-rich ^{77}Cu by means of β-delayed γ-ray spectroscopy.

An experimental campaign to study neutron-rich nuclei took place at the Radioactive Isotope Beam Factory of the RIKEN Nishina Center [28, 29]. The present data were collected during two separate beam times in which radioactive isotopes were produced via in-flight fission of ^{238}U projectiles with an incident energy of 345 A·MeV on thick ^{9}Be targets. The targets had a thickness of 3 mm and the average primary beam intensity was around 10 pnA during both experiments. Nuclei in the secondary beam were identified in atomic number (Z) and mass-to-charge ratio (A/Q) by measuring their time of flight (TOF), magnetic rigidity ($B\rho$), and energy loss (ΔE), and delivered to the final focal plane through the BigRIPS fragment separator and ZeroDegree spectrometer [30–33]. Ions arriving at the focal plane were degraded with an aluminum foil to implant them in the central sections of the silicon detector array WAS3ABi [34], consisting of 8 Double-Sided Silicon Strip Detectors (DSSSD). The WAS3ABi array served as an active stopper to detect the implantation of ions and electrons from the β decay and subsequent internal conversion processes. The EURICA spectrometer (EUroball RIken Cluster Array) [34, 35] surrounded the active stopper to detect γ rays emitted after the β decay of the implanted ions. It consisted of 84 HPGe detectors in 12 clusters with an absolute full peak efficiency of approximately 8% at 1 MeV. Nuclei identified as ^{77}Ni were correlated with a total of 41806 subsequent β decays on an event-by-event basis by requiring that the implanted ion and the β-decay electron were detected in the same or in neighboring pixels of the same Si layer within a time window of 1 s.

Figure 1 shows the total spectrum of γ rays correlated with ^{77}Ni ions implanted into WAS3ABi. The strongest γ-ray transitions originate from ^{77}Cu, but the spectrum can be expected to contain also transitions from the short-lived subsequent β decay (^{77}Zn) and from the β-delayed neutron emission branch (^{76}Cu, ^{76}Zn). The β-delayed neutron emission probability obtained in the present data is reported as 24 (16)% in Ref [36]. Those transitions that could be associated with subsequent decay products are indicated in Fig. 1. All other transitions are assumed to originate from ^{77}Cu and are labeled by their energies. Absolute intensities are listed in Table I.

The analysis of γ-γ coincidences allowed the construction of a decay scheme of ^{77}Cu for the first time. Figure 2 shows examples of coincidence spectra gated on the 946-, 830- and 293-keV transitions. Transitions that appear rather weakly in the coincidence spectra were only included in the level scheme, and hence used to establish excited states, if their energy matched that of competing cascades. The decay scheme resulting from the coincidence analysis is shown in Fig. 3. Weak transitions, which are associated with ^{77}Cu, but could not be placed in the decay scheme due to insufficient coincidence relationships, are given in parentheses in Figures 1 and 2 and Table I. The 2068-keV transition is relatively strong in the singles spectrum, but appears only very weakly in the spectrum gated on the 946-keV transition, which suggests that the transitions are parallel and the weak coincidence is random.

Spin and parity assignments were performed on the basis of $\log(ft)$ values, γ-decay branching ratios, and systematics. A beta-decay half-life of 158.9(42) ms [36] and the β-decay energy of 11.765(526) MeV [37] were adopted for the evaluation of the $\log(ft)$ values. The ground-state spin-parity of the ^{77}Ni parent nucleus was assumed to be $9/2^+$, dominated by an odd neutron hole in the $1g_{9/2}$ orbital in the SM calculations described below. The $\log(ft)$ values indicate in most cases a first-forbidden decay which could arise from decay of a neutron in the $1g_{9/2}$ orbital into the proton $1f_{5/2}$ orbital within the major shell. It should be pointed out that the reported $\log(ft)$ values given in Fig. 3 should be considered to be lower limits due to possible non-detection of high-energy γ rays.

State-of-the-art Monte Carlo Shell Model (MCSM) calculations [38, 39] were performed for ^{77}Cu to interpret the experimental results and draw conclusions about the single-particle structure near ^{78}Ni. The calculations used a valence space comprising the full pf shell in addition to the $1g_{9/2}$ and $2d_{5/2}$ orbitals for both protons and neutrons, *i.e.* a ^{40}Ca core, and the A3DA interaction including minor corrections [38]. The resulting energy levels for ^{77}Cu are included and compared to the experimental results in Fig. 3. Overall agreement obtained between experiment and theory, in particular below 2 MeV excitation energy, supports spin and parity assignments proposed in the present work.

To determine the probability of a state having a single-paricle structure, spectroscopic factors, C^2S were calculated for initial (^{76}Ni) and final (^{77}Cu) wave functions. We note that, in the present case, spectroscopic factors can be identified as probabilities of the particle-core excitations under the assumption that the $Z = 28$ closed shell holds and the neutron wave function does not change between the initial and final states. Standard effective charges of $e_\pi = 1.5e$ for protons and $e_\nu = 0.5e$ for neutrons were used to calculate $B(E2)$ transition probabilities.

The calculations find the spin of $5/2^-$ for the ground state, consistent with the previous experimental studies [25–27]. The lowest $3/2^-$ excited state at 293 keV compares rather well with the calculated value of 184 keV. The upper limit for the β-decay branching of 1.2 % to the $3/2^-$ state suggests additional γ-ray feedings from higher excitation energies for which the detection efficiency is lower. Spectroscopic factors for the two states are calculated to be $C^2S(5/2^-_1) = 0.64$ for the $\pi 1f_{5/2}$ and $C^2S(3/2^-_1) = 0.62$ for the $\pi 2p_{3/2}$ orbitals, indicating a predominant single-particle character for both states. The changing of the ground-state spin and parity from $3/2^-$ to $5/2^-$ as a function of N is primarily due to the characteristic feature of the tensor force: the $1f_{5/2}$ proton orbital is lowered relative to the $2p_{3/2}$ orbital by the monopole effect from the eight neutrons in the $1g_{9/2}$, as shown in terms of effective SPE (ESPE) in Fig. 4. As seen in the figure, the inversion between the $2p_{3/2}$ and $1f_{5/2}$ orbits, however, does not occur in ^{75}Cu but in ^{77}Cu. The present calculations give an improved description of this inversion by including correlation effects due to multipole interaction. These correlation effects are stronger for the $5/2^-_1$ state than for the $3/2^-_1$ state. As a consequence, the inversion of the physical states occurs already at N=46, whereas the orbitals do not cross before N=48. In addition, the calculations predict a rather low spectroscopic factor $C^2S(5/2^-_1) = 0.46$ for the $\pi 1f_{5/2}$ orbital and a $C^2S(5/2^-_1) = 0.24$ for the $1f_{5/2}$ orbital coupled to the 2^+_1 core of ^{74}Ni in ^{75}Cu. The collectivity originating from the $1g_{9/2}$ neutrons is reduced in ^{77}Cu compared to ^{75}Cu, where the number of neutron holes in the $1g_{9/2}$ orbital is two and four, respectively, in the naive normal configuration. Consequently, the C^2S values involving the $1f_{5/2}$ proton and the 2^+_1 core of ^{76}Ni are rather small ($C^2S = 0.18$ and 0.19 for $5/2^-_1$ and $3/2^-_1$, respectively). We emphasize that the single-particle nature of the $5/2^-_1$ and $3/2^-_1$ in ^{77}Cu is thus confirmed.

The experimental $9/2^-$ and $7/2^-$ states at 946 and 1154 keV excitation energy are well reproduced by the calculations, which find corresponding states at 970 and 1070 keV, respectively. They are identified as states arising from $1f_{5/2}$ and $2p_{3/2}$ protons coupled to the 2^+_1 state in ^{76}Ni. The calculations indicate that the $9/2^-_1$ state is dominated by the $\pi 1f_{5/2} \otimes 2^+_1(^{76}\mathrm{Ni})$ component with $C^2S = 0.70$, while the $7/2^-_1$ state is rather mixed and mainly based on the $\pi 2p_{3/2} \otimes 2_1^+(^{76}\mathrm{Ni})$ and $\pi 1f_{5/2} \otimes 2_1^+(^{76}\mathrm{Ni})$ particle-core couplings with $C^2S = 0.51$ and $C^2S = 0.19$, respectively. Another indication for their core-coupling character is the fact that the excitation energy of both states is close to the energy of the 2_1^+ state in ^{76}Ni at 991 keV [40, 41]. The larger calculated transition strengths, relative to the single-particle one, of $B(E2; 5/2_1^- \to 9/2_1^-) = 10$ *W.u.* and $B(E2; 3/2_1^- \to 7/2_1^-) = 8$ *W.u.* lend further support to this picture.

The energies of the $13/2^-$ and $11/2^-$ states at 1775 and 1954 keV, respectively, are well reproduced by the calculations, except that their ordering is reversed. The $13/2_1^-$ state is found to have considerable strength ($C^2S = 0.48$) from a $1f_{5/2}$ proton coupled to the 4_1^+ state in ^{76}Ni, while the $11/2_1^-$ state is dominated by the $\pi 2p_{3/2} \otimes 4_1^+(^{76}\mathrm{Ni})$ configuration ($C^2S = 0.30$) with a second component from the $\pi 1f_{5/2} \otimes 4_1^+(^{76}\mathrm{Ni})$ coupling ($C^2S = 0.09$). In addition to the fact that both states have similar excitation energies compared to the 4_1^+ state in ^{76}Ni at 1921 keV [40, 41], also the calculated transition strengths of $B(E2; 9/2_1^- \to 13/2_1^-) = 7$ *W.u.* and $B(E2; 7/2_1^- \to 11/2_1^-) = 5$ *W.u.* indicate their non-single particle nature, supporting the interpretation of states based on particle-core coupling configurations. The calculated $B(E2)$ values for the low-lying transitions in ^{77}Cu, together with the good general agreement between the calculations and the experimental results, are indicative of a collective nature of the 2_1^+ and 4_1^+ states in ^{76}Ni.

The calculations predict a second $7/2^-$ state at 1389 keV. A considerable fraction of the wave function (74%) is calculated for a 7 proton occupancy in the $\pi 1f_{7/2}$ orbital, indicating a proton excitation across the $Z = 28$ shell gap. More specifically, the $7/2_2^-$ state is dominated by the coupling of a $1f_{7/2}$ proton hole to the 0_2^+ state of the ^{76}Ni core, *i.e.* $\pi 1f_{7/2} \otimes 0_2^+(^{76}\mathrm{Ni})$. The state observed at 2068 keV is tentatively assigned to have $J^\pi = 7/2^-$ from the obtained $\log(ft)$ value and is a possible candidate for the $\pi 1f_{7/2}^{-1}$ hole state. Further experimental work is needed to clarify the situation.

Figure 4 shows the proton ESPE for the Ni isotopes and the above-mentioned inversion of the $2p_{3/2}$ and $1f_{5/2}$ orbitals at $N = 48$. The $Z = 28$ shell gap is reduced from more than 6.5 MeV at $N = 40$ to approximately 5 MeV at $N = 50$. With the crossing of the two orbits found to occur later than previously thought, a smaller reduction of the shell gap, compared to the value of 4.6 MeV in Ref. [10], is obtained in the present work. This result reported here is therefore essential for fixing the value of the shell gap at $N = 50$.

In conclusion, 11 excited states of ^{77}Cu were simultaneously identified through β-delayed γ-ray spectroscopy of ^{77}Ni at the RIKEN Nishina Center. Intense primary uranium beam and efficient particle and γ-ray detectors made it possible to perform the spectroscopic study of such an exotic nucleus which was not accessible in the past. The level scheme for ^{77}Cu was established for the first time in this work up to an excitation energy of 3.4 MeV. The present experimental study, together with the MCSM calculations, indicates a single-particle dominant domain and a collective (or core excited) one in ^{77}Cu, separating the two domains as the former below ~ 0.3 MeV and the latter above ~ 1 MeV. A rather large Z=28 gap is consistent with this, while the gap decreases modestly by ~ 2 MeV from $N = 40$ to 50.

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FIGURES

FIG. 1. Singles γ-ray spectrum of ^{77}Cu correlated with the β decay of ^{77}Ni. Transitions in ^{77}Cu are labeled with their energies. Transitions originating from successive decays are labeled with the respective nuclides. Transitions that could not be assigned unambiguously are labeled with energies in parentheses.

FIG. 2. Coincidence spectra for ^{77}Cu gated on the indicated transitions. Transitions labeled in parentheses could not be placed in the level scheme.

FIG. 3. Level scheme of ^{77}Cu obtained in this work together with the β-decay branchings (I_β) and log(ft) values (left). The given β-decay branching values should be considered only as upper limits and the log (ft) values as lower limits. Level scheme from the SM calculations is also shown (right).

FIG. 4. Calculated proton ESPEs for the Ni chain.

TABLES

TABLE I. Energies and absolute intensities of γ rays observed following the β decay of ^{77}Ni. Transitions that could not be placed in the ^{77}Cu level scheme are given in parentheses.

$E_\gamma[keV]$[a]	*Intensity* [%]	$E_\gamma[keV]$	*Intensity* [%]
179	2 (1)	(1542)	1 (1)
(256)	3 (1)	(1552)	2 (1)
(278)	1 (1)	1636	2 (1)
293	5 (1)	(1708)	1 (1)
(335)	1 (1)	(1741)	2 (1)
543	1 (1)	2068	5 (2)
801	2 (1)	(2163)	1 (1)
829	12 (2)	(2238)	2 (1)
860	4 (1)	(2313)	1 (1)
946	38 (1)	(2348)	1 (1)
1009	4 (1)	(2402)	2 (1)
(1045)	1 (1)	(2440)	1 (1)
1093	3 (1)	(2521)	2 (1)
1133	3 (1)	(2611)	1 (1)
1154	5 (1)	(2800)	1 (1)
(1451)	3 (1)	3008	2 (1)

[a] Uncertainties are within 1 keV.

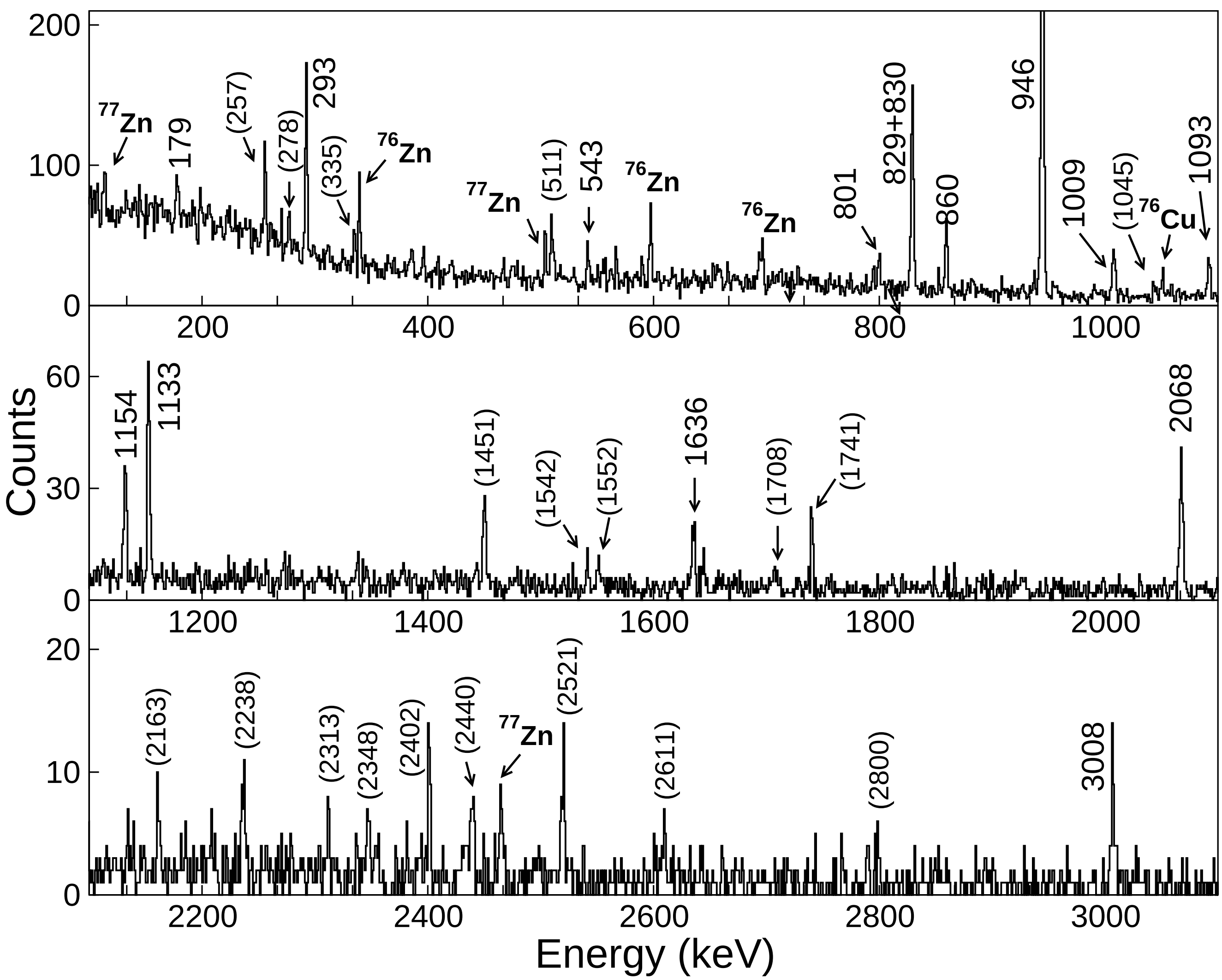

Figure 1 12May2017

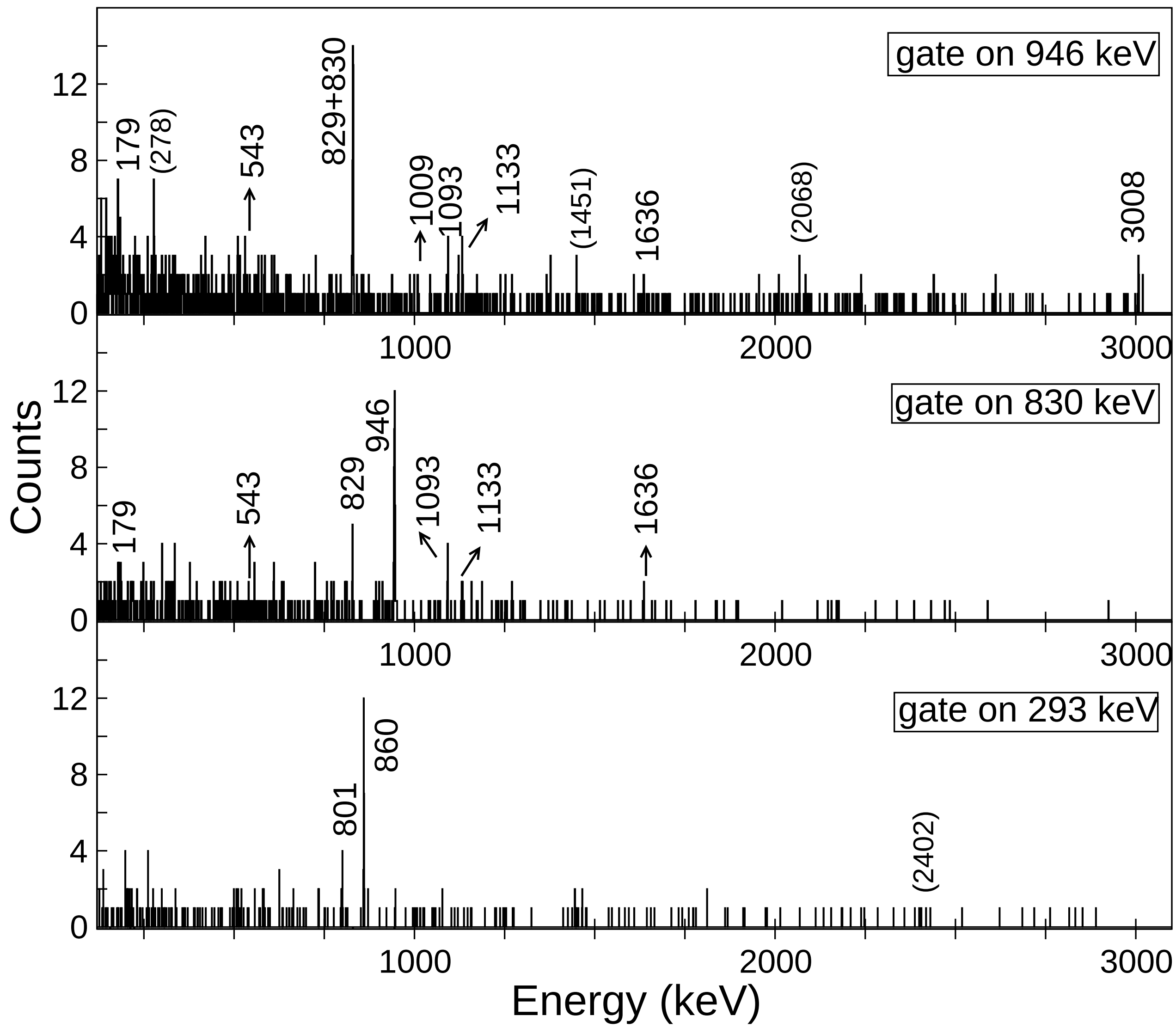

Figure 2 12May2017

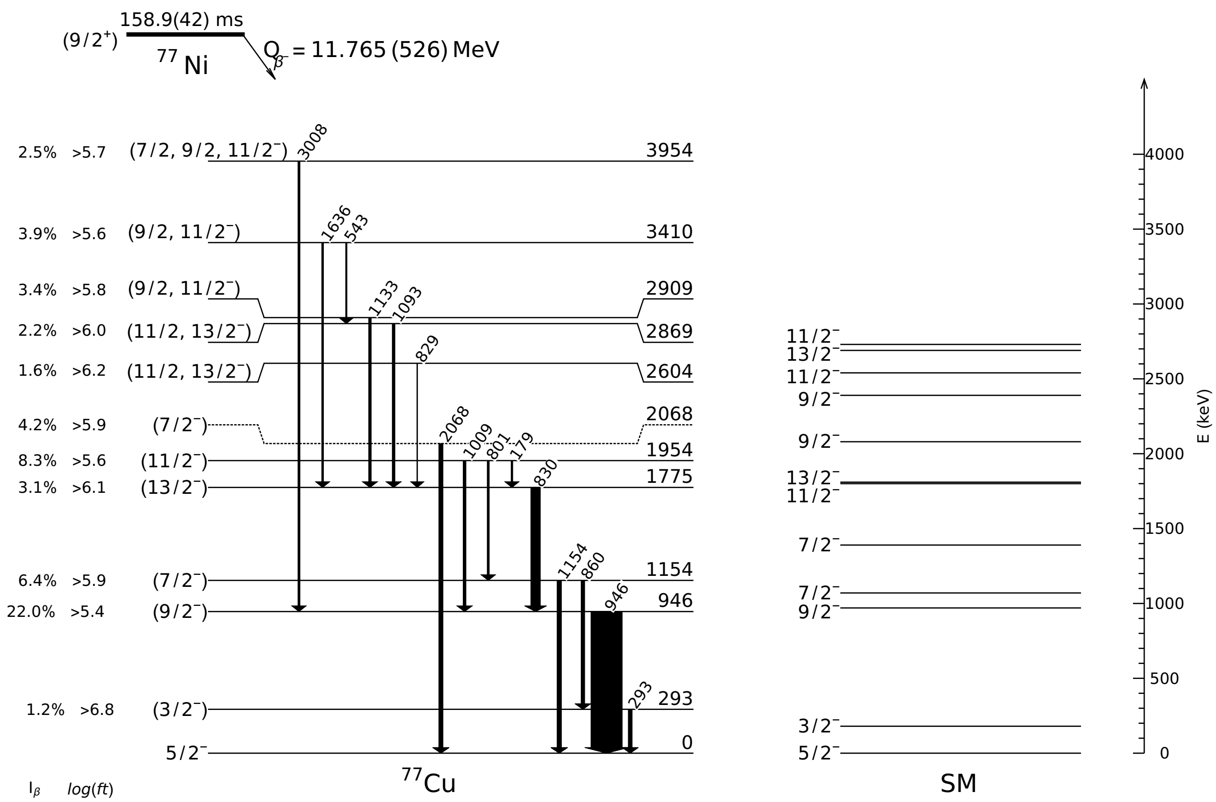

Figure 3 12May2017

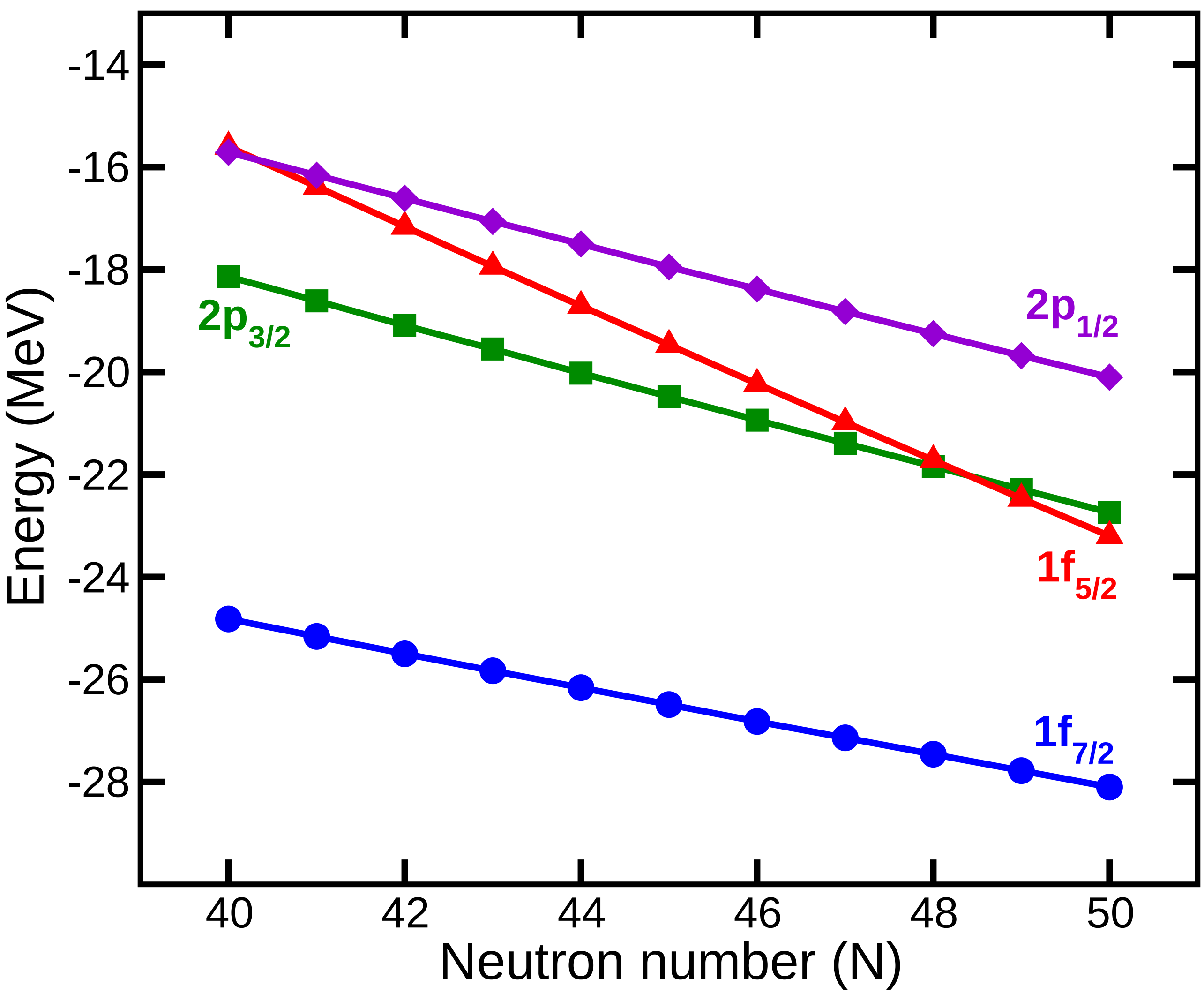

Figure 4 12May2017