Observation of Characteristic X Rays Emitted during Sequential Proton Evaporation by the ^{112}Xe Compound Nucleus

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(Received 3 January 1990)

We have observed Doppler-shifted x rays characteristic of Sb and Sn atoms in coincidence with ^{108}Sn evaporation residues resulting from the emission of four protons by the compound nucleus (CN) formed in the reaction ^{58}Ni+^{54}Fe. We have attributed the Sb x rays to atomic inner-shell vacancies which are created on the way into the nuclear reaction and filled before the emission of the last proton in the deexcitation cascade. The mean proton partial width of the nuclear states, formed at a mean excitation energy of 25 ± 4 MeV by the evaporation of three protons by the CN, has been deduced.

PACS numbers: 25.70.Gh, 34.50.FaP

In nuclear reactions induced by heavy ions, the atomic inner shells and nuclei can be simultaneously excited. The excitation energy of the compound nucleus (CN) is released by sequential emission of particles followed by a cascade of γ rays until the ground state of the evaporation residue (ER) is reached. An atomic vacancy which has been created by the time-varying electric field during the approach of the collision partners may decay at different stages of the CN deexcitation, depending on the relative lifetimes of the nuclear states and the atomic vacancy.[1] Because the atomic transition energies depend on the nuclear charge at the time of deexcitation, the spectrum of x rays emitted by the decay of such an atomic vacancy (AT x rays) may include radiation characteristic of atoms ranging from the ER to the CN. The AT x rays emitted during the lifetime of the CN have been observed in proton-induced reactions on neutron deficient targets,[2,3] but have not been observed in the highly excited CN formed in heavy-ion-induced reactions.[4-6] The AT x rays emitted by ER's from heavy-ion fusion reactions have been observed recently.[7,8] The AT x rays were separated from those due to internal conversion (IC x rays) by detecting the x rays at 0° with respect to the beam direction. This method exploits the fact that the atomic vacancies have a lifetime $\tau_K \sim 10^{-17}$ s much shorter than the stopping time of the recoiling ER $\tau_r \sim 10^{-12}$ s so only Doppler-shifted AT x rays are generated by recoiling ER's. However, the time τ_r is, in general, short compared to the time associated with the nuclear electromagnetic transitions responsible for IC x rays, so that IC x rays are mainly emitted by atoms at rest. In previous work[7] we have shown that the interpretation of such experiments can be greatly simplified if the x-ray spectra are taken in coincidence with γ rays from a particular ER. The same technique, employing improved Doppler separation and reaction-channel selection efficiency, is used in the present work.

In this paper we show the first evidence for x rays originating from intermediate states populated by particle emission in the decay of a CN. We have studied the ^{112}Xe CN formed in the ^{58}Ni+^{54}Fe reaction at 4.1 MeV/nucleon. A pure selection of the ^{108}Sn+4p reaction channel allows us to measure unambiguously AT x rays emitted before and after the evaporation of the last proton. The relative intensities of the x-ray peaks give a measurement of the time associated with the decay of intermediate nuclear states formed during sequential proton emission from the excited CN.[1] The use of a 4π particle detector in conjunction with a sum γ-ray spectrometer enables us to determine the mean position of these states in the γ-multiplicity–excitation-energy plane.

The ^{58}Ni beam, in the 19^+ charge state, was accelerated by the 18-MV tandem accelerator of the Centre de Recherches Nucleaires de Strasbourg onto a 700-μg/cm^2, isotopically enriched, ^{54}Fe target made by implantation in a 12-mg/cm^2 tantalum substrate. The beam was stopped in a 6.8-mg/cm^2 Ti backing. The selection of the ^{108}Sn residual nuclei resulting from the evaporation of four protons by the CN was made by selecting the fourfold events in a 4π particle multidetector. This detector was made of seventeen independent plastic scintillators (3 mm thick) packed in a close geometry to form a 6-cm hollow cube enclosing the target, while permitting excellent γ-ray transmission. The energy signals of each detector could be processed so that the total kinetic energy released by the evaporated charged particles in the center-of-mass (c.m.) frame, $E_{\rm TKE}$, can be estimated. Details of the geometry and performance of this instrument have been given in a previous publication.[9] The particle detector was mounted in the center of a 4π γ-ray spectrometer, "le château de cristal," which consists of 74 independent BaF_2 crystals.[10] The number of BaF_2 crystals fired and the total energy of γ rays deposited in the château de cristal were recorded for all events. These quantities yield, after suitable efficiency calibration,[11] parameters M^i and E^i which give a relative measure of the location of the entry line in the γ-multiplicity–excitation-energy (M-E) plane for each reaction channel i. The experimental setup for monitoring the nuclear excitation was completed by a Ge detector for selecting a parameter ER produced in the reaction.[9] A Si(Li) x-ray detector was mounted at 0° with respect to the beam. The entrance window of the x-ray detector was located 4 cm from the target. The intensity of the characteristic radiation emitted by the target, the projectile, and the backing was strongly attenuated by a set of Al, Ni, and Be absorbers. The x-ray attenuation due to the plastic scintillator was 8% at 26 keV.

For each triple-coincident event between the x-ray detector, the particle detector, and the château de cristal, the time and energy signals of all detectors were digitized and written on tape.

The x-ray spectrum gated by requiring that at least one of the seventeen particle detectors has been triggered with an energy greater than that of a 4-MeV proton and that at least three BaF_2 detectors have fired is shown in Fig. 1(a). For each reaction channel we may observe in the spectrum the following:

(a) The characteristic x rays of particular residual nuclei due to internal conversion (IC) in the electromagnetic deexcitation cascade.

(b) The AT x rays, characterized by a maximum Doppler shift in the x-ray energy equal to 4.8% of the x-ray energy emitted by an atom at rest in the laboratory.

The prominent lines observed in the spectrum [Fig. 1(a)] correspond to the IC x-ray lines In $K\alpha$ (24.1 keV), Sn $K\alpha$ (25.2 keV), and Sb $K\alpha$ (26.3 keV) and Sb $K\beta$ (29.5 keV) from the reaction channels ^{105}In(α,3p), ^{108}Sn(4p), ^{106}Sn(α,2p), ^{109}Sb(3p), and ^{108}Sb(3p,n). The relative intensities of the $K\alpha$ lines depend upon the mean value of the IC coefficient for the cascade of electromagnetic transitions in a given ER, as well as the efficiency with which the particular ER is produced and detected. The continuous background is mainly from Compton interaction of γ rays in the Si(Li) detector.

The extraction of events corresponding to the (4p) reaction channel from the set of data described above was achieved by requiring that four distinct particle detectors have been triggered and at least one of the BaF_2 time signals was delayed by more than 2.5 ns with respect to the first firing detector. The latter condition permits discrimination between the (4p) and (α,3p) channels by selecting those events which decay through a 6-ns isomeric state in ^{108}Sn.[9] The x-ray spectrum taken in coincidence with ^{108}Sn ER's selected in this way is given in Fig. 1(b). The $K\alpha$ and $K\beta$ IC x-ray lines of Sb and In are no longer present in the spectrum, reflecting the high quality of the ^{108}Sn residual nuclei selection.

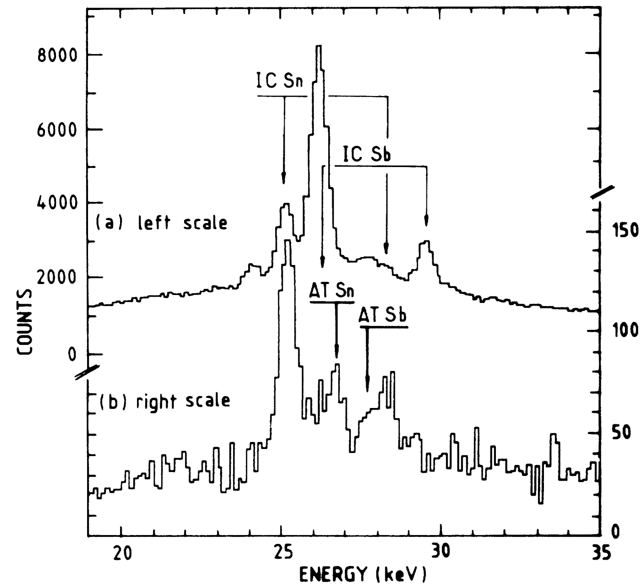

FIG. 1. X-ray spectra at 0° in coincidence with γ-ray fold ≥ 3. (a) Spectrum gated on at least one particle consists mainly of IC x rays. The small fraction of Doppler-shifted AT x rays is barely visible between 27 and 29 keV. (b) Spectrum gated on four particles and one delayed γ ray. Only x rays emitted from the ^{108}Sn residual nucleus appear in this spectrum.

The spectrum has been analyzed by a least-squares-fit procedure with the results shown in Table I and plotted in Fig. 2. The line shape and width (600 eV) used in the fitting routine have been established from the IC $K\alpha$ line of Sb. The background shape used in the analysis, fitted by a polynomial, is indicated by the dashed line in Fig. 2. The mean energy of the most intense line in this spectrum (25.24 keV) corresponds exactly to the energy of a Sn $K\alpha$ transition taking place in an atom at rest. The corresponding Sn $K\alpha$ transitions are present in the spectrum at the mean energy of 28.46 keV. After correction

TABLE I. Intensities and energies of the K x-ray lines found in the spectra of Fig. 2. Measurements refer to the $K\alpha$ line unless otherwise indicated.

Peak	Energy (keV)	Counts	Relative efficiency
IC Sn ($K\alpha$)	25.24 ± 0.06	597 ± 47	1.00
AT Sn	26.77 ± 0.06	253 ± 37	1.23
AT Sb	27.87 ± 0.09	111 ± 33	1.38
IC Sn ($K\beta$)	28.46 ± 0.07	182 ± 36	1.46

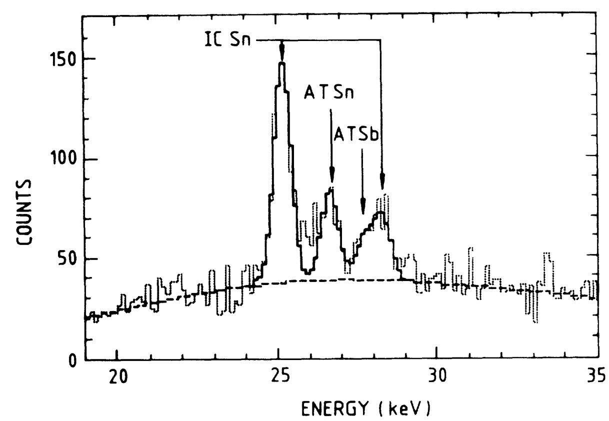

FIG. 2. Fit (solid line) to spectrum of Fig. 1(b). IC and AT denote internal-conversion and atomic-decay x rays, respectively. The dotted line indicates the assumed background shape.

for the variation of the detector efficiency (Table I), the ratio between the $K\alpha$ and $K\beta$ intensities (0.21 ± 0.05) agrees with the values measured in a neutral atom.

Since all the events in the x-ray spectrum are uniquely associated with a ^{108}Sn final state in the reaction, the remaining lines in the spectrum must be attributed to the filling of 1*s vacancies occurring before a complete stoppage of the ER.* The value expected for the energy of the Doppler-shifted AT $K\alpha$ x rays emitted in a singly ionized Sn atom after the emission of four protons by the CN (AT Sn) is 26.45 keV, while the actual energy of the second line found in the spectrum (Fig. 2) is 26.77 ± 0.06 keV. As suggested by Sujkowski *et al.*,[8] this energy shift is due to multiple L-shell vacancies in the ER. Using the shift of 76 eV per $2p$ vacancy given by Burch *et al.*,[12] we obtain a mean number of 4 ± 1 L-shell vacancies in the recoiling ER. Under such conditions we believe first that the M shell should be almost empty and second that the energy of the $K\beta$ transitions should be widely dispersed, since each L-shell vacancy induces an energy shift of 200 eV. For these reasons the Sn AT $K\beta$ transitions are not observed in the spectrum. The poor quality of the fit in the region between the IC Sn line and the AT Sn line can be accounted for by IC decay of nuclear states with a mean lifetime of the order of the stopping time τ_r of the recoiling ER.[13]

The third line in the spectrum is at an energy of 27.87 ± 0.09 keV. The energy separation deduced from the fitted values given in Table I is equal to 1.1 ± 0.1 keV which corresponds to the K x-ray energy difference introduced by one additional unit of nuclear charge, provided that the radiation is emitted from a recoiling ion with an identical number of L-shell vacancies. These Sb AT $K\alpha$ rays have the energy of fully Doppler-shifted $K\alpha$ Sb x rays. This indicates that *some of the vacancies which are made on the way into the nuclear reaction decay after the emission of three protons, but before the emission of the fourth proton* leading to the ^{108}Sn final reaction product.

We can make a quantitative analysis of this interpretation as follows: Consider a number N_R of excited atomic systems remaining after the evaporation of three protons from the CN and which will be detected as a ^{108}Sn ER. The system may decay at this third step either by filling the K-shell vacancy with a partial width $\Gamma_K = h/\tau_K$ before evaporating the last proton, therefore emitting an Sb AT, or by emitting first a proton with a partial width Γ_P. The number of events in the AT Sb peak, N_3, is related to N_R and to the total width Γ_3 of the excited system by

$$N_3 = N_R(\omega_K \epsilon)_3 \Gamma_K/\Gamma_3 , \qquad (1)$$

where ω_K is the fluorescence yield of the atom in the given electronic configuration and ϵ is the detection efficiency of the Si(Li) detector at the energy of the Sb AT x ray.

Since all vacancies which are not filled at the third step will *necessarily decay* by emitting an Sn AT x ray, the number of events in the AT Sn x-ray peak, N_4, is directly proportional to the fraction of N_R atoms which decay by proton evaporation at the third step. Then we may write

$$N_4 = N_R(\omega_K \epsilon)_4 \Gamma_P/\Gamma_3 . \qquad (2)$$

Assuming that the atomic configuration of the outer shell does not change between the third and fourth steps, the intensity ratio of the AT Sn and At Sb peaks is a direct measurement of the ratio Γ_K/Γ_P.[1] From the corrected intensities in Table I we find $\Gamma_K/\Gamma_P = 0.39 \pm 0.13$. The value of Γ_K in a neutral Sb atom is 12 eV.[14] Assuming the actual width is proportional to the number of electrons in the L shell at the time of the decay of the K vacancy, $n_L = 4$, we compute a mean proton partial width for the nuclear states populated in the continuum after the emission of three protons by the ^{112}Xe CN equal to $\Gamma_P = 15 \pm 5$ eV. The quoted uncertainty does not account for a n_L value differing from 4 at the time of deexcitation. Any change in n_L will modify Γ_K introducing an additional error of the order of 20%. The location of these states in the (M,E) deexcitation plane can be inferred from the measured values $\bar{M}^4 = 15 \pm 1$, $\bar{E}^4 = 16 \pm 3$ MeV, and $E_{\rm TKE} = 28 \pm 4$ MeV corresponding to the entry line of the ^{108}Sn ER. Assuming that the fourth proton is emitted with a mean kinetic energy $E_{\rm TKE}/4$ (7 MeV), angular momentum $1\hbar$ and has a binding energy 1.5 MeV in the ^{109}Sb nucleus,[15] we find that the mean width $\Gamma_P = 15 \pm 5$ eV is associated with nuclear states characterized by $\bar{E}_3 = 25$ MeV and $\bar{M} = 15 \pm 1$. Assuming that the yrast cascade is reached after the emission of one statistical E_1 and that an average of one E_1 transition is involved in each yrast cascade,[16] we deduce from M an estimate of the mean value of the nuclear spin state $\bar{J}_3 = (29 \pm 4)\hbar$. A modified version of the evaporation code GROGI[17] used with a standard value of the level-density parameter $a = A/6$, A being the mass of the ER and a, the moment of inertia equal to the moment of a spherical rigid rotor, predicts that the states populated after emission of three protons in the reaction are characterized by $\bar{E}_3 = 27$ MeV and $\bar{J}_3 = 27\hbar$ and a mean partial width $\Gamma_P = 23$ eV. According to the uncertainties on the experimental values of $\bar{E}_3$ and $\bar{J}_3$ and to the strong dependence of Γ_P on these two parameters, the agreement with the experimental values of Γ_P is found very satisfying. As an example the calculated width of the Sb states corresponding to $\bar{E}_3 = 25$ MeV and $\bar{J}_3 = 29\hbar$ is $\Gamma_P = 5.5$ eV.

In conclusion, we have demonstrated that x rays emitted during the deexcitation by proton evaporation of a CN can be used to determine the proton partial width of intermediate states in the CN decay. This is the first time that the "atomic-clock" method suggested by Gugelot thirty years ago has been successfully applied to deduce, in a model-independent way, decay-time information concerning high-spin states formed in heavy-ion fusion reactions.

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