Nuclear Lifetimes near 10^{-17} s from X-Ray Spectrum in Inelastic Proton Scattering on ^{112}Sn

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A particle x-ray coincidence experiment for the compound nuclear reaction ^{112}Sn(p,p') at 12 and 10 MeV proton energy is presented. A mean nuclear lifetime of 3.4×10^{-17} s for ^{113}Sb at 15 MeV excitation, and of 4.0×10^{-17} s at 13 MeV is deduced.

The question of nuclear time delay in scattering is a long-standing subject of reaction theory.[1,2] The invention of the crystal blocking technique has made it a subject of direct experimental investigation[3] while the study of statistical cross-section fluctuations has yielded rich, though less direct, information on compound-nuclear level widths.[4,5] Improved detection techniques for x rays and the much refined understanding of inner-shell ionization allow reaction-time studies to be approached in new ways.[6-8] The determination of a nuclear lifetime by comparison with the known K-shell–vacancy lifetime serving as a "clock" makes a range of 10^{-17} to 10^{-15} s accessible to experiment. Such a measurement, where the nuclear states with mean life of several 10^{-16} s are populated by electron capture, has recently been performed,[9] while we have pursued the somewhat different direction to form the intermediate nuclear state in the scattering of a heavy charged projectile. We report in this Letter on the measurement of the mean life for ^{113}Sb of 3.4×10^{-17} s at excitation $E^*=15$ MeV, and of 4.0×10^{-17} s for 13 MeV.

Our experiment is based on the following principle. The projectile which is scattered through an intermediate nuclear state of energy E^* also creates, with a certain probability, an atomic K-shell vacancy. The combined excited system of compound nucleus and K-shell vacancy decays into alternative channels with relative probability depending on the nuclear lifetime: (i) The K-shell–vacancy state of total width $\Gamma_K=\Gamma_K{}^r/\omega_K$ deexcites by emission of a united-atom x ray while the nucleus is still in the intermediate state. Here, $\Gamma_K{}^r$ is the known[10] radiative decay width, and ω_K the K-shell fluorescence yield.[11] (ii) Alternatively, the intermediate nuclear state of total width $\Gamma_N(E^*)$ decays in the presence of the K-shell vacancy, and x rays characteristic for the residual nucleus atomic number will eventually be emitted. If the nuclear state at E^* decays by charged-particle emission these two decay channels can be distinguished experimentally by the x-ray energy. If N_1 and N_2 are the numbers of events measuring the decay rate into the respective channel and $N=N_1+N_2$, one can form a branching ratio and relate it to the widths Γ_K and Γ_N by

$$N_1/N=\Gamma_K(\Gamma_K+\Gamma_N)^{-1}. \qquad (1)$$

It is implicit in Eq. (1) that atomic and nuclear deexcitation are uncoupled, and that the modification of the exponential decay law due to overlapping levels at E^* can be disregarded in first approximation. Γ_N is then the average level width at E^*.

We have chosen the ^{112}Sn(p,p') reaction to determine the branching defined by Eq. (1) in a proton–x-ray coincidence measurement. The numbers N_1 and N are obtained as follows: $N_1=N_c(\mathrm{Sb})T_0/\Omega\epsilon\omega_K$ is the total number of K-shell vacancies decaying in the presence of the nucleus excited to E^*. It is derived from N_c(Sb), the number of coincidences between united-atom x-rays and nuclear evaporation protons. The efficiency of x-ray detection for the Sb K lines is $\Omega\epsilon$, and T_0 corrects for the coincidence dead time. The sum $N=N_1+N_2=N^{\mathrm{inel}}P_K{}^{\mathrm{in}}$ is the number of combined excited systems (of K-shell vacancy and intermediate nuclear state E^*) that decay by charged-particle emission. It is connected to the number of detected inelastic particles, N^{inel}, by the probability $P_K{}^{\mathrm{in}}$ for K-shell ionization by the projectile "on the way in." We approximate $P_K{}^{\mathrm{in}}$ by $\frac{1}{2}P_K$ which is measured in the same experiment that determines N_1:

$$P_K=N_c(\mathrm{Sn})(N^{\mathrm{el}})^{-1}T_0(\Omega\epsilon\omega_K)^{-1}=2P_K{}^{\mathrm{in}}, \qquad (2)$$

where N^{el} is the number of detected elastic particles, N_c(Sn) the corresponding number of coincidences with target x rays, and $\Omega\epsilon$ and ω_K are now taken for the target element. We have found experimentally[12] that the dependence of $P_K(\theta_p)=P_K(90°)(1+B\cos\theta_p)$ on particle angle θ_p in the large-angle region is, for 7- and 12-MeV protons on Sn, compatible with an anisotropy parameter $B=-0.03$ and $B=0.1_9$ respectively, obtained in a semiclassical calculation.[13] Since $B=0$ for scattering with long nuclear time delay,[6] where $P_K{}^{\mathrm{in}}$

$=\frac{1}{2}P_K$ holds exactly, we believe the approximation of Eq. (2) well justified. Solving Eq. (1) for the nuclear width, we finally obtain

$$\Gamma_N/\Gamma_K = N^{\text{inel}}N_c(\text{Sn})[2N^{\text{el}}N_c(\text{Sb})]^{-1} - 1. \tag{3}$$

In Eq. (3) the small difference in ω_K and ϵ for target and united atom is neglected.

The following experimental setup is used: The proton beam from the Universität Köln FN tandem Van de Graaff accelerator is focused onto a self-supporting 100-μg/cm^2 target 80% enriched in ^{112}Sn. A 200-mm^2 × 5-mm-thick Kevex Si(Li) detector is placed at 90°, the crystal being 13.5 mm away from the beam spot. Absorbers of 1 mm Lucite and 0.1 mm Al, and a 50-μm Be window stop scattered protons and low-energy electrons and attenuated the intense L x rays. Two 450-mm^2 × 1-mm-thick silicon surface-barrier detectors in inclined positions detect protons with a solid angle of 1.6 sr at 130° ± 30°. Low-energy electrons are stopped by 7-μm Al foils. Proton and x-ray singles spectra are measured at a count rate of 12 kHz in the Si(Li) which corresponds to 1-kHz proton rate so that particle dead time is negligible. A fast-slow coincidence with 12-ns time resolution (full width at half maximum) selects coincidences that are event recorded for the parameters proton energy, x-ray energy, and time amplitude, and analyzed off line with energy windows on the evaporation protons.

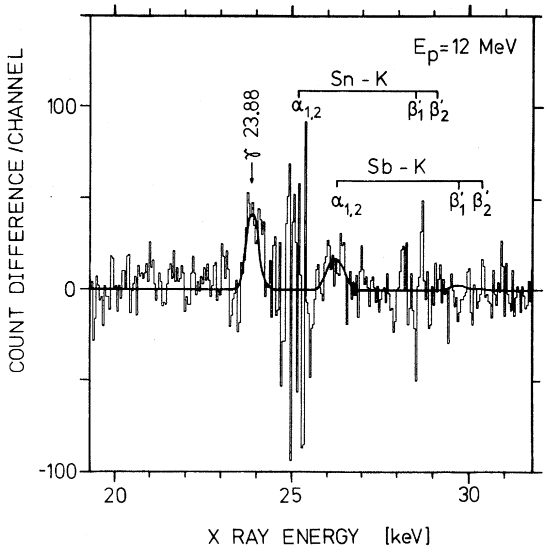

FIG. 1. Coincident x-ray spectrum, after background subtraction as explained in the text. The proton window is 3.2 to 9.2 MeV. The fit (continuous curve) of the Sb $K\alpha$ line and the impurity γ line at 23.88 keV uses experimental line shapes and positions (see text).

The spectrum of coincident x rays for 12-MeV projectile energy, after background subtraction which will be discussed below, is shown in Fig. 1. There clearly is the expected peak at the Sb $K\alpha$ position, with an area of 250 ± 80 counts. This number results from a fit with fixed experimental Sb $K\alpha$ position and line shape as measured under identical detection conditions. Since the $K\beta$ line of Sb is too weak it is accounted for by the known[10] ratio $K\beta/K\alpha = 0.2266$, to yield $N_c(\text{Sb}) = 307 \pm 98$. The Sn $K\alpha$ and $K\beta$ peaks are used for energy calibration and are eliminated in the spectrum of Fig. 1 by the background subtraction. They leave only large fluctuations that sum up to zero. Using $\Gamma_K(\text{Sb}) = \Gamma_K{}^r/\omega_K = 9.19$ eV, with $\Gamma_K{}^r = 7.97$ eV from Ref. 10, and the N_c(Sb) just obtained, Eq. (3) yields $\Gamma_N(\text{Sb}, E^* = 15 \text{ MeV}) = 19.1 \pm 11.1$ eV. This corresponds to a mean life of $(3.4 \pm 2.0) \times 10^{-17}$ s. In Table I are summarized the results of this and an additional measurement, at 13 MeV excitation.

The narrower line at 23.88 keV is due to a γ transition in ^{119}Sn which is a 1.78% impurity in the target. For the fit, position and line shape are taken from a measurement with a ^{119}Sn target under unchanged conditions. We checked experimentally that no other tin isotope has a low-energy γ ray which could interfere with the Sb K lines. Real-to-random ratio for the events in the Sb $K\alpha$ window from 25.6 to 26.9 keV is 0.95, N_c(Sb) is therefore not too sensitive to time structure in the beam. We monitored the beam over the whole duration of the runs and found no structure that affected N_c(Sb). The use of an rf ion source was essential in obtaining such a constant beam.

The coincidences of Sn x rays with inelastic protons are contaminated by x rays from internal conversion. We therefore removed them together with the background by the following procedure. We generated a reference spectrum containing only Sn K x rays, under identical detection condi-

TABLE I. Results for nuclear widths Γ_N in ^{113}Sb. Beam energy is E_p, excitation energy is E^*, the number of inelastic protons from Sn, contained in the windows given in the text, is N^{inel}, and N_c(SB) is the number of coincidences with Sb K x rays.

E_p (MeV)	E^* (MeV)	N^{inel} (10^8)	N_c(Sb)	Γ_N (eV)
10	13	0.434 ± 0.065	98 ± 57	16.6 ± 15.7
12	15	1.14 ± 0.17	307 ± 98	19.1 ± 11.1

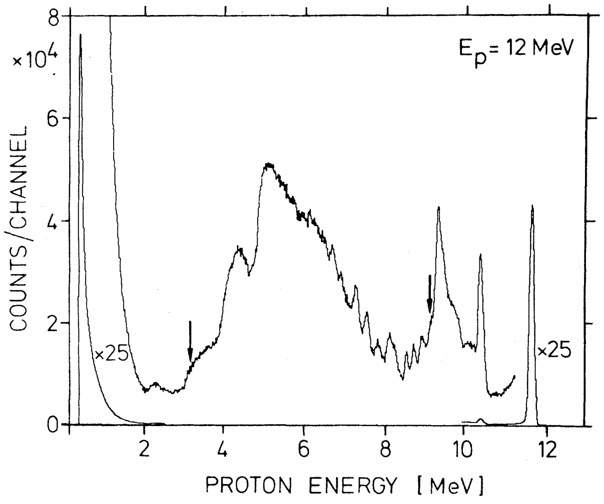

FIG. 2. Particle singles spectrum at $\theta_p = 130° \pm 30°$. The intense low-energy events are electrons. C and O contaminants at 5.2, 4.3, and 3.5 MeV are removed before extracting N^{inel}.

tions, by lowering the beam energy to 5 MeV. Stability of shape of the reference spectrum was carefully checked at 5, 10, and 12 MeV. Reference and coincidence spectra were normalized at Sn $K\alpha$, and a linear background was chosen to fit the coincidence spectrum below and above the x-ray lines. Subtraction yields the spectrum of Fig. 1.

The window in the particle spectrum shown in Fig. 2 extends from 3.2 to 9.2 MeV at $E_p = 12$ MeV, and from 3.2 to 8.7 MeV at $E_p = 10$ MeV. It is deliminated by arrows in the figure. No conversion electrons from the (p,xn) reaction are present in these windows, their maximum energy loss in traversing the 1-mm silicon detector perpendicularly is only 700 keV. This is important as such electrons would simulate proton–Sb-x-ray coincidences. We tested that no electrons are present in the proton windows by analyzing the lower and upper halves of the proton windows separately. The number of coincident Sb x rays per inelastic proton remains unchanged. This excludes the possibility that we have detected spurious events. A check for possible pileup of electron signals with proton signals yielded an upper limit of sixteen such events in the proton window belonging to the spectrum in Fig. 1.

We evaluate separately Eq. (2) for the ionization probability P_K. The results are summarized in Table II. For $E_p = 10$ MeV we give also the value of $P_K(15°)$ which we have actually used to evaluate Γ_N at this energy. The negligible experimental anisotropy at large angles for 7 and 12 MeV discussed above[12] guarantees that we may replace $P_K(130°)$ by $P_K(15°)$ with sufficient accuracy. Because of a real-to-random ratio less favorable, at backward angles, for $N_c(\mathrm{Sn})$ than for $N_c(\mathrm{Sb})$, a weak time structure could not safely be excluded in the run for $P_K(130°)$ at 10 MeV. This is taken into account in the error bar. The $P_K(15°)$ involves a better ratio and therefore smaller error. Also given in Table II are the theoretical predictions[14] for P_K from the relativistic semiclassical approximation which show for 130° satisfactory agreement with our data. At 15°, the theory overestimates the experiment by 45%. Such deviations are also encountered in other collision systems.[15]

With the nuclear widths Γ_N given in Table I we have demonstrated that the time delay in scattering through an intermediate nuclear system at moderate excitation can successfully be studied by particle-induced x rays. This shows that times of the order 10^{-17} s can be measured even though the time duration of the wave packets of the beam particles[2] is of the order 10^{-10} s. As we can choose the intermediate nuclear system and its excitation energy by the projectile, further applications may become possible, such as the measurement of reaction times, e.g., in ana-

TABLE II. Experimental (P_K^{expt}) and theoretical (P_K^{theor}, Ref. 14) ionization probabilities for $\theta_p = 130°$, 15°. Number of elastic protons, N^{el}, of coincidences with Sn K x rays, $N_c(\mathrm{Sn})$, and $T_0/\Omega\epsilon$ for Eq. (2) are also given.

E_p (MeV)	θ_p (deg)	N^{el} (10^8)	$N_c(\mathrm{Sn})$	$T_0/\Omega\epsilon$	P_K^{expt} (10^{-4})	P_K^{theor} (10^{-4})
10	130	1.05 ± 0.03	1434 ± 1050	31.8 ± 1.9	5.1 ± 3.7	6.2
10[a]	15	0.327 ± 0.01	3161 ± 150	4.19 ± 0.3	4.7 ± 0.5	6.8
12	130	1.10 ± 0.03	1815 ± 270	35.1 ± 2.1	6.7 ± 1.1	6.7

[a] Measured by use of a NaI x-ray detector (see Ref. 12).

log resonances and in the fission process.

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Angular Momentum Transfer in Incomplete-Fusion Reactions

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The measured correlation of charged-particle energies and angles with γ-ray multiplicities indicate that the average angular momentum transferred in the capture of ^{4}He, ^{8}Be, and ^{12}C from 153-MeV ^{16}O projectiles by a ^{154}Sm target increases linearly with captured mass. These incomplete-fusion processes are shown to originate from undamped peripheral collisions.

It has been known for some time[1,2] that in heavy-ion reactions energetic light charged particles are produced in larger yield than predicted by the evaporation theory and that they have forward-peaked distributions. Recent measurements[3-5] of γ-ray intensities in coincidence with high-energy α particles at forward angles show a lack of side feeding to states with $J^\pi \lesssim 10^+$. These observations have been taken to indicate the existence of an incomplete fusion mechanism in heavy-ion reactions.[3,4] Excitation functions for (^{12}C, α) and (^{12}C, 2α) have been explained successfully in terms of successive critical angular momenta for various degrees of incomplete fusion.[6] All these results suggest but do not establish that this process occurs mainly for high l values in the entrance channel.

The experiment described here correlates energies and angles of charged particles from specific exit channels with γ-ray multiplicity and provides for the first time direct information on the angular momenta involved in various degrees