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Mean lifetimes of the γ cascades in the ^{61}Cu continuum

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The reduction of the Doppler shift for several bound-state transitions in ^{61}Cu due to the intervening γ cascades from the continuum was measured, using the Doppler-shift-attenuation method in a p-γ coincidence arrangement that employed the ^{58}Ni$(\alpha, p\gamma)^{61}$Cu reaction at 19.7 MeV. It is found that the mean lifetimes of cascades that begin at the most probable excitation energy of ~9.5 MeV in ^{61}Cu and populate the 2336.2-keV ($9/2^-$), 2611.8-keV ($9/2^-$), and 3015.6-keV ($11/2^-$) states are, respectively 0.29 ± 0.12, 0.19 ± 0.07, and 0.43 ± 0.14 ps. The mean lifetimes of the cascades feeding the above three states were found to increase with increasing total energy available for the cascades with an approximately linear dependence with slopes of 40 ± 22, 29 ± 12, and 69 ± 20 fs/MeV. These results are consistent with an increase in the γ multiplicity in the cascades with increasing total available cascade energy.

[NUCLEAR REACTIONS ^{58}Ni$(\alpha, p\gamma)^{61}$Cu, $E_\alpha = 19.7$ MeV; measured $\bar{\tau}(E^*)$, the energy dependence of the mean lifetimes of the γ cascades in ^{61}Cu. Enriched targets, Ge(Li) γ detectors, annular Si(Li) detector, Doppler-shift analysis of line shapes.]

I. INTRODUCTION

Knowledge of the detailed properties, such as multipole character and multiplicity, of the γ cascades that originate from the continuum is essential in understanding the deexcitation mechanism[1,2] in reactions of the type $(\alpha, xn\gamma)$ or (HI, $xn\gamma$). The multipole character of the continuum γ rays in conjunction with the available decay energy and the nuclear level density determine the multiplicity of the cascade and consequently the over-all lifetime for a particular cascade path. The various cascade paths in turn determine the over-all "feeding" time between the emission of the last particle and the population of a bound state. Values for the over-all "feeding" times from all excitation energies in the continuum following (HI, $xn\gamma$) reactions have been recently reported.[3-5] Thus Diamond, Stephens, Kelly, and Ward[3] found (11 ± 3) ps for the feeding of the 8^+ state in ^{158}Er via the (^{40}Ar, $4n\gamma$) reaction; Ward, Andrews, Geiger, Graham, and Sharpey-Schafer[4] obtained the values of 1.5, 1.6, and 2.4 ps for the population of the 14^+, 12^+, and 10^+ states, respectively, in ^{158}Er via the (^{32}S, $4n\gamma$) reaction; and Newton, Stephens, and Diamond[5] reported 11 ± 3, 5 ± 2.5, 3 ± 3, and $12^{+2.5}_{-4}$ ps for the "feeding" of the 12^+, 10^+, 14^+, and 12^+ states in $^{166, 168, 170}$Hf and ^{178}Os, respectively, via the (^{20}Ne, $4n$) and (^{28}Si, $4n$) reactions. Similar experiments were carried out by Kutchera *et al.*[6] for reactions leading to $^{120, 122}$Xe and $^{126, 128}$Ba but explicit values for the feeding times were not given.

In this work we report the first experimental evidence for the dependence of the cascade feeding time on the excitation energy in the continuum from where the cascade starts. The measurements were carried out for cascades in ^{61}Cu following the ^{58}Ni$(\alpha, p)^{61}$Cu reaction at 19.7 MeV. Under these conditions cascades starting from 5.5–12.0 MeV of excitation in ^{61}Cu were investigated. At these excitation energies ^{61}Cu is unbound toward proton emission. Since the anticipated[7] feeding times would be shorter than 1 ps, the Doppler-shift-attenuation technique was employed in $p\gamma$ coincidence experiments.

II. EXPERIMENTAL PROCEDURES

In this work the Doppler-shift-attenuation technique was employed in measurements of the line shapes of four γ rays from bound-state transitions in ^{61}Cu. The line shapes of the Doppler-shifted γ rays were measured in 3 two-parameter $p\gamma$ coincidence experiments with the ^{58}Ni$(\alpha, p\gamma)^{61}$Cu reaction at 19.7 MeV. The protons were detected with an annular 300-mm^2 area, 1-mm-thick Si surface-barrier diode positioned 14.5 mm from the target. The α beam was stopped in 0.25 mm Pb. The γ rays were detected with a 35-cm^3 Ge(Li) detector positioned at 0° to the beam and 4.5 cm from the target. The targets were self-supporting 4.05-mg/cm^2 foils of ^{58}Ni enriched to 99.95%. In the first two experiments the contribution to the line shape from the escaping recoils that decayed in vacuum was calculated and included in the analysis as described by Hoffman *et al.*[8] Although relatively thick targets were employed, the contribution to the shift from the escaping recoils was found to be ≃30%. In order to reduce errors due to the escaping recoils a third experiment was carried out in which 1.8 mg/cm^2 of Au were evaporated on the back side of the target foil to catch the escaping recoils. The results from this latter experiment had in general smaller uncertainties and were found in agreement within experimental error with the results of the two earlier experiments.

The data were recorded on magnetic tape with the aid of a 4096-channel pulse-height analyzer interfaced with a PDP-8/L computer with a 24-bit related address buffer-tape capability. By proper programming the system could sample singles events on both the particle and the γ-ray axis for a preselected small fraction of the time. Singles rates of approximately 12 000 count/sec were maintained on the charged particle and the γ-ray detectors. This, under the geometry employed, yielded a true coincidence rate of $\simeq 380$ count/sec with a random rate below 5% of the total coincidence rate. In each experiment ~2×10^7 coincidence events were recorded. Line shapes with acceptable statistical quality could be obtained by scanning the data with proton energy intervals of ~1.2 MeV. This permitted lifetime information to be obtained for cascades that start from 1.2-MeV-wide intervals within an excitation range of 5.5–12.0 MeV in ^{61}Cu.

III. RESULTS AND DISCUSSION

The levels at 2336.2 keV ($\frac{9}{2}^-$), 2611.8 keV ($\frac{9}{2}^-$), and 3015.6 keV ($\frac{11}{2}^-$) in ^{61}Cu were employed in this work in order to measure the reduction of the Doppler shift due to the intervening γ cascades from the continuum. These levels in turn have respective lifetimes of 621 ± 64, 411 ± 51, and 425 ± 56 fs, as measured by Sarantites *et al.*[9] via the Doppler-shift-attenuation technique by direct population involving the (α, p) reaction at 10.0–12.3 MeV. Furthermore these levels are known[10] to receive the major portion of their population via cascades originating the continuum and do not involve other known[8] higher-lying levels in ^{61}Cu. Thus, the above three levels receive the respective feedings of 90.4, 69.1, and 100% from the continuum. The remaining feeding for the 2336.2- and 2611.8-keV levels at this bombardment energy proceeds via states of known lifetimes[9] and it was determined by Barker *et al.*[10] to be as follows: for the 2336.2-keV level 7.0 and 2.6% via the 3015.6- and 2626.8-keV levels, respectively; and for the 2611.8-keV level 30.2 and 0.7% via the 3259.6- and 2923.9-keV levels, respectively. The experimental line shapes were analyzed with multiple components as in Ref. 8 by treating the branch through the continuum as participating in the line shape via two-component decay chains with lifetimes of τ_{level} and τ_c (cascade), and the branches through the higher-lying levels as participating via three-component decay chains with the cascade lifetime τ_c taken to be the same as that for the direct branch. In Figs. 1(a)–1(c) are shown some of the line shapes obtained for the 879.3-, 1366.4-, and 1705.4-keV γ rays observed in coincidence with protons whose energies define the indicated excitation energies in ^{61}Cu.

The line shapes shown in Fig. 1 were obtained with the Au backing and therefore have no contribution from escaping recoils. In these spectra the contribution from the random events and from the underlying Compton events of higher-energy γ rays has been subtracted. The solid lines in Figs. 1(a)–1(c) are the calculated theoretical shapes, which include the fixed level lifetime[9] and correspond to the value of τ_c that gave the minimum values for χ^2 to the corresponding data.

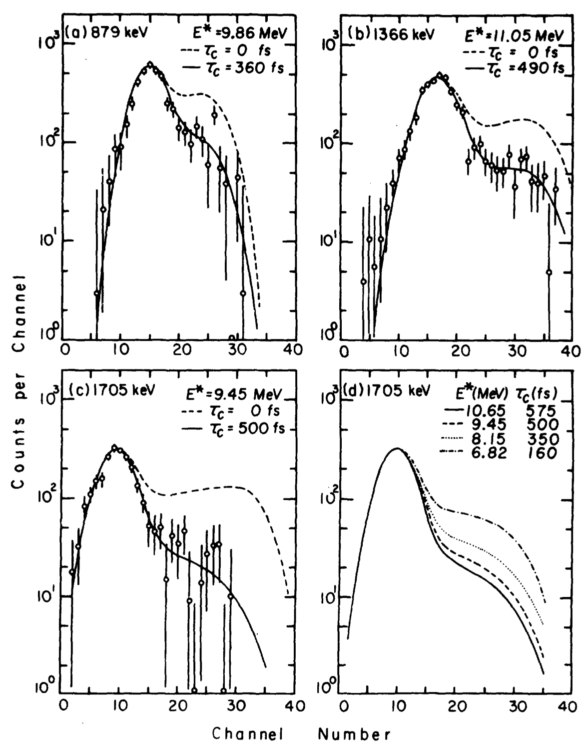

FIG. 1. Comparison of the calculated line shape (solid curves) to the experimental data for three typical peaks [(a), (b), and (c)]. The dashed curves are the theoretical line shapes assuming zero cascade lifetime. The fourth frame, (d), contains plots of the best fits to the line-shape data for the 1705.4-keV γ ray for various indicated values of excitation energy. It is seen that the Doppler shift decreases with increasing available total cascade energy.

The broken lines are the theoretical shapes corresponding to $\tau_c \doteq 0$. The shapes at $\chi^2_{\min}$ for the 1705.4-keV γ ray are shown in Fig. 1(d) and correspond to the indicated excitation energies in ^{61}Cu. It is seen from Fig. 1(d) that the reduction in the Doppler-shift increases with increasing excitation energy available for the cascade leading to this 3015.6-keV level. Similar results were obtained for the shifts from the γ rays deexciting the 2336.2- and 2611.8-keV levels.

The mean lifetimes for the γ cascades that populate the 2336.2-, 2611.8-, and 3015.6-keV levels in ^{61}Cu extracted from the line-shape analysis are summarized in Fig. 2, where the deduced values for the τ_c are plotted vs the excitation energy E^* in ^{61}Cu. Although the experimental error in the individual values is considerable, there is

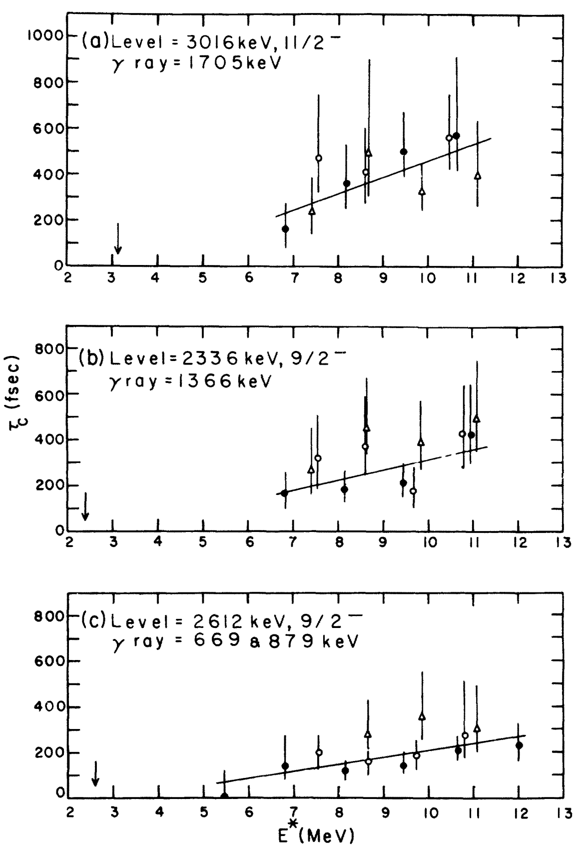

FIG. 2. Plots of the extracted cascade lifetimes as a function of excitation energy in ^{61}Cu from where the cascades started. The straight lines are least-squares fits to the data. The arrows indicate the level energies where the cascades terminate. The deduced slopes and lifetime values at $E^* = 9.5$ MeV are summarized in Table I. The data are the result of three independent experiments, indicated by the open triangles and the open and closed circles.

a definite upward trend with increasing ^{61}Cu excitation energy. The values for the 2611.8-keV level in Fig. 2(c) are averages of the results from the shapes of the 669.3- and 879.3-keV γ rays. The uncertainties shown on the data points correspond to the 90% confidence limit and were evaluated using the procedure of Cline and Lesser[11] for the estimation of errors in a nonlinear χ^2 analysis of data. The errors indicated in Fig. 2 include the uncertainties introduced from the standard deviations of the lifetimes used for the corresponding levels[9] which were found to make only a minor contribution to the over-all uncertainties. Assuming as a first approximation a linear dependence with energy, one obtains the values of the slopes summarized in Table I together with the values of τ_c evaluated at the most probable population which occurs[10] at 9.5 MeV for this reaction. The slopes of the line segments shown in Fig. 2 were obtained by least-squares fits to the data.

First it should be pointed out that the feeding times reported here are substantially shorter than those from the (^{40}Ar, $4n$), (^{32}S, $4n$), (^{20}Ne, $4n$), and (^{28}Si, $4n$) reactions leading to ^{158}Er or ^{166,168,170}Hf and ^{178}Os reported earlier.[3-5] This is understood in terms of the lower multiplicity for the cascades along the ^{61}Cu yrast line compared to the heavy-ion-induced reactions. The trends observed in the results of Fig. 2 can be understood in terms of a statistical model analysis similar to that of Refs. 7 and 10. The increase of the mean cascade time with excitation energy is consistent with an increase in the average multiplicity which is deduced by examining the E-J distribution from which the cascades start. (See Fig. 7 in Ref. 7.) In the case of the $\frac{9}{2}^-$ and $\frac{11}{2}^-$ states populated by the cascades under discussion, a considerable fraction of the cascades are expected

TABLE I. Summary of the mean lifetimes of the γ cascades in ^{61}Cu corresponding to the most probable excitation energy of 9.5 MeV in ^{61}Cu and slopes for an approximate linear dependence of the mean lifetimes with total cascade energy.

Level energy (keV)	J^π	Observed γ ray (keV)	Mean lifetime for cascades starting at 9.5 MeV (ps)	Slope [a] (fs/MeV)
2336.2	$\frac{9}{2}^-$	1366.4	0.29 ± 0.12	40 ± 21
2611.8	$\frac{9}{2}^-$	669.3, 879.3	0.19 ± 0.07	29 ± 12
3015.6	$\frac{11}{2}^-$	1705.4	0.43 ± 0.14	69 ± 20

[a] Values obtained by a least-squares fit using statistical weights. These values are applicable to an approximate range of 5.5–12.0 MeV in ^{61}Cu.

to proceed via the yrast line while the remaining cascades proceed via a near vertical path with a small change in J along the cascade. Furthermore, the average J value of the beginning of the cascade is predicted to increase considerably with increasing excitation energy and this would be mainly responsible for the higher expected multiplicity for transitions originating from higher excitation. The 2336.2-keV ($\frac{9}{2}^-$) level, for example, which lies very close to the yrast line is predicted to receive its population from continuum states with average $J \sim 1.4\hbar$ higher than that of the 2611.8-keV ($\frac{9}{2}^-$) state. The uncertainties in the present values, however, are too large to directly confirm this prediction. The higher observed feeding time for the 3015.6-keV level is explained by a sizable fraction of the cascade proceeding via the yrast line. More detailed calculations will be needed in order to depict the relative dipole and quadrupole transition strengths that are consistent with the present results for the feeding time.

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