PHOTOACTIVATION ANALYSIS

New measurements concerning a non-resonant photoactivation cross section for $^{115}\text{In}$

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In recent years, several groups have reported measurements of a finite non-resonant photoactivation cross section for $^{115}\text{In}$. Present evaluations of this same parameter have made use of an irradiation arrangement and detector which differ from those of other groups. Our values for the resonant and non-resonant contribution to the photoactivation cross-section are $(1.6\pm0.3)\times10^{-28}$ cm$^2$ keV and $(4.0\pm0.9)\times10^{-28}$ cm$^2$, respectively, comparing favourably with counterpart results by TUSTONIC et al.$^3$ of $(1.3\pm0.1)\times10^{-28}$ cm$^2$ keV and $(5.5\pm0.8)\times10^{-28}$ cm$^2$.

Introduction

X-ray and Auger electron emission are well-understood modes of atomic de-excitation following photoactivation. Less well known is a low probability de-excitation process which occurs as a result of nuclear excitation in an electron transition (NEET) and which involves inner-shell electrons of high-Z atoms. A description of the process and a possible application to the separation of $^{235}\text{U}$ has been provided by MORITA.$^1$

While NEET has most typically been ascribed to resonant interactions, recent studies have indicated that non-resonant interactions contribute significantly to the overall interaction cross section. Current interest is in examining photoactivation of $^{115}\text{In}$, a target atom which in terms of NEET processes has been studied by a number of other workers, allowing us to make comparisons with previous results. Particular interest focuses on the suggested existence of a significant non-resonant contribution to the NEET cross section.$^2$

Since photoactivation of $^{115}\text{In}$ is dominated by excitation of the 336 keV isomeric state, populated via resonance fluorescence to the 1078 keV level, non-resonant contributions might only be expected to be observed through use of a highly active irradiation source. To discriminate between resonant and non-resonant processes use has been made of the differential absorption of these two components in iron attenuators. Minimisation of chi-squared values has been carried out in an effort to determine the cross sections.

In studies with which the present work is to be compared, irradiation and detection were achieved using a teletherapy $^{60}\text{Co}$ unit and a Ge(Li) or HPGe detector respectively. Since the source was surrounded by substantial shielding material a 12% contribution from radiation scattered in the collimator was allowed for, this value being in agreement with manufacturer specifications. In present studies use has been made of a Gamma Cell Irradiator (Nordion International Inc.) and a relatively large volume (3"x3") NaI (TI) detector. Distances and the large angles of scattering implied by the geometry, ensure that, at the position of the target, the ratio of scattered radiation to primary photon flux is very small. It is also to be anticipated that use of the NaI detector will provide significant improvement in counting statistics compared with previous studies.

Excitation via resonant and non-resonant processes

As a result of exposure to $^{60}\text{Co}$ gamma-rays, resonant photoactivation of the 1078 keV level of $^{115}\text{In}$ will occur, with prompt de-excitation to the 336 keV isomeric state. The absorption cross section for an isolated level in a stationary nucleus is given by

$$\sigma_{\text{abs}} = \frac{\pi g_k^2 \Gamma_0 \Gamma}{2[(E-E_R)^2 + \Gamma^2/4]} \quad (1)$$

with $\chi = h c / E$, $E$ the photon energy 1078 keV, $g$ the statistical weight factor, $(2I+1)/(2I_0+1)$, containing the total angular momenta $I$ of the excited level and $I_0$ the ground state, $\Gamma_0$ the ground state transition width, and $\Gamma$ the total width of the level.

For a flux of resonant energy photons, $\phi_R(E_R)$, the probability of exciting a particular level in the nucleus is given by

$$P_R = \pi g_k^2 \Gamma_0 \phi_R(E_R) \quad (2)$$

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For decay to an isomeric state, the probability per nucleus of populating the level is given by

\[ P_R = \pi^2 G K^2 \frac{\Gamma_0^{iso}}{\Gamma} \phi_R (E_R) \]  
(3)

where \( \Gamma^{iso} \) is the partial width for decay to the isomeric state.

For \(^{115}\text{In}\), the 1078 keV level is dominant in populating the isomeric level, other excited states of \(^{115}\text{In}\) being either too narrow to be strongly excited by resonance fluorescence, or otherwise producing decays which do not populate the isomeric state. The probability of non-resonant excitation of the isomeric level is given by

\[ P_{NR} = \phi_{NR} \sigma^T_{NR} \]  
(4)

where \( \phi_{NR} \) is the number of non-resonant photons, and \( \sigma^T_{NR} \), the associated total cross section, is given by

\[ \sigma^T_{NR} = \sigma_{NR} (E_{iso}) + \sum_i \sigma_{NR} (E_i) \frac{\Gamma^{iso}}{\Gamma_i} \]  
(5)

where, \( E_{iso} \) is the energy of the isomeric level, the \( i \)th level has energy \( E_i \) and width \( \Gamma_i \) and partial width \( \Gamma_{i0}^{iso} \) for decay to the isomeric level, \( \sigma_{NR} (E_{iso}) \) is the cross section for non-resonant excitation of the isomeric level, and \( \sigma_{NR} (E_i) \) represents the cross section for non-resonant excitation of the \( i \)th level.

A mechanism for non-resonant processes has been proposed by Liubicic.\(^3\) In this approach an interaction is viewed to occur via an intermediate state which decays to the isomeric level. With only one level contributing significantly to the resonance fluorescence using \(^{60}\text{Co}\), and allowing for non-resonant excitation, the probability of exciting an isomeric level is given by

\[ P = \phi_R (E_R) \sigma_R + \phi_{NR} \sigma^T_{NR} \]  
(6)

where \( \sigma_R = \pi^2 G^2 (\Gamma_0^{iso}/\Gamma) \), represents the integrated cross section for the resonance fluorescence contribution, and \( \phi_{NR} \) is dominated by the flux of primary photons.

**Experimental**

The flux of resonant photons \( \phi_R (E_R,d) \) is given by

\[ \phi_R (E_R,d) = \phi_{Cd} (E_R,d) + \phi_{abs} (E_R,d) + \phi^R (E_R,d) \]  
(7)

where \( \phi_R (E_R,d) \) is the sum of fluxes resulting from: (1) Compton scattering of source energy photons in the source material itself, \( \phi_{Cd} (E_R) \); (2) Compton scattering in the absorbers, \( \phi_{abs} (E_R,d) \), and; (3) Compton scattering in the target, \( \phi^R (E_R) \).

\[ \phi_R (E_R,d) = \frac{A}{4\pi r^2} e^{-\mu d} \left[ \frac{2k}{1332} + \delta_{abs} (E_R,d) + \delta_{tg} (E_R) \right] \]  
(8)

In Eq. (8), the linear attenuation coefficients, \( \mu \), in the absorbing medium, for photons of 1173 keV and 1332 keV, are assumed equal, \( A \) is the activity of the \(^{60}\text{Co}\) source (in the present experiments use was made of a Gamma Cell, Model 220 \(^{60}\text{Co}\) irradiator (Nordion International Inc.) of activity 59.4 TBq), \( r \) is the distance between the indium target and the \(^{60}\text{Co}\) source, \( k \) is the ratio of scattered to primary photons for the \(^{60}\text{Co}\) source, \( \delta_{abs} (E_R,d) \) represents the ratio of number of scattered photons with resonant energy in the absorber to the number of primary photons of energy 1332 keV, and \( \delta_{tg} (E_R) \) is the same effective ratio for the target. The flux of non-resonant photons, which depends on the primary gamma-ray flux and, is a function of absorber thickness, is given by

\[ \phi_{NR} (d) = \frac{2 A}{4\pi r^2} e^{-\mu d} \]  
(9)

The theoretical probability \( P_T \) of excitation of the isomeric level is thus given by

\[ P_T = P_R + P_{NR} \]  
(10)

where \( P_R \) and \( P_{NR} \) are the component probabilities for excitation via resonant and non-resonant excitation, such that

\[ P_T (d) = \frac{A}{4\pi r^2} e^{-\mu d} \left[ \frac{2k}{1332} + \delta_{abs} (E_R,d) + \delta_{tg} (E_R) \right] \sigma_R + 2\sigma^T_{NR} \]  
(11)

In present studies a value for \( k \) of 0.12 has been assumed. Given the improbability of large angle scattering of high energy photons, as would be demanded in the present set-up, this is expected to be a highly conservative estimate. For a sample of indium (in this experiment 99.999% pure natural indium of mass 10 g was used), irradiated in the presence of an absorber of thickness \( d \), the number of excitations to the isomeric level, is given by

\[ \lambda N (d,t_{irr}) = N_t (1 - e^{-2\mu d}) P_E (d) \]  
(12)

where \( \lambda \) is the decay constant for the isomeric level, \( N_t \) is the number of \(^{115}\text{In}\) nuclei in the target, \( t_{irr} \) is the period of irradiation and, \( P_E (d) \) is the excitation probability to