the peaks of cross sections are matched. The angle between pions is fixed at $\theta_{\pi^\pm\pi^0}=10°$; the angle $\theta_{\pi^\pm\gamma}=100°$. All the IB spectra are normalized to cross sections of the corresponding nonradiative processes at the same angle $\theta_{\pi^\pm\pi^0}$ and in the same nuclear model.

The cusps are well distinguished so that their experimental detection should be possible. Compared with the pure nuclear processes, the reactions with pions may be more advantageous from the experimental point of view. Since pions have larger specific charge than nuclear particles, the ratio of radiative to nonradiative reaction is larger than in nuclear processes. In the vicinity of cusps the probability of IB emission is raised by one order of magnitude; also the width of cusps is rather large—usually several MeV. In reactions with pions the cusps may also be found at higher photon energies so that the nuclear background radiation will have less influence on the measurements.

The experimental detection of cusps would provide a solid argument for the existence of a triangle mechanism in pion-charge-exchange reaction and would eventually help to select the dominant triangle mechanism.

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LIFETIMES OF LOW-LYING LEVELS IN ^{57}Ni†

C. R. Gould, E. C. Hagen, R. V. Poore, and N. R. Roberson
Duke University and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706

and

G. E. Mitchell and D. R. Tilley
North Carolina State University, Raleigh, North Carolina 27607, and
Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706
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Lifetimes of low-lying levels in ^{57}Ni have been investigated using the reaction ^{54}Fe(α, n)^{57}Ni and the Doppler-shift attenuation method. The lifetimes are not in agreement with single-particle predictions and, together with the presence of new low-lying levels in ^{57}Ni, confirm the presence of core excitation of ^{56}Ni.

Although the $f_{7/2}$ shell closure at ^{56}Ni is often assumed to be complete,[1] recent work has suggested that the ground state of ^{56}Ni may contain considerable admixtures of up to four-particle, four-hole configurations.[2] The departure from shell closure for ^{56}Ni would of course imply that the low-lying levels of ^{57} are not pure single-particle states. The present paper describes the first measurements of the lifetimes of low-lying excited states of ^{57}Ni in an attempt to investigate this point, and also reports the observation of two new excited states below 3 MeV. The results are consistent with appreciable core excitation in ^{56}Ni.

The levels studied here are shown in Fig. 1 and were populated in the reaction ^{54}Fe$(\alpha,n)^{57}$Ni. The single-particle levels are the $p_{3/2}$ ground state, the $f_{5/2}$ level at 0.769 MeV, and the $p_{1/2}$ level at 1.112 MeV. The $\frac{7}{2}^-$ level at 2.576 MeV is strongly populated in pickup reactions[3] and appears to be the lowest two-particle, one-hole state arising from an excitation out of the $f_{7/2}$ shell. As mentioned, the (α, n) reaction studied here also populated two new levels whose existence has not previously been reported. These were of energies 2.443 and 3.003 MeV. Only ground-state transitions were observed from these levels. Because the 3.003-MeV level was

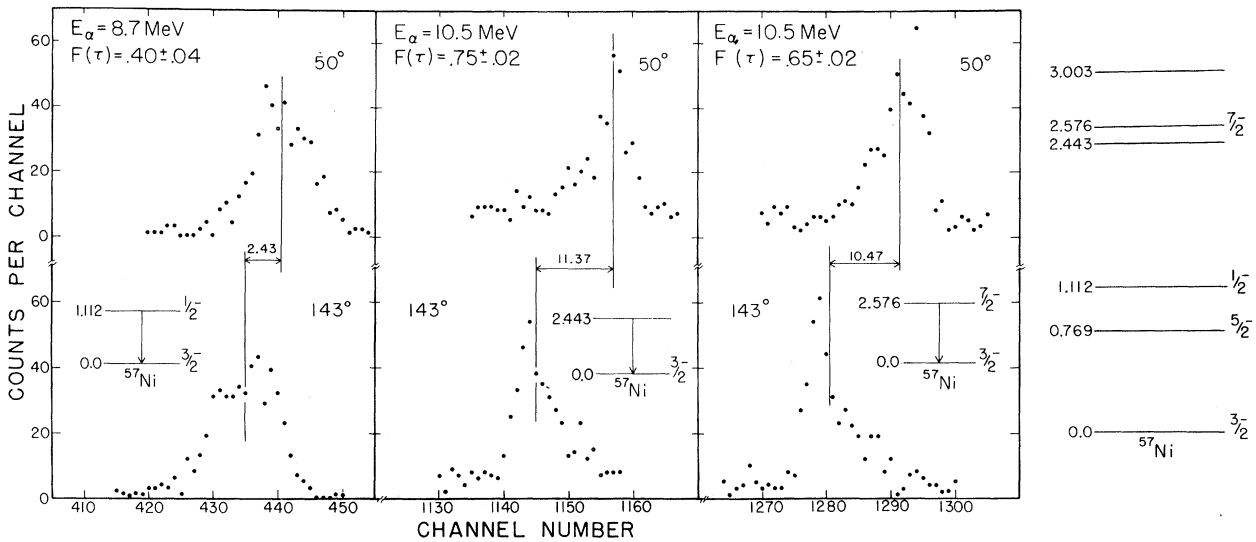

FIG. 1. The levels observed in the present study and typical 50° and 143° line shapes for the decays of the 1.112-, 2.443-, and 2.576-MeV states obtained with a thick ^{54}Fe target. The data were taken in coincidence with neutrons detected at 0° and show the full-energy peaks for the ground-state transitions. The energies were extracted from 90° data (not shown) and have uncertainties of ±1 keV. Average centroid shifts are shown in keV and were obtained from six sets of data for the 1.112-MeV state and two sets of data for the 2.443- and 2.576-MeV states. The data for the 0.769- and 3.003-MeV state decays are not shown as the first excited state spectra were essentially unshifted and the 3.003-MeV state was too weakly populated.

rather weakly populated, no lifetime was obtained for this state.

The lifetimes were measured using the Doppler-shift attenuation method. The target (a 4-mg/cm^2 rolled iron foil enriched to 97% ^{54}Fe) was bombarded with 100-nA beams from the Triangle Universities Nuclear Laboratory's High Voltage Engineering Corporation model FN tandem Van de Graaff accelerator. The γ rays were detected in a 30-cm^3 Ge(Li) detector having a resolution of 2.7 keV at 1.33 MeV. Spectra were taken in singles at bombarding energies of 8.7 and 9.2 MeV and in coincidence with neutrons, at 8.7, 9.2, and 10.5 MeV. The neutrons were detected at 0° in a 12.7×10.2-cm^2 NE213 liquid scintillator mounted on an XP1040 phototube. Pulse-shape and flight-time discrimination were employed to distinguish γ-ray events from neutron events in the scintillator. Coincidence data were necessary for the higher levels in ^{57}Ni because of the presence of many competing γ rays from the more strongly populated (α, p) reaction leading to ^{57}Co. Coincidences were also necessary for the 1.112-MeV state because of the possibility of interference from the second escape peak of the γ ray from the ground-state decay of the 2.113-MeV level in ^{57}Co.

The coincidence data taken at 10.5 MeV clearly showed the presence of peaks of energies 2.443 and 3.003 MeV along with the γ ray from the 2.576-MeV level. Spectra taken at a beam energy equivalent to threshold energy for a level of 2.433 MeV in ^{57}Ni showed no such γ rays. Corroboration that these γ rays arise from the decays of new levels in ^{57}Ni comes from a recent study[4] of the reaction ^{58}Ni(^{3}He, α)^{57}Ni in which levels at ~2.45 and 3.00 MeV were observed.

The energies used in the present experiment are such that the beam comes below threshold within the target for the states of interest and therefore no vacuum recoil effects are expected. Excitation curves were measured for the lower states and were used in the determination of the average recoil velocity of the ^{57}Ni ions. The theoretical attenuation factors $F(\tau)$ were calculated using the computer code FTAU[5] based on the work of Blaugrund[6] and the stopping-power theories of Lindhard, Scharff, and Schiøtt.[7]

Figure 1 shows coincidence spectra for the ground-state decays of the 1.112-, 2.443-, and 2.576-MeV levels. Average centroid shifts are shown in keV, and establish lifetimes of 130 ± 30, 40 ± 10, and 60 ± 10 fsec for the 1.112-, 2.443-, and 2.576-MeV states, respectively.

Although the line shape obtained from singles spectra for the 0.769-MeV γ ray showed slight broadening at 0° and 143°, the $F(\tau)$ value of 0.02 ± 0.02 is consistent with zero. This does, however, allow a lower limit of 2 psec to be set on the lifetime from this measurement. Two further experiments were performed in an attempt to improve on this limit for the first excited state.

The first experiment involved a recoil distance lifetime measurement with the reaction $^{54}Fe(\alpha, n)^{57}Ni$ using a plunger described elsewhere.[8] No significant stopped peak was detected at a distance of 30 μm and a conservative upper limit of 25 psec was set on the lifetime from this measurement.

The second experiment was a set of Doppler-shift attenuation measurements performed with thin ^{54}Fe targets on thick metallic ^6Li backings. Because of its lower density and stopping power, lifetimes in the range 1-10 psec were expected to be accessible. Targets were prepared by evaporating 1 mg/cm^2 of ^6Li onto iron targets of 80-100 μg/cm^2 thickness of enriched ^{54}Fe. Two typical spectra taken in singles at 8.7 MeV and angles of 90° and 143° are shown in Fig. 2. Forward angles were avoided because of the high neutron flux from reactions in the ^6Li backing. The average shift observed for ten sets of runs on four separate targets is shown in keV and yields an $F(\tau)$ value of 0.09 ± 0.02. However, the interpretation of this result is difficult since, as discussed by Paul, Olness, and Warburton,[9] the stopping power of the backing is substantially altered by oxidation of the lithium. Because of the difficulty in quantitatively characterizing this degree of oxidation, only lower and upper limits of 1.5 and 8 psec are given for the lifetime of the 0.769-MeV state from this measurement. These values are based on the two limiting $F(\tau)$ curves, regions of which are shown in Fig. 2. The lower limit was obtained by assuming a 100-μg/cm^2 target with a $^6LiO_2$ backing and the upper limit by assuming an 80-μg/cm^2 target with a pure ^6Li backing.

Table I summarizes the lifetime results for

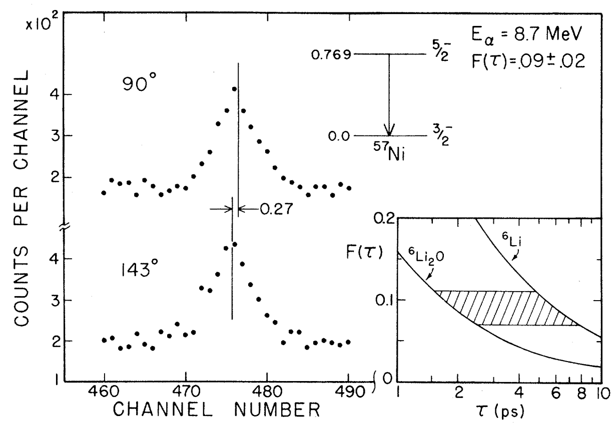

FIG. 2. Two typical line shapes from the decay of the first excited state, obtained at 90° and 143° using a lithium-backed iron target. The average centroid shift from ten sets of runs on four separate targets is shown in keV. Inserted are regions of the two $F(\tau)$ curves used to analyze the observed shift, as discussed in the text.

the four states and shows the $M1$ and $E2$ enhancements in Weisskopf units for the ground-state transitions from these levels. The $M1$ decay of the 0.769-MeV state is Δl forbidden and the mixing ratio, which implies 95% $M1$, already indicates that the state cannot be pure single particle. The short lifetime of the 2.443-MeV level indicates that its spin is $\leq \frac{7}{2}$. This would imply that this state is not the $g_{9/2}$ single-particle level but is instead a state of fairly complicated structure arising perhaps from a coupling of single-particle levels to the excited states in ^{56}Ni. It should be noted that the $E2$ enhancement of the decay of the 2.576-MeV level is close to the value of 10.0 obtained for the enhancement of the first 2^+-to-ground transition in ^{58}Ni,[10] and might also imply a dominant collective admixture in this state.

Table II summarizes the experimental reduced transition probabilities in nuclear magnetons

Table I. Lifetime results from the present set of experiments and the enhancements in Weisskopf units for the ground-state transitions in the cases where spins and mixing ratios are known.

Level[a] (MeV)	Lifetime (psec)	Transition	Mixing ratio[b]	Multipolarity	$\|M\|^2$ (Weisskopf units)
0.769	$2<\tau<8$	$\frac{5}{2}^- \to \frac{3}{2}^-$	−0.23	$M1$	$0.008 < \|M\|^2 < 0.033$
				$E2$	$1.46 < \|M\|^2 < 5.85$
1.112	0.130 ± 0.030	$\frac{1}{2}^- \to \frac{3}{2}^-$	···	$M1$	0.18[c]
2.443	0.040 ± 0.010	···	···	···	···
2.576	0.060 ± 0.010	$\frac{7}{2}^- \to \frac{3}{2}^-$	0.0	$E2$	9.2

[a]All ±0.001 MeV. [b]Ref. 3. [c]Assumes transition is all $M1$.

Table II. Experimental and theoretical reduced transition probabilities in nuclear magnetons squared for the Δl-forbidden and allowed $M1$ decays from the first and second excited states, respectively.

Transition	Experiment	Single-particle	McGrory
$0.769 \rightarrow 0.0$	$0.015 < B(M1) < 0.06$	0	0.0014
$1.112 \rightarrow 0.0$	0.32^{a}	2.2	1.04

[a] Assumes transition is all $M1$.

squared for the forbidden and allowed $M1$ decays of the first and second excited states, respectively. These $B(M1)$ values are compared with the single-particle estimates and the results of a preliminary shell-model calculation by McGrory,[11] in which particles are distributed in the four f-p shell orbits outside an inert ^{40}Ca core. The calculation is similar to one described by Gatrousis et al.[12] and includes all configurations with at least fourteen particles in the $f_{7/2}$ shell. The matrix elements used for the two-body interaction are those derived for this region by Kuo and Brown[13] from the Hamada-Johnston potential. The bare nucleon magnetic moment operator was used and the single-particle energies used were 0.0, 3.4, 5.6, and 8.2 MeV for the $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ levels, respectivley. These energies gave reasonable values for the excitation energies of the first two excited states of ^{57}Ni. The agreement of this calculation with the experimental $M1$ strengths is fair for the Δl-allowed transition from the 1.112-MeV level, differing only by about a factor of 3 from experiment. However, the 0.769-MeV Δl-forbidden transition is stronger than the theoretical prediction by at least a factor of 10. The inclusion of mesonic effects[14] might explain a part of this latter discrepancy because the transition is relatively weak. On the other hand, these results probably indicate the need to include more complicated configurations in the core, especially in view of the existence of the level at 2.443 MeV whose presence is not explained by any simple shell-model configurations.

Experiments are in progress to determine the spin of the 2.443-MeV level as well as the mixing ratio of the 2.443 to ground-state transition.

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