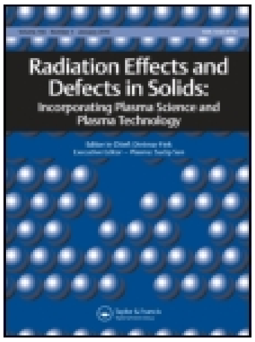

Radiation Effects and Defects in Solids

Incorporating Plasma Science and Plasma Technology

ISSN: 1042-0150 (Print) 1029-4953 (Online) Journal homepage: http://www.tandfonline.com/loi/grad20

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Radiation Effects & Defects in Solids
Vol. 164, Nos. 5–6, May–June 2009, 283–286

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(*Received 24 May 2008; final version received 8 February 2009*)

This paper presents the spectrum of the bremsstrahlung emission accompanying the α-decay of ^{226}Ra ($E_\alpha = 4.8\,$MeV) by measuring the $\alpha-\gamma$ coincidences. We analyze the spectrum by using the model presented in our previous study on the α-decay of ^{214}Po ($E_\alpha = 7.7\,$MeV). We compare the experimental data with the quantum mechanical calculation and find a good agreement between theory and experiment. We analyze the bremsstrahlung emission contributions from the tunneling and external regions of the nucleus barrier into the total spectrum, and find destructive interference between these contributions.

Keywords: α-decay; photon bremsstrahlung; spectrum for ^{226}Ra; sub-barrier and external contributions; interference; tunneling

PACS: 23.60.+e; 23.20.Js; 41.60.−m; 03.65.XP; 27.90.+b

In this paper, we present the results of the bremsstrahlung emission in α-decay of ^{226}Ra. We also analyze and discuss the comparison between the experimental and theoretical results of the photon emission related to the deformed ^{226}Ra nucleus.

The experimental setup was the same as described in our previous paper (*1*). The source of ^{226}Ra with an activity of about 10^4 α-particles/s was used. Along the decay chain of this nucleus, the α-particles were recorded. The diameter of the radioactive spot on the source surface was about 8 mm, and α-particles were detected by a silicon surface-barrier detector with an energy resolution of about 20 keV at the α-particle energy of 4.8 MeV. The α-detector was 200 mm^2 in area and was placed at the distance of about 1 cm from the source. The time resolution of the α–γ coincidence technique was $\tau = 10\,$ns.

The γ-rays were detected using a NaI(Tl)-detector with a diameter of 3 cm and thickness of 3 cm, and the distance between the source and the γ-detector was about 1.6 cm. The angles between the two detectors and the normal axis to the surface of the source were 45°. So the total angle between the α and γ detectors was about 90°. This angle value was chosen to increase the yield of E1-dipole

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ISSN 1042-0150 print/ISSN 1029-4953 online

DOI: 10.1080/10420150902804917
http://www.informaworld.com

bremsstrahlung photons and to reduce the influence of γ-rays from E2-quadrupole transitions of excited states of daughter nuclei. For other details on the recorded events and analysis, see our previous paper (*1*) and references therein.

To take into account the defined angular dimensions of detectors, we used the same procedure to obtain the angular averaged probability of the photon emission $\mathrm{d}P/\mathrm{d}E_\gamma$ as described in (*2, 3*), where the α–γ angular correlation function $W(\theta)$ for the case of E1-dipole photon emission and point-like α–γ source is

$$W(\theta) = 1 + A_2 \cdot Q_2 \cdot P_2(\cos\theta), \tag{1}$$

where $\mathrm{A}_2 = -1$ for the dipole E1 transitions, $P_2(\cos\theta)$ is the second-order polynome of Legendre and Q_2 is the total geometrical attenuation coefficient of the second order: $Q_2 = Q_2^\alpha \cdot Q_2^\gamma$, $Q_2^{\alpha,\gamma}$ being the geometrical attenuation coefficients for α-particle and photon detectors.

The angular correlation function $W(\theta)$, in the case of γ-ray E2-transitions, can be presented as (*4, 5*)

$$W(\theta) = 1 + A_2 \cdot Q_2 \cdot P_2(\cos\theta) + A_4 \cdot Q_4 \cdot P_4(\cos\theta), \tag{2}$$

where $A_2 = 5/7$, $A_4 = -12/7$, $Q_{2,4} = Q_{2,4}^\alpha \cdot Q_{2,4}^\gamma$, $Q_4^\alpha = 0.68$, $Q_4^\gamma = 0.16$ for $E_\gamma = 100\,\mathrm{keV}$ and $Q_4^\gamma = 0.37$ for $E_\gamma = 800\,\mathrm{keV}$. The bremsstrahlung spectra have been averaged over a photon energy interval of 25 keV. The measured values of the photon emission probability $\mathrm{d}P/\mathrm{d}E_\gamma$ due to the bremsstrahlung process accompanying the α-decay of ^{226}Ra are shown by solid squares in Figure 1.

According to Maydanyuk and Olkhovsky (*6*), we define the bremsstrahlung probability as

$$\frac{\mathrm{d}P(w,\vartheta)}{\mathrm{d}E_\gamma} = N_0 k_f w |p(w,\vartheta)|^2, \tag{3}$$

where

$$p(w,\vartheta) = -\sqrt{\frac{1}{3}} \cdot \sum_{l=0}^{+\infty} i^l (-1)^l (2l+1) P_l(\cos\vartheta) \cdot \sum_{\mu=-1,1} h_\mu J_{m_f}(l,w). \tag{4}$$

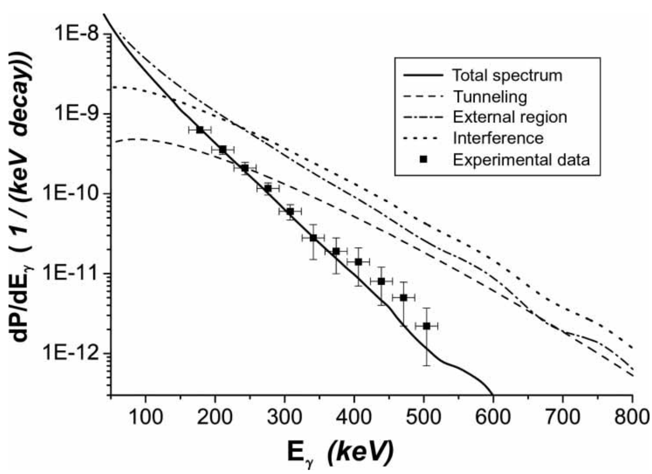

Figure 1. Photon emission probability $\mathrm{d}P/\mathrm{d}E_\gamma$ accompanying the α-decay of ^{226}Ra. Full squares are the experimental data, and the full line is the total spectrum of photons calculated by Equation (3). We also report the spectra of photons emitted from the tunneling region (dashed line), external region (dash-dotted line) and the absolute value of the contribution of the interference term (dotted line).

To describe the interaction between the α-particle and the daughter nucleus (A, Z), we use the following potential (*7*):

$$V(r, \theta, l, Q) = v_{\mathrm{C}}(r, \theta) + v_{\mathrm{N}}(r, \theta, Q) + v_{\mathrm{l}}(r), \tag{5}$$

where Coulomb $v_{\mathrm{C}}(r, \theta)$, nuclear $v_{\mathrm{N}}(r, \theta, Q)$ and centrifugal $v_{\mathrm{l}}(r)$ components have the following form:

$$v_{\mathrm{C}}(r, \theta) = \begin{cases} \dfrac{2Ze^2}{r} \left(1 + \dfrac{3R^2}{5r^2} \beta_2 Y_{20}(\theta)\right), & \text{for } r \geq r_m, \\ \dfrac{2Ze^2}{r_m} \left\{\dfrac{3}{2} - \dfrac{r^2}{2r_m^2} + \dfrac{3R^2}{5r_m^2} \beta_2 Y_{20}(\theta) \left(2 - \dfrac{r^3}{r_m^3}\right)\right\}, & \text{for } r < r_m \end{cases} \tag{6}$$

and

$$v_{\mathrm{N}}(r, \theta, Q) = \frac{V(A, Z, Q)}{1 + \exp\left(r - r_m(\theta)\right)/d}, \quad v_{\mathrm{l}}(r) = \frac{l(l+1)}{2mr^2}. \tag{7}$$

Here, Q is the Q-value for the α-decay, R the radius of the daughter nucleus, $V(A, Z, Q, \theta)$ the strength of the nuclear component, r_m the effective radius of the nuclear component, d the parameter of diffuseness, $Y_{20}(\theta)$ the spherical harmonic function of the second order, θ the angle between the direction of the leaving α-particle and the axis of the axial symmetry of the daughter nucleus, and β_2 the parameter of the quadruple deformation of the daughter nucleus. The parameters of the Coulomb and nuclear components are defined in (*1, 7*).

In order to obtain the spectrum, we have to know wave functions in the initial and final states. In the spherically symmetric approximation, one can rewrite the total wave functions by separating the radial and angular components:

$$\begin{aligned} \varphi_i(r, \theta, \phi) &= R_i(r)\, Y_{l_i m_i}(\theta, \phi) = \frac{\chi_i(r)}{r}\, Y_{l_i m_i}(\theta, \phi), \\ \varphi_f(r, \theta, \phi) &= R_f(r)\, Y_{l_f m_f}(\theta, \phi) = \frac{\chi_f(r)}{r}\, Y_{l_f m_f}(\theta, \phi). \end{aligned} \tag{8}$$

We find the radial components $\chi_{i,f}(r)$ numerically on the base of the given α-nucleus potential. Here, we use the following boundary conditions: the i-state of the system before photon emission is a pure decaying state, and therefore for its description we use the wave function for the α-decay; after photon emission, the state of the system is changed, and it is more convenient to use the wave function as the scattering of the α-particle by the daughter nucleus for the description of the f-state. It is interesting to estimate how much is the emission of photons from the tunneling region and the ones from the internal and external regions concerning the barrier versus the distance r.

Equation (3) of the bremsstrahlung probability is transformed into the following:

$$\frac{\mathrm{d}P(w, \vartheta)}{\mathrm{d}E_\gamma} = \frac{\mathrm{d}P_{\mathrm{tun}}(w, \vartheta)}{\mathrm{d}E_\gamma} + \frac{\mathrm{d}P_{\mathrm{ext}}(w, \vartheta)}{\mathrm{d}E_\gamma} + \frac{\mathrm{d}P_{\mathrm{interference}}(w, \vartheta)}{\mathrm{d}E_\gamma}, \tag{9}$$

where the three components P_{tun}, P_{ext} and $P_{\mathrm{interference}}$ are defined through the finite integrals $J_{m_f}^{(\mathrm{tun})}$ and $J_{m_f}^{(\mathrm{ext})}$ (*8*).

In particular, at $l = 0$ (and assuming that the radial wave function $R_f(r)$ in the final f-state does not depend on the quantum number m_f at $l_f = 1$ like Coulomb functions), one can obtain

$$\frac{\mathrm{d}P_{\mathrm{tun}}(w, \vartheta)}{\mathrm{d}E_\gamma} = \frac{2}{3} N_0 \, k_f \, w \, |J^{(\mathrm{tun})}(0, w)|^2, \tag{10}$$

$$\frac{\mathrm{d}P_{\mathrm{ext}}(w, \vartheta)}{\mathrm{d}E_\gamma} = \frac{2}{3} N_0 \, k_f \, w \, |J^{(\mathrm{ext})}(0, w)|^2, \tag{11}$$

$$\frac{\mathrm{d}P_{\mathrm{interference}}(w, \vartheta)}{\mathrm{d}E_\gamma} = \frac{4}{3} N_0 \, k_f \, w \, \Re(J^{(\mathrm{tun})}(0, w) \cdot J^{(\mathrm{ext}),*}(0, w)). \tag{12}$$

Therefore, we can affirm the following:

(i) the total bremsstrahlung spectrum is not simply the summation of the direct (pure) probabilities from tunneling and external regions P_{tun} and P_{ext}, but it also includes the interference term $P_{\mathrm{interference}}$ (see also *9*, *10*);

(ii) the probabilities P_{tun} and P_{ext} from tunneling and external regions are only positive, whereas the interference term $P_{\mathrm{interference}}$ can be positive or negative.

We have applied the above described method to calculate the bremsstrahlung spectrum emitted during the α-decay of the ^{226}Ra nucleus. The results are presented by the full line in Figure 1.

The slope of the bremsstrahlung spectrum is defined directly by the principal difference between the emission of photons during tunneling of the α-particle and the emission of photons during its motion.

In the figure, we report the tunneling and external contributions of the γ-emission accompanying the α-decay of ^{226}Ra nuclei and the interference term which is calculated by Equations (10)–(12). We can establish that the interference term has negative values in the whole energy region of the emitted photons and plays a destructive role, in addition to the contributions from tunneling and external regions in the forming of the total spectrum. The contribution from the external region overcomes the total bremsstrahlung spectrum and experimental data. This result clearly confirms that without the appreciable contribution of the photon emission during tunneling and the interference term (negative for this case), it is impossible that the total bremsstrahlung emission can reach and agree with the experimental results.

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