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

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We report on the production and identification of a 3.4(7) s isomeric state in ^{69}Ni, which has a closed-shell number of protons and one neutron outside a semi-magic shell closure at N = 40. Broda *et al.* [1] 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] have 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 gamma-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 3.0 s β decay half-life for this state 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.

Franchoo *et al.* [3] 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 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 beta decay is shown in Figure 1, along with the states observed following the decay of the 0.439 μs isomer in ^{69}Ni.

We have studied the decay properties of ^{69}Ni nuclides produced at the NSCL by fragmentation of a 70 MeV/nucleon ^{76}Ge beam 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 energy loss of the fragments in 300 μm Si PIN detectors and the fragment time-of-flight between the PIN detectors and a thin plastic detector placed in the beam at the first dispersive image of the A1200.

A portion of the β-delayed γ-spectrum collected when the A1200 was set for the peak production of ^{69}Ni is shown in Figure 2(a). All major transitions in the entire β-delayed γ-ray 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 in inset in Figure 2(a). A single component fit to this curve revealed a half-life of approximately 4 s, which is inconsistent with the known half-lives of the six constituents in the beam. 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 nearly 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-ray spectrum for the A1200 tune set for peak production of ^{71}Cu is shown in Figure 2(b). A

1297-keV doublet was present in the β-delayed γ-ray 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 approximately 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 ($T_{1/2}$ = 19.5s). 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 [4].

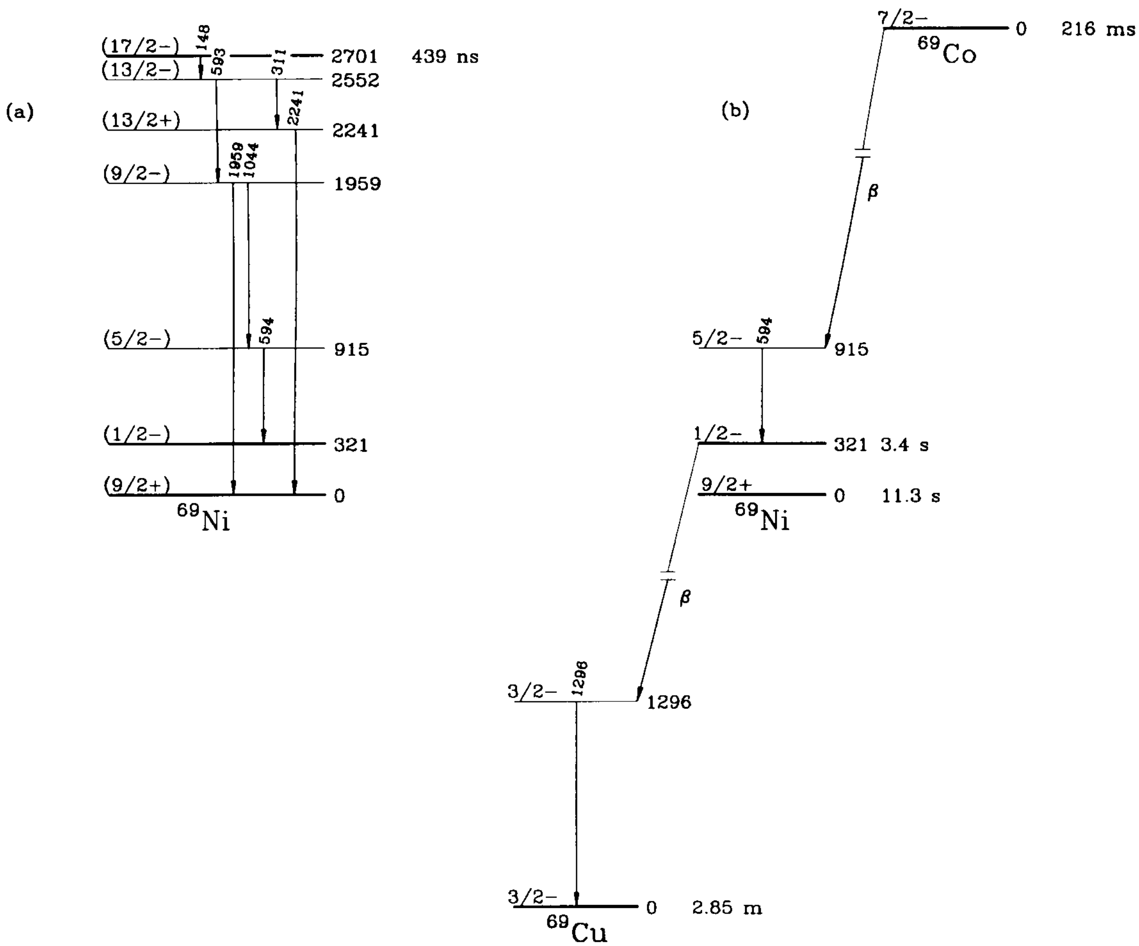

Figure 1: (a) The ^{69}Ni levels are those identified by Grzywacz et al. [2] (b) Sequence of ^{69}Co - ^{69}Ni β decay as proposed by Franchoo *et al.*[3].

The half-life curve obtained when the A1200 was set for the peak production of ^{69}Ni in Figure 2(a) was fitted taking into account a contribution from the 1298-keV transition now assigned to the beta 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. 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 beta-delayed gamma-ray transition originates from a 3.4(7) s isomer in ^{69}Ni.

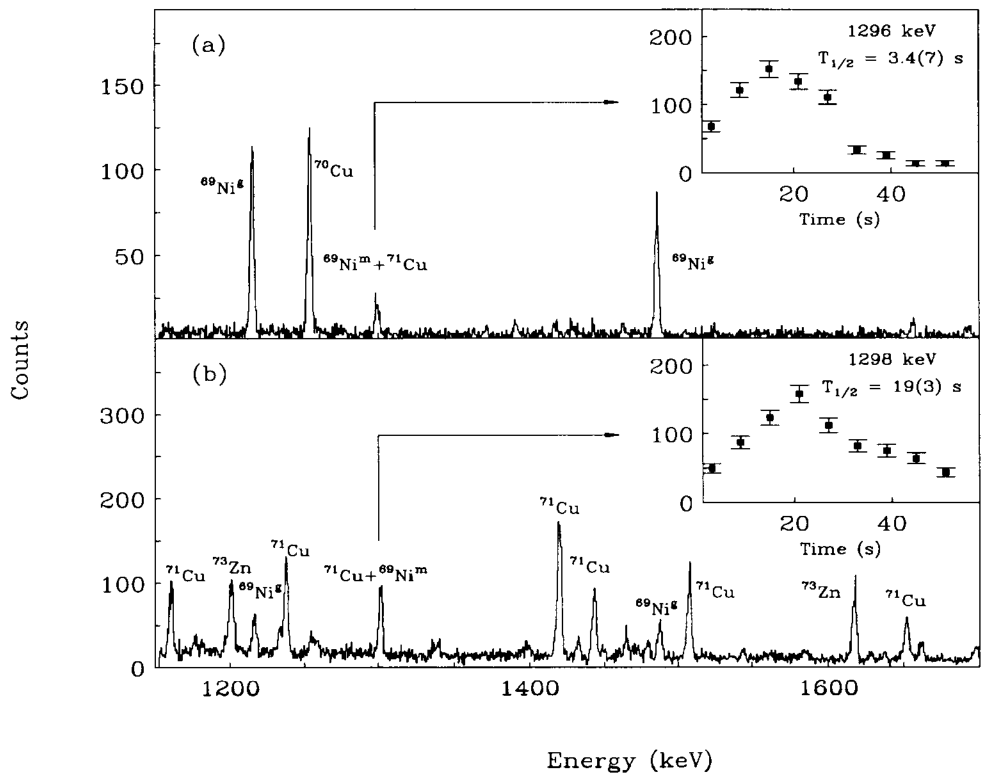

Figure 2: β-delayed γ-ray spectrum obtained when the A1200 separator was tuned for peak production of (a) ^{69}Ni and (b) ^{71}Cu. Known γ-ray transitions are labeled. The half-life curve shown as an inset in each spectrum corresponds to the 1297-keV doublet.

Making use of the matrix element for a pure single-particle $\nu 2p_{1/2} \rightarrow \pi 2p_{3/2}$ transition, we can obtain a first estimate of $T_{1/2}$ = 0.25 s for the half-life of the parent $1/2^-$ state isomeric state of ^{69}Ni. This value, however, is one order of magnitude shorter than the experimental value of $T_{1/2}$ = 3.4(7) s.

The $\nu 2p_{1/2} \rightarrow \pi 2p_{3/2}$ transition has been studied in detail by Semon *et al.* [5] for the β decay of the ^{57}Cu $3/2^-$ ground state to the excited $1/2^-$ state at 1113 keV in ^{57}Ni. The dominant configurations of the parent and daughter states are $\pi 2p_{3/2}$ and $\nu 2p_{1/2}$, respectively. Their shell-model calculations were able to reproduce all the measured *ft* values by introducing an effective GT operator, which resulted in the quenching of the allowed GT transition strength to about 60% of the value calculated within the *fp* shell. An alternative study using the particle-vibration coupling model, by Trache *et al.* [6], reached the same conclusion concerning the quenching of the GT strength. Using the value of 40% for the quenching of the $\pi 2p_{3/2} \rightarrow 2\nu p_{1/2}$ Gamow-Teller strength, the estimate for the half-life of the $1/2^-$ state in ^{69}Ni becomes $T_{1/2}$ = 0.42 s. This value is nearly twice as large as the pure single-particle estimate, but still an order of magnitude lower than the experimental half-life.

Perhaps the most realistic estimate of the effective matrix element for the decay $\nu 2p_{1/2} \rightarrow \pi 2p_{3/2}$ in ^{69}Ni → ^{69}Cu can be obtained from the neighboring pair of nuclei ^{67}Ni → ^{67}Cu. The β decay of the $1/2^-$ ground state of ^{67}Ni proceeds with a branching of 98% to the $3/2^-$ ground state of ^{67}Cu [7]. The parent and daughter configurations involved, with respect to the ground state of ^{66}Ni (considering particle instead of hole excitations), can be written as:

$$|1/2^-_1;\ ^{67}\text{Ni}\rangle = |\nu 2p_{1/2}\rangle \qquad (1)$$

and

$$|3/2^-_1;\ ^{67}\text{Cu}\rangle = |\pi 2p_{3/2}\rangle, \qquad (2)$$

The matrix element for the Gamow-Teller decay is the same as in the case of ^{69}Ni $\rightarrow$ ^{69}Cu. Comparing the B(GT) value extracted from the experimental half-life of ^{67}Ni with the single-particle estimate ($T_{1/2}$ = 2.9(6) s) we obtain a quenching of around 97% for the GT strength.

The above value for $B(GT)_{exp}/B(GT)_{sp}$ for the ^{67}Ni ground state decay is less than 40% of the one extracted for ^{69}Ni, meaning that the effective B(GT) value for the decay ^{67}Ni $\rightarrow$ ^{67}Cu is only about one-third of the effective B(GT) value for the decay ^{69}Ni($1/2^-$; isomer) $\rightarrow$ ^{69}Cu($3/2^-_2$). Since the discrepancy between the two B(GT) values is significant, we should reexamine the assumptions under which they were deduced. The assumptions were that (i) the states involved have pure configurations, and (ii) the β decay of the $1/2^-$ isomer in ^{69}Ni proceeds only to the excited $3/2^-$ state in ^{69}Cu.

The parent and daughter configurations for ^{67}Ni and ^{67}Cu are quite similar to the parent and daughter configurations for ^{69}Ni and ^{69}Cu. The pairs of initial and final states, respectively, differ by one additional pair of $1g_{9/2}$ neutrons for the system with A = 69. This additional pair of neutrons is not expected to be involved in the β decay process under study. Nevertheless, the two extra $1g_{9/2}$ neutrons can give rise to additional configurations and configuration mixing, when coupled to either one neutron in the orbital $2p_{1/2}$ or one proton in the orbital $2p_{3/2}$. Qualitatively, one would expect an increase in configuration mixing in the structure of the $1/2^-$ isomer of ^{69}Ni when compared to the $1/2^-$ ground state of ^{67}Ni, as well as in the structure of the first excited $3/2^-$ state of ^{69}Cu when compared to the $3/2^-$ ground state of ^{67}Cu. The half-life of the β decaying $1/2^-$ isomer of ^{69}Ni will, of course, be influenced by the configuration mixing. A naive expectation would be that increased configuration mixing leads to a longer half-life (larger quenching of the GT strength), but for a quantitative prediction, detailed calculations for all four nuclei are needed.

Under the assumption that the parent and daughter states in the decay ^{67}Ni $\rightarrow$ ^{67}Cu have pure configurations, the half-life of the $1/2^-$ isomer in ^{69}Ni can then be calculated from the measured half-life of ^{67}Ni. Using the Q-values and log *f*-values from the literature, the measured half-life of 21(1) s for ^{67}Ni and the value of 98% for the decay branching to the ground state of ^{67}Cu, we obtained $T_{1/2}$ = 8.4(4) s for the $1/2^-$ isomer in ^{69}Ni. Supposing now that the configuration assumed for the $3/2^-_2$ state of ^{69}Cu belongs, in fact, to the ground state of ^{69}Cu, we obtained $T_{1/2}$= 2.6(1) s for the isomer. Since the experimental half-life for the decay of the $1/2^-$ isomer in ^{69}Ni lies in between the two values, it can be reproduced assuming that the $\pi 2p_{3/2}\,(\nu 2p_{1/2}^{-2}\nu 1g_{9/2}^{2})_{0+}$ configuration, to which the beta decay proceeds, is distributed over the two $3/2^-$ states. The values needed to reproduce the experimental half-life are 39% of the $\pi 2p_{3/2}(\nu 2p_{1/2}^{-2}\nu 1g_{9/2}^{2})_{0+}$ configuration in the excited $3/2^-_2$ state and 61% of the configuration in the ground state of ^{69}Cu.

The amplitude of the $\pi 2p_{3/2}(\nu 2p_{1/2}^{-2}\ \nu 1g_{9/2}^{2})_{0+}$ configuration in the ground state of ^{69}Cu, extracted above, is only an upper limit due to the assumption that the ground states of ^{67}Ni and ^{67}Cu have pure configurations. To obtain an estimate for a lower limit of the admixture, we further suppose that the transition probability for the isomer decay to the excited $3/2^-$ state in ^{69}Cu is well approximated by the value extracted from ^{67}Ni, but in addition the ground state of ^{69}Cu has an admixture of the configuration $\pi 2p_{3/2}(\nu 2p_{1/2}^{-2}\ \nu 1g_{9/2}^{2})_{0+}$. The lower limit is obtained supposing that the isomer decay to this component in the ground state of ^{69}Cu proceeds with a B(GT) given by the single-particle estimate and a 40% quenching, as obtained for ^{57}Cu ($3/2^-$) $\rightarrow$ ^{57}Ni($1/2^-$). An admixture of only 2% of the configuration $\pi 2p_{3/2}\,(\nu 2p_{1/2}^{-2}\nu 1g_{9/2}^{2})_{0+}$ in the ground state is needed.

While a rather large quantity of new experimental data has become available in the region of ^{68}Ni over the last few years, our theoretical understanding of the region is still far from complete. Large-scale shell model calculations and alternative theoretical studies are needed.

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