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BETA DECAYING $T_{1/2}$ = 3.4 s ISOMER IN ^{69}Ni

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Abstract

A radioactive beam of ^{69}Ni was produced by the fragmentation of a 70 MeV/nucleon ^{76}Ge beam in a Be target. P-delayed y-ray studies were performed using two thin plastic scintillators and two large-volume Ge detectors following implantation of the ^{69}Ni nuclei into a foil of a collection wheel apparatus. A 1296-keV γ-ray transition with a half-life of 3.4(7) s was identified and has been attributed to the decay of the $\nu p_{1/2}^{-1}$ isomeric state in ^{69}Ni. The relative population of the low-spin $J^{\pi} = 1/2^{-}$ isomer to the known high-spin J^{π} = $(17/2^{-})$ isomer was determined to be 6:1 for production of ^{69}Ni via fragmentation of ^{76}Ge, based on an upper limit of 36% extracted for the ^{69}Ni^{m1} P-decay branch to the $3/2^{-}$ ground state of ^{69}Cu. The half-life and branching of the ^{69}Ni^{m1} β decay is discussed in light of possible two

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particle-two hole excitations in the low-energy structure of ^{69}Cu.

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I. INTRODUCTION

Experimental studies of the low-energy structure of the neutron-rich nickel isotopes provide valuable information for the testing and development of theoretical models to better describe the properties of exotic nuclides at and beyond doubly-magic $^{78}_{28}Ni_{50}$. Advances in ion source development [1] and the detection of microsecond isomers [2] have led to new spectroscopic data for the neutron-rich Ni isotopes in the region $40 \leq N \leq 50$. The focus of this work is the low-energy structure of $^{69}Ni_{41}$, which has a closed-shell number of protons and one neutron outside a semi-magic shell closure at $N = 40$. Broda *et al.* [3] suggested the existence of a subshell closure at $N = 40$, $Z = 28$ through the measurement of the first excited 2^+ state in ^{68}Ni with an energy of 2.033 MeV. Grzywacz *et al.* [2] identified several new microsecond isomeric states in the neutron-rich nuclides near ^{68}Ni, including a 0.439(3) μs state at 2.70 MeV in ^{69}Ni. The depopulation of this isomeric state in ^{69}Ni follows mainly a three γ-ray cascade to the ground state. Two weak γ-ray cascades were also observed from this isomer, one terminating at a previously unidentified level at 321 keV in ^{69}Ni. The authors proposed the 321-keV state as a second isomer in ^{69}Ni with $I^\pi = 1/2^-$ (based on an assumed spin-parity of $I^\pi = 17/2^-$ for the 2.70 MeV isomeric state and a cascade of four stretched $E2$ transitions). They estimated a half-life, based on the Weisskopf estimate, of ≈ 14 days for an $M4$ transition from the proposed 321-keV isomeric state to the $9/2^+$ ground state of ^{69}Ni. The more probable decay path for this isomeric state, as pointed out in [2], is β decay to the $I^\pi = 3/2^-$ ground state of ^{69}Cu. Assuming a log*ft* value similar to that observed for the decay of the $I^\pi = 1/2^-$ ground state of ^{67}Ni to the $I^\pi = 3/2^-$ ground state of ^{67}Cu, a β decay half-life of ≈ 3 s was predicted [2].

Franchoo *et al.* [4] have recently studied the β decay of ^{69}Co and its subsequent daughters. The parent nuclei were produced by proton induced fission of ^{238}U, and the Ion Guide Laser Ion Source [5] at the Leuven Isotope Separator On-Line was used to selectively ionize and efficiently extract the Co isotopes from the production target. They observed a 594-keV β-delayed γ-ray transition, which they attributed to the decay of ^{69}Co, and a 1296-keV transition assigned as a β-delayed γ ray following the decay of a 3.5(5) s isomeric state in ^{69}Ni. The proposed sequence for the ^{69}Co β decay is shown in Fig. 1, along with the states observed following the decay of the 0.439 μs isomer in ^{69}Ni.

The recent improvement in the intensities of metal primary beams at the National Superconducting Cyclotron Laboratory at Michigan State University has allowed access to new regions of the chart of the nuclides for nuclear structure measurements. By fragmenting a ^{76}Ge beam in a Be target, nuclides in the range ^{67}Co to ^{75}Zn have been produced with sufficient intensity to perform β-delayed γ ray spectroscopic studies [6]. In this paper we report on the production and identification of a 3.4(7) s isomeric state in ^{69}Ni via projectile fragmentation. Preliminary results from this work have been reported in Ref. [7].

II. EXPERIMENTAL TECHNIQUE

The ^{69}Ni nuclides were produced by fragmentation of a 70 MeV/nucleon ^{76}Ge beam provided by the K1200 Cyclotron at the National Superconducting Cyclotron Laboratory at Michigan State University in a 202 mg/cm^2 Be target. The A1200 fragment analyzer, with a 70 mg/cm^2 Al wedge placed at the second dispersive image of the device, was used to separate the fragments. The fragment momentum acceptance was set to 1% of the central momentum using a slit at the first dispersive image of the A1200. Further M/q separation was achieved using the Reaction Product Mass Separator (RPMS). Identification of secondary fragments at both the A1200 and the experimental endstation was accomplished by measuring ΔE of the fragments in a 300 μm Si PIN detector and the fragment time-of-flight between the PIN detector and a thin plastic detector placed in the beam at the first dispersive image of the A1200.

^{69}Ni fragments, along with ^{67}Co, ^{68}Ni, ^{70,71}Cu, and ^{72}Zn fragments (which were contaminants in the beam), were implanted into one of nine Al catcher foils mounted on a rotating collection wheel. Rotation of the wheel was achieved using a stepper motor, whose controller was interfaced with the data acquisition system. A data collection cycle of 24 s beam implantation, 36 s decay (beam inhibited), and 250 ms wheel rotation was chosen to optimize detection of decays originating from ^{69}Ni^{g} ($T_{1/2}$ = 11.4(3) s). Data were collected during both the implantation and decay periods.

The detector configuration was identical to that used in the elucidation of the low-energy level structure of ^{73}Zn [6]. Two 3 mm plastic scintillators coupled to photomultiplier tubes and two large volume (80% and 120%) Ge detectors were placed around the implantation position for the detection of β and γ emissions, respectively. The β and γ detectors were arranged as scintillator-Ge pairs, with the plastic β detectors placed immediately in front of the Ge detectors. The total β counting efficiency was measured to be 40(2)%, and the Ge detectors had a summed absolute peak γ-ray detection efficiency of 4.3% measured at 1.274 MeV. Experimental β and γ-ray singles and β-γ and γ-γ coincidence data were collected event-by-event and written to 8 mm magnetic tapes.

III. RESULTS

A portion of the β-delayed γ-spectrum collected when the A1200 was set for the peak production of ^{69}Ni is shown in Fig. 2(a). All major transitions in the β-delayed γ spectrum could be attributed to known γ rays from the decay of ^{69}Ni or from the decays of ^{67}Co, ^{68}Ni, ^{70,71}Cu, and ^{72}Zn (the major beam contaminants) except for a peak at 1297-keV. The half-life curve for the 1297-keV transition is shown as an inset in Fig. 2(a). A single component fit to this half-life curve revealed a half-life of $\approx$ 4 s, which is inconsistent with the known half-lives of the six constituents in the beam. For comparison, the half-life curve for the 1297-keV transition is shown in Fig. 3 along with the half-life curves for the major γ-ray transitions from five of the six radioactive nuclides comprising the secondary beams. In addition, the full-width at half-maximum (FWHM) of the 1297-keV peak in the β-gated γ-ray spectrum was found to be $\approx$ 50% larger when compared to the FWHM of other peaks in this energy region, suggesting this peak is a doublet.

To investigate the origin of the components of the 1297-keV doublet, we changed the tune of the A1200 fragment analyzer to implant a different subset of nuclei from the ^{76}Ge fragmentation reaction. This second tune was set for the peak production of ^{71}Cu. In addition to this isotope, the secondary beam contained the radioactive nuclides ^{68}Co, ^{69,70}Ni, ^{72}Cu, and ^{73}Zn. A portion of the β-delayed γ-spectrum for the A1200 tune set for peak production of ^{71}Cu is shown in Fig. 2(b). A 1297-keV doublet peak was present in the β-delayed γ-spectrum; however, the relative ratio of the two components of the doublet changed significantly. The half-life curve obtained for the 1297-keV transition when the A1200 was tuned for the peak production of ^{71}Cu is shown as an inset in Fig. 2(b). A single component fit to this half-life curve revealed a half-life of $\approx$ 19 s.

Based on our γ-γ coincidence and time-dependent γ-ray singles data we have assigned the higher-energy member of the 1297-keV doublet to the decay of ^{71}Cu ($T_{1/2}$ = 19.5 s). This 1298-keV transition, not previously assigned to the β decay of ^{71}Cu, is observed to be coincident with the known 489-keV transition in ^{71}Zn. Several other inconsistencies with the known [8] low-energy level scheme of ^{71}Zn have been observed, and will be detailed elsewhere [9].

The half-life curve obtained when the A1200 was set for the peak production of ^{69}Ni (Fig. 3) was fitted taking into account a contribution from the 1298-keV transition now assigned to the β decay of ^{71}Cu ($T_{1/2}$ = 19.5 s). The two-component fit resulted in a deduced half-life of 3.4(7) s for the low-energy member of the 1297-keV doublet. The short half-life of this 1296-keV γ ray cannot be attributed to the ground state decay of any species implanted when the A1200 was tuned for peak production of ^{69}Ni. Although the half-life for the 1296-keV transition is only slightly outside the 1σ value of the measured half-life for ^{70}Cu^g, the β decay of this nucleus is known [10] to feed only the ground and first excited (885 keV) states of ^{70}Zn. There was no evidence of a 1296-885 coincidence in our γ-γ data, and the relative peak intensities of these transitions would imply a direct β feeding of $> 10\%$ if the 1296-keV transition directly populated the ground state of ^{70}Zn.

Since the 1296-keV transition was observed in the β-delayed γ-ray spectra for both A1200 tunes, it may be attributed to a β-decaying isomer in either ^{69}Ni or ^{71}Cu, which were the only two nuclei present in both radioactive beam implantations. From the difference in the production intensities of ^{69}Ni and ^{71}Cu and the change in the 1296-1298 γ-ray intensities (see Fig. 2), the 1296-keV activity is correlated with the production of ^{69}Ni. This suggests that the 1296-keV β-delayed γ-ray transition originates from a 3.4(7) s isomer in ^{69}Ni.

We found no evidence in our β-delayed γ ray data for other transitions having a half-life similar to the 1296-keV transition. This implies that the 1296-keV state in ^{69}Cu is the only excited state significantly populated following the $\beta-$decay of ^{69}Ni^{m1}. An upper limit of 36% was extracted for the β-branch of the ^{69}Ni $1/2^-$ isomer proceeding to the ground state of ^{69}Cu by comparing the total number of ^{69}Ni nuclei detected in our 300 μm Si PIN ΔE detector with the intensities of γ rays following the β decay of the $1/2^-$ isomeric state and the ground state of ^{69}Ni. Using the measured half-life and branching for the ^{69}Ni^{m1} $\beta-$decay to the two $3/2^-$ states in ^{69}Cu, as well as the β-decay Q-value from Ref. [10], logft values of 4.48 (upper limit) and 5.24 (lower limit) to the $3/2_2^-$ and $3/2_1^-$ states in ^{69}Cu, respectively, have been deduced.

IV. DISCUSSION

The β-decaying $\nu p_{1/2}^{-1}$ isomeric state at 321 keV as proposed by Grzywacz *et al.* [2] has been identified both via study of the $A = 69$ β decay chain ^{69}Co $\rightarrow$ ^{69}Ni $\rightarrow$ ^{69}Cu by Franchoo *et al.* [4] and also from direct production of the isomer via projectile fragmentation as observed in this work. We discuss below the direct production of the low-spin $\nu p_{1/2}$ isomer in ^{69}Ni, as well as the low-energy structures of ^{69}Ni and ^{69}Cu.

A. Production of the $p_{1/2}$ isomeric state in ^{69}Ni via fragmentation

The mechanism for the production of isomeric states in intermediate-energy heavy-ion reactions was first discussed by Young *et al.* [11] when they observed a change in ^{26}Al^m production when the fragmentation conditions (beam, target, and primary beam energy) were modified. However, little progress has been made in providing quantitative understanding of the variation of isomer population with changing reaction conditions. Daugas *et al.* [12] have recently explored the variation of isomer ratios as a function of the velocity of the outgoing fragment. Using a primary beam of 60 MeV/nucleon ^{92}Mo on a thin ^{27}Al target, they observed that the formation probability of isomeric states was strongly dependent on the outgoing fragment velocity in a regular way. A minimum (maximum) in the isomeric yield was observed when the fragment velocity v was near the initial beam velocity v_0 for cases when the isomer spin was greater (less) than the spin of the ground state. This suggests that the isomer ratio is influenced by the initial angular momentum transferred in the reaction, which is expected to be minimum at $v = v_0$.

From the measured counting rates (see Fig. 2) of the 1296 and 1213 keV γ-ray transitions from the decay of ^{69}Ni^m and ^{69}Ni^g, respectively, and using the derived upper limit of 36% for the β branching from the $1/2^-$ isomeric state in ^{69}Ni to the ground state of ^{69}Cu, we deduce a production rate of 13(2)% for the $1/2^-$ isomeric state relative to the ground state. However, the 439 ns isomeric state at 2.70 MeV in ^{69}Ni is known to directly populate the lower energy $1/2^-$ isomer [2]. We have weak evidence for a 1959 keV transition in our γ-ray singles spectrum, which would indicate direct production of the 439 ns isomeric state in ^{69}Ni produced via fragmentation of ^{76}Ge at 70 MeV/nucleon. The relevant portion of this spectrum for both beam off and beam on conditions is shown in Fig. 4. Accounting for the time-of-flight of about 690 ns for ^{69}Ni particles to reach the detection endstation and the γ-ray branching in ^{69}Ni [2], 5(1)% of the population of the $1/2^-$ isomer can be attributed to the decay of the high-spin, 439 ns isomer identified by Grzywacz *et al.* [2].

The isomeric ratio F is defined as the number of nuclei produced in an isomeric state divided by the total number of detected nuclei for a given A and Z. The F values deduced for ^{69}Ni produced by the fragmentation of a ^{76}Ge beam at 70 MeV/A in a thick Be target are F(2701 keV, $17/2^-$) = 2(1)% and 6% < F(321 keV, $1/2^-$) < 12%. The upper value for the range of F(321 keV, $1/2^-$) is derived using the upper limit (36%) for the ground state branch of the ^{69}Ni^{m1} β decay. The lower limit of F(321 keV, $1/2^-$) is attained when the ground state branch of the ^{69}Ni^{m1} β decay is taken to be zero.

Reports on the relative population of two different isomeric states of the same nucleus via projectile fragmentation have been given for ^{90}Nb [12], ^{82}Y [13], and ^{66}As [14]. The ground state spin of ^{90}Nb lies between the spins of the two isomeric states at 1880 keV ($J^{\pi} = 11^{-}$) and 122 keV ($J^{\pi} = 6^{+}$), which is similar to the ^{69}Ni case. The behavior of F as a function of outgoing fragment velocity is entirely different for the two isomers. The one common feature, as noted earlier, is a minimum in F(1880 keV, 11^{-}) and a maximum in F(122 keV, 6^{+}) near $v = v_0$. The relative population of the low-spin, low-energy isomer to the high-spin, high-energy isomer in ^{90}Nb near $v = v_0$ is about 7:1. The isomer ratio measurements reported here for ^{69}Ni were made with the A1200 fragment separator tuned at the peak of the ^{69}Ni momentum distribution. Although we did not determine the variability of F as a function of outgoing fragment velocity for ^{69}Ni, we note that the low-spin, low-energy to high-spin, high-energy isomer ratio of 6:1 is similar to that observed near $v = v_0$ for ^{90}Nb fragments, which were produced using a ^{92}Mo beam at 60 MeV/nucleon on a thin ^{27}Al target.

For the other multi-isomer nuclei ^{66}As and ^{82}Y, the spin values of the two isomeric states are greater than that of the ground state. For ^{82}Y, the ground state spin is 1^{+} and F = 38(14) for the lower-energy 4^{-} isomer and F = 16(6) for the higher-energy 6^{+} isomeric state. The F values are 21(3) and 8(4) for the higher- and lower-spin isomers of ^{66}As, which has a ground state spin-parity 0^{+}.

B. Configuration mixing in ^{69}Cu

From the experimental data, we can conclude that the $\beta-$decay of the $1/2^{-}$ isomer in ^{69}Ni mainly proceeds through the excited $3/2^{-}$ state at 1296 keV in ^{69}Cu. No other excited state in ^{69}Cu has been observed in the isomer $\beta-$decay, neither in the present study nor in the data of Franchoo *et al.* [4]. The allowed character of the Gamow-Teller transition from the $1/2^{-}$ isomer in ^{69}Ni to the excited $3/2^{-}$ in ^{69}Cu can be understood schematically assuming the pure configurations indicated in Fig. 5. Taking the ground state of ^{68}Ni as the reference state, the initial $1/2^{-}$ configuration in ^{69}Ni can be written as:

$$\left|1/2^-\right\rangle = \left|\nu 2p_{1/2}^{-1}\left(\nu 1g_{9/2}^{2}\right)_{0+}\right\rangle \tag{1}$$

and the final $3/2^-$ configurations in ^{69}Cu are:

$$\left|3/2_2^-\right\rangle = \left|\pi 2p_{3/2}\left(\nu 2p_{1/2}^{-2}\,\nu 1g_{9/2}^{2}\right)_{0+}\right\rangle \tag{2}$$

$$\text{and} \qquad \left|3/2_{\text{g.s.}}^-\right\rangle = \left|\pi 2p_{3/2}\right\rangle \tag{3}$$

We can rewrite the configurations given in Eqs. 1–3 describing all the excitations in terms of particles instead of particles and holes. This reduces to using the ground state of ^{66}Ni as a reference state. The expressions become:

$$\left|1/2^-\right\rangle = \left|\nu 2p_{1/2}\left(\nu 1g_{9/2}^{2}\right)_{0+}\right\rangle \tag{4}$$

for the $1/2^-$ state in ^{69}Ni and

$$\left|3/2_2^-\right\rangle = \left|\pi 2p_{3/2}\left(\nu 1g_{9/2}^{2}\right)_{0+}\right\rangle \tag{5}$$

$$\text{and} \qquad \left|3/2_{\text{g.s.}}^-\right\rangle = \left|\pi 2p_{3/2}\left(\nu 2p_{1/2}^{2}\right)_{0+}\right\rangle \tag{6}$$

for the excited $3/2^-$ state and the ground state of the daughter nucleus ^{69}Cu.

It is a good approximation to assume that the pair of $1g_{9/2}$ neutrons, present in the wave-function of the parent $1/2^-$ state, plays no role in the β decay process. The matrix elements for the Gamow-Teller decay then reduce to

$$\left\langle 3/2_2^- \| T(GT) \| 1/2^-\right\rangle = \left\langle \pi 2p_{3/2} \| T(GT) \| \nu 2p_{1/2}\right\rangle \tag{7}$$

$$\left\langle 3/2_{\text{g.s.}}^- \| T(GT) \| 1/2^-\right\rangle \simeq 0. \tag{8}$$

Therefore, assuming the wave functions of the parent and daughter states can be described by pure configurations, the β decay of the $1/2^-$ isomer of ^{69}Ni should proceed only to the excited $3/2^-$ state at 1296 keV in ^{69}Cu. Some configuration mixing, resulting in a fragment of the $\pi 2p_{3/2} \otimes \nu(1g_{9/2}^2 2p_{1/2}^{-2})$ configuration in the ground state of ^{69}Cu, can produce a branching to the ground state in the decay of ^{69}Ni^{m1}.

The upper limit of 4.48 for the logft value for the decay of the $1/2^-$ isomer in ^{69}Ni to the $3/2_2^-$ state in ^{69}Cu compares rather well with the value log$ft \simeq 4.7$ obtained for the decay of ^{67}Ni $1/2^-$ ground state ($T_{1/2} = 21(1)$ s) to the $3/2^-$ ground state of ^{67}Cu [15]. This agreement is only qualitative, since the variation of the reduced transition probability B(GT) is roughly a factor of 1.7 for the log$ft-$values quoted above. The configuration mixing in the $1/2^-$ and $3/2^-$ states connected by the GT transition seems to decrease when going from A=67 to A=69. The two particle-two hole (2p-2h) configuration involved in the structure of the $3/2_2^-$ state in ^{69}Cu is expected to be mainly concentrated in this state, and some fragmentation is needed to account for branching to the ground state. Using the upper limit of 36% obtained for the $\beta-$branching to the ground state of ^{69}Cu in the decay of ^{69}Ni^{m1}, the amount of 2p-2h configuration mixing in the ground-state is obtained to be 15%.

A similar 2p-2h admixture was calculated for the ground-state of ^{67}Co, using a QRPA approach, in a recent $\beta-$decay study of the ^{67}Co $\rightarrow ^{67}$Ni by Weissman *et al.* [16]. In that case, the neutron 2p-2h admixture in the $7/2^-$ ground state of ^{67}Co can produce a $\beta-$branch to a state with mainly a $\nu 1 f_{5/2}^{-1} \otimes \nu(1g_{9/2}^2 2p_{1/2}^{-2})$ configuration via the allowed $\nu 1 f_{5/2} \rightarrow \pi 1 f_{7/2}$ GT transition. Experimental evidence was found for the population of a second $5/2^-$ state at 2.1 MeV with log$ft = 5.5$. Its interpretation in terms of the above configuration is only tentative. Particle-vibration coupling can give rise to fragmentation of the single-particle strength in nuclei around closed shells (see for example, the study of ^{57}Cu $\rightarrow$ ^{57}Ni by Trache *et al.* [17]), and a non-negligible fragment of the hole-state $f_{5/2}^{-1}$ in a state with main $2^+(^{68}\mathrm{Ni}) \otimes p_{1/2}^{-1}$ structure can be expected around the energy of 2.1 MeV.

In our case, the 15% 2p-2h mixing deduced for the ground state of ^{69}Cu is only an upper limit, derived from the upper limit of 36% on the $\beta-$branching from the ^{69}Ni $1/2^-$ isomer to the ^{69}Cu ground state. Taking the β branch for this decay as zero, which would translate to no 2p-2h mixing in the ground state of ^{69}Cu, the logft value for the $3/2_2^-$ state in ^{69}Cu becomes 4.3. It should be noted that if the branch for the ^{69}Ni^m decay to the ground state of ^{69}Cu is near the established upper limit, its origin can be readily explained by the configuration mixing arguments presented above. In fact, the 2p-2h configuration is the only low-lying configuration expected to be populated in the allowed GT transition from the 2p-1h $1/2^-$ isomer. Another higher-energy GT transition $\nu 1f_{5/2} \rightarrow \pi 1f_{5/2}$ can lead to the $\pi 1f_{5/2} \otimes (\nu 2p_{1/2}^{-1} \nu 1f_{5/2}^{-1} \nu 1g_{9/2}^{2})$ configuration. This has some overlap with the particle-vibration configuration $\pi 1f_{5/2} \otimes 2^+(^{68}\mathrm{Ni})$ and can give a small admixture in the $3/2^-_{g.s.}$. The quadrupole matrix element for $f_{5/2} - p_{3/2}$ is small, due to the spin-flip involved. The resulting admixture would result in a $\beta-$ branch with a relatively large logft value.

The degree of 2p-2h correlations in the ground state of ^{68}Ni, made on the basis of the configuration mixing derived experimentally in ^{69}Cu, can provide a measure of the goodness of the $N = 40$ subshell closure. Supposing the $\nu(1g_{9/2}^{2} 2p_{1/2}^{-2})$ mixing in the ground state of ^{68}Ni is similar to that deduced for ^{67}Co and ^{69}Cu, such a small value (15%) suggests "double-magic" (proton shell closure and neutron subshell closure) character of this nucleus. However, this interpretation is not substantiated by the present data availabe (experimental and extrapolated) for two-neutron separation energies in the Ni isotopes [18]. A reduced mixing is also consistent with the predicted deformed character of the 0_2^+ state in ^{68}Ni [19].

V. SUMMARY

A 3.4(7) s isomeric state has been directly populated in ^{69}Ni following fragmentation of a ^{76}Ge beam at 70 MeV/nucleon in a Be target. This state, proposed to have a configuration $\nu p_{1/2}^{-1} \nu g_{9/2}^{2}$, was observed to populate a single excited $3/2^-$ state at 1296 keV in the daughter ^{69}Cu with an allowed GT transition (log$ft \leq 4.48$). A β branch to the $3/2^-$ ground state of ^{69}Cu in the β decay of the ^{69}Ni $1/2^-$ isomer can result from a neutron two particle - two hole admixture in the ground state of ^{69}Cu. Based on an upper limit of 36% for this β branch, an upper limit of 15% was deduced for this mixing, similar to that deduced for ^{67}Co [16].

In addition, we have explored the relative population of the isomeric states in ^{69}Ni in the intermediate-energy fragmentation of a ^{76}Ge beam. The relative populations of the high-spin and low-spin isomers in ^{69}Ni was found to be similar to that observed for the low- and high-spin isomers in ^{90}Nb populated following ^{92}Mo fragmentation. Improved understanding of the mechanism behind the production of isomeric states following fragmentation may provide a more practicle means for exploiting isomeric radioactive ion beams for nuclear structure and reaction measurements.

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FIGURES

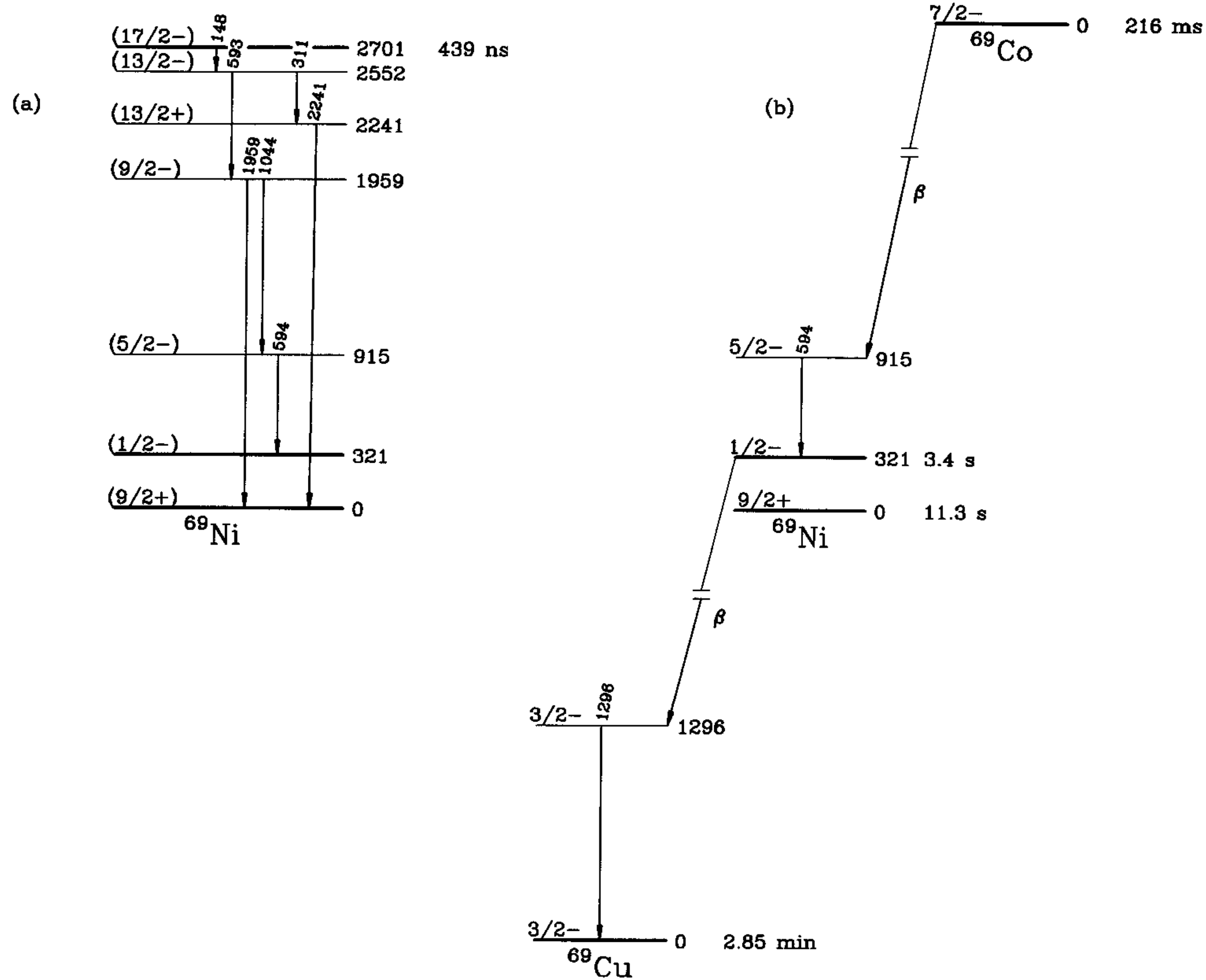
FIG. 1. (a) The ^{69}Ni levels are those identified by Grzywacz *et al.* [2]. (b) Sequence of ^{69}Co - ^{69}Ni β decay as proposed by Franchoo *et al.* [4]

FIG. 2. β-delayed γ-ray spectrum obtained when the A1200 separator was tuned for peak production of (a) ^{69}Ni and (b) ^{71}Cu. Known γ-ray transitions are labeled. The half-life curve shown as an inset in each spectrum corresponds to the 1297-keV doublet.

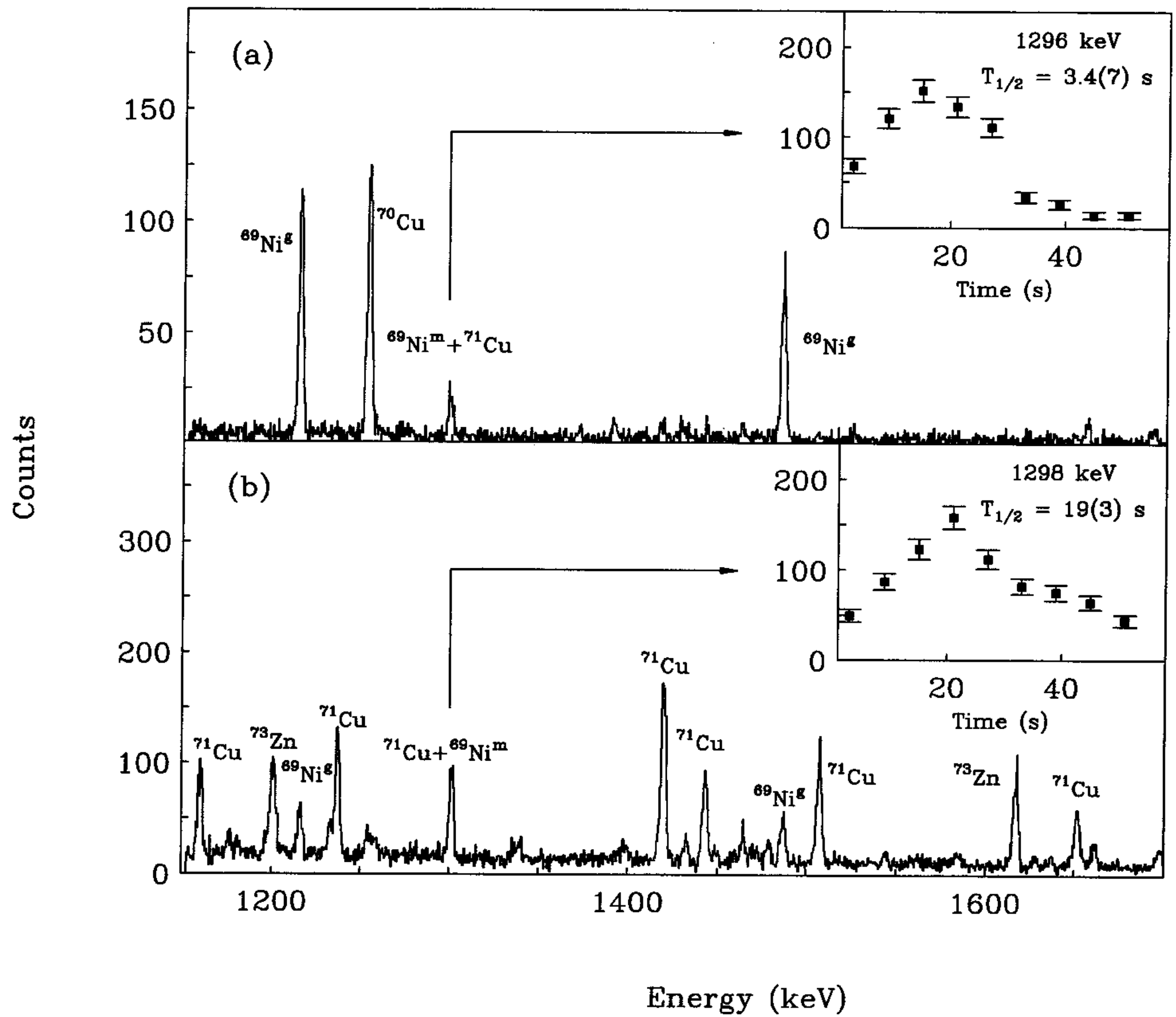
FIG. 3. Decay time curves for selected γ-ray transitions identified during implantation of ^{67}Co, ^{68,69}Ni, ^{70,71}Cu, ^{72}Zn.

FIG. 4. γ-ray singles spectrum obtained during peak production of ^{69}Ni in the region around 2.0 MeV for (a) beam on and (b) beam off conditions.

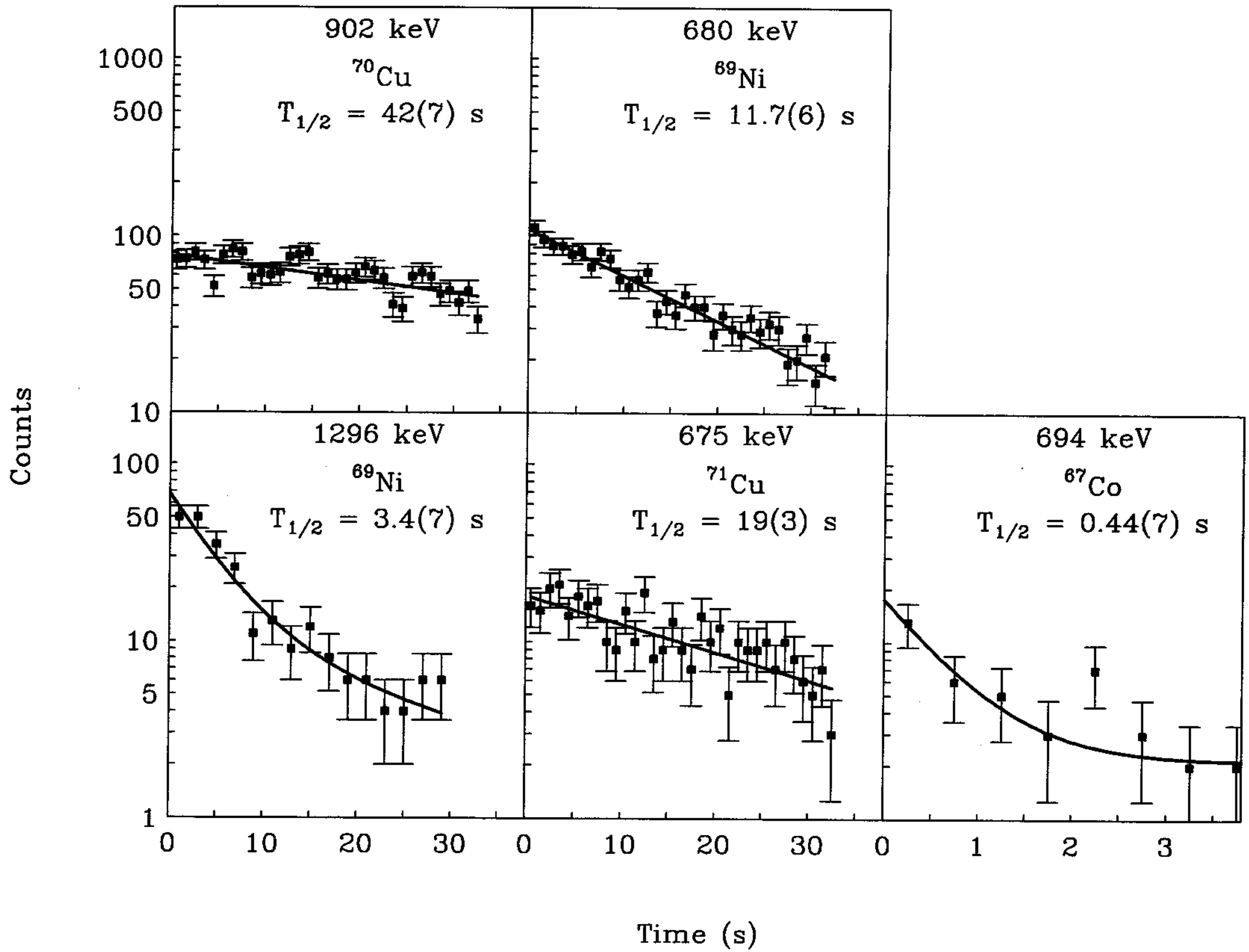
FIG. 5. Schematic of the β decay of ^{69}Ni depicting the configurations discussed in the text.

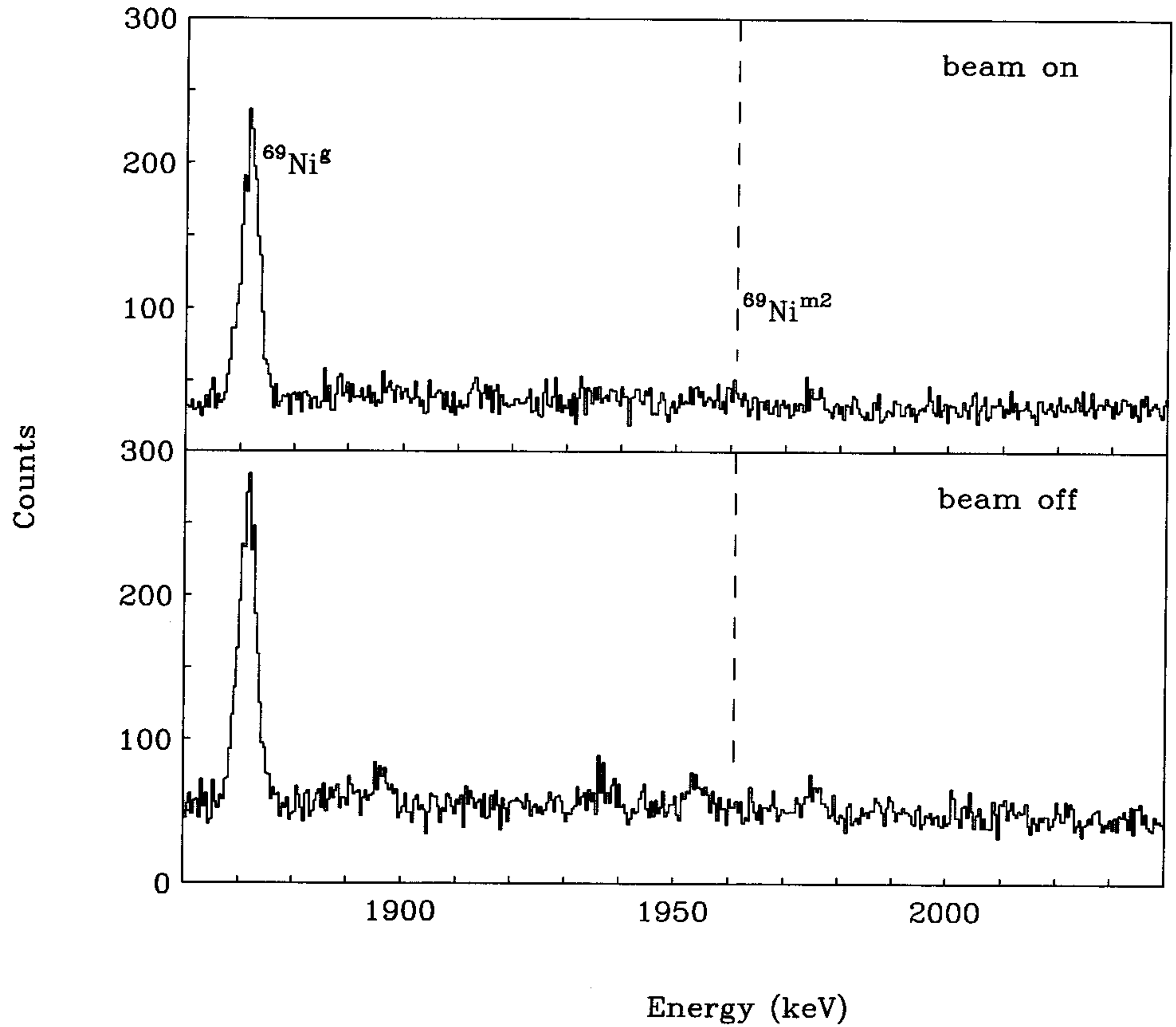


(a)
(17/2−)
(13/2−)
(13/2+)
(9/2−)
(5/2−)
(1/2−)
(9/2+)
148
593
311
2241
1959
1044
594
2701
439 ns
2552
2241
1959
915
321
0
69Ni
(b)
7/2−
69Co
0
216 ms
β
5/2−
594
915
1/2−
321
3.4 s
9/2+
0
11.3 s
69Ni
β
3/2−
1296
1296
3/2−
0
2.85 min
69Cu

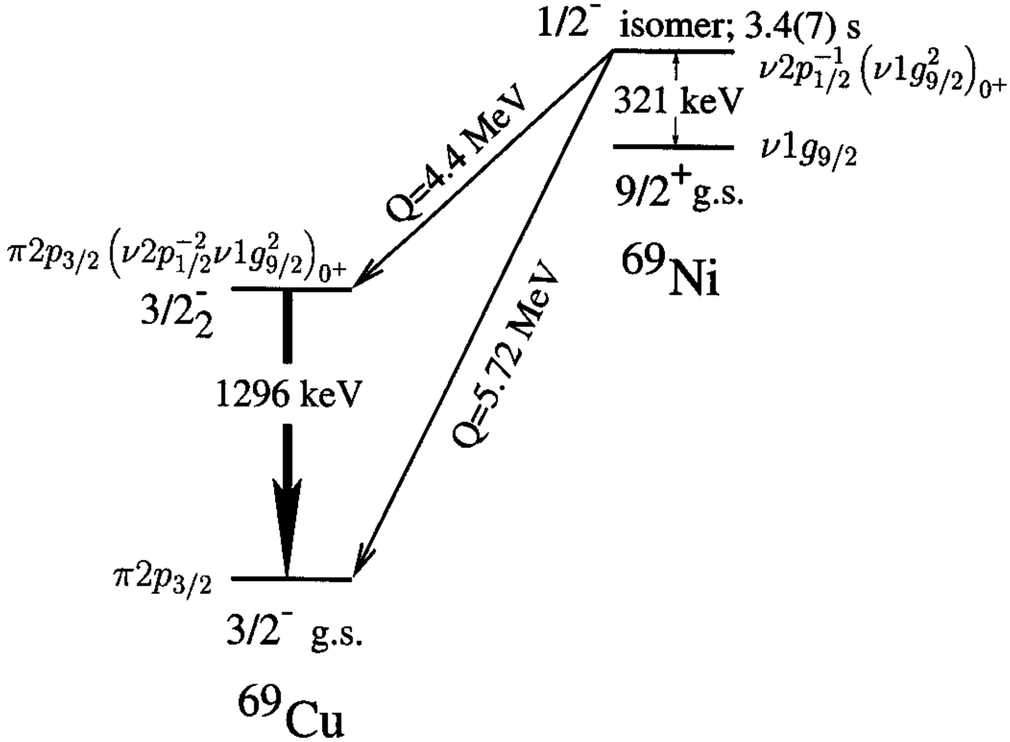


(a)
(b)
1296 keV
T1/2 = 3.4(7) s
1298 keV
T1/2 = 19(3) s
Time (s)
69Nig
70Cu
69Nim+71Cu
71Cu
73Zn
71Cu+69Nim
Counts
Energy (keV)


902 keV
^{70}Cu
$T_{1/2}$ = 42(7) s
680 keV
^{69}Ni
$T_{1/2}$ = 11.7(6) s
1296 keV
^{69}Ni
$T_{1/2}$ = 3.4(7) s
675 keV
^{71}Cu
$T_{1/2}$ = 19(3) s
694 keV
^{67}Co
$T_{1/2}$ = 0.44(7) s
Counts
Time (s)
1000
500
100
50
10
100
50
10
5
1
0
10
20
30
0
10
20
30
0
1
2
3



beam on
beam off
69Ni g
69Ni m2
Counts
0
100
200
300
1900
1950
2000
Energy (keV)



1/2⁻ isomer; 3.4(7) s
$\nu 2p_{1/2}^{-1}\left(\nu 1g_{9/2}^{2}\right)_{0+}$
321 keV
$\nu 1g_{9/2}$
9/2⁺g.s.
^{69}Ni
Q=4.4 MeV
Q=5.72 MeV
$\pi 2p_{3/2}\left(\nu 2p_{1/2}^{-2}\nu 1g_{9/2}^{2}\right)_{0+}$
$3/2^-_2$
1296 keV
$\pi 2p_{3/2}$
3/2⁻ g.s.
^{69}Cu