Nuclear Resonance Fluorescence in $^{94}$Mo, $^{95}$Mo and $^{96}$Mo

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Using gaseous sources of Tc$_2$O$_7$ containing the radioactive isotopes $^{94}$Tc, $^{95}$Tc and $^{96}$Tc, levels at 871.0 keV ($^{94}$Mo), 765.8, 820.6, 947.8, 1074.0 keV ($^{95}$Mo) and 778.3 keV ($^{96}$Mo) have been excited. From the effective cross sections for nuclear resonance scattering and from the lifetimes of the 947.8, 1074.0 and 778.3 keV levels known from Coulomb excitation experiments the profiles of the γ-lines have been determined. A broadening of the γ-lines due to Coulomb explosion of the molecules has been observed. Making use of the line profiles, lifetimes of $\tau = (6.4 \pm 1.0)$ ps and $\tau = (0.90 \pm 0.20)$ ps have been determined for the 765.8 and 820.6 keV levels, respectively. The angular distribution of the resonantly scattered radiation yields an amplitude ratio $\delta$ for the mixed M1-E2 765.8 keV transition of $\delta = 0.14 \pm 0.08 - 0.09$. The $B(E2)$ from a Coulomb excitation experiment and the lifetime $\tau$ from the present experiment yield $|\delta| = 0.07 \pm 0.01$ for the 820.6 keV transition.

1. Introduction

The lifetimes of the excited levels of $^{95}$Mo up to 1100 keV have recently been determined by Coulomb excitation [1, 2], except for the levels at 765.8 and 820.6 keV which have ground state transitions of predominantly M1 multipolarity. Using gaseous Tc$_4$O$_7$ sources and applying the nuclear resonance scattering technique the lifetime of the 765.8 keV level has been determined in 1967 by Langhoff et al. [3] with an accuracy of about 40%. This large error was mainly due to the use of a NaI-detector which did not separate the 765.8 and 778.3 keV resonantly scattered γ-lines. Furthermore, at that time the information on the influence of molecular binding on the profiles of γ-lines emitted by gaseous sources was very scare. Therefore, the determination of the fraction $N(E_t) \, dE$ of primary photons in an interval $dE$ around the absorption line, and consequently the determination of the lifetime, contained uncertainties.

The present work has been commenced in order to determine the lifetimes of the 765.8 and 820.6 keV levels of $^{95}$Mo which are populated in the decay of $^{93}$Tc (20 h) and $^{95m}$Tc (61 d), respectively. We applied the same method as formerly used by Langhoff et al. [3] with some essential modifications. A large-volume high-resolution Ge(Li)-detector was used instead of a NaI-detector. The line profiles of the emission lines were determined with much larger accuracy making use of recent studies [4] on Coulomb explosion of molecules, and of lifetimes of levels in $^{95}$Mo determined by Coulomb excitation experiments [1].

2. Experiments and Results

The Tc-isotopes were produced by bombarding Mo-foils with deuterons ($E_d = 24$ MeV) in the internal beam of the Göttingen synchro-cyclotron. The active foils together with $5\,$mg of $^{99}$Tc carrier were transferred into a quartz-pyrex system. After evacuating, dry O$_2$-gas was filled into the system which then was sealed off. By heating to 1000°C the elements combined, forming MoO$_3$ and Tc$_2$O$_7$. The two compounds were separated by distilling the volatile Tc$_2$O$_7$ into a pyrex ampoule of about 3 cm$^3$ volume. Then the O$_2$-pressure was reduced to about 160 Torr by cooling one part of the quartz-pyrex system with liquid nitrogen. Hereafter, the ampoule containing the radioactive Tc$_2$O$_7$ was sealed off.
In order to ascertain that the source was completely in the gaseous phase, the distribution of the activity in the ampoule was measured before starting the experiment. The active material was uniformly distributed at 300 °C, whereas it condensed to one spot at room temperature.

The experiment was carried out with the source heated to 350 °C. The detector was a 76 cm³ Ge(Li)-crystal with a resolution of 2.1 keV (FWHM) at 1.33 MeV. The scatterer consisting of 760 g Mo was periodically exchanged by a comparison scatterer, consisting of 370 g Cd and 360 g Zn. The scatterers were matched in order to yield the same nonresonant scattering rate. The matching was checked by comparing the scattering rates of strong nonresonant γ-lines emitted by the source. Further details of the experimental arrangement have been previously described [4].

From the counting rate of resonantly scattered photons \( N_{sc} \) the effective cross section for nuclear resonance scattering \( \sigma_{res} \) has been calculated by means of the relation

\[
N_{sc}/(N_p r^2) = \sigma_{res} N_{at} G
\]

where \( N_p \) is the counting rate of primary photons, measured when the source was placed in a distance \( r \) from the effective centre of the detector and corrected for absorption losses in air. The quantity \( N_{at} \) is the number of atoms of the resonant isotope and \( G \) the geometrical factor. \( G \) takes into account the angular correlation between the primary and the scattered photons, the distances between scatterer and source and detector, respectively, the electronic absorption and a small correction due to resonant absorption. The results obtained for \( \sigma_{res} \) are contained in Table 1. The effective cross sections \( \sigma_{res} \) listed in Column 4 have been previously measured by Langhoff et al. [3] and are in good overall agreement with the present data.

Figure 1 shows the spectra obtained with the two scatterers. Since the isotopes have different half-lives, \(^{94}\)Tc (4.9 h), \(^{95}\)Tc (20 h), \(^{95m}\)Tc (61 d), \(^{96}\)Tc (4.28 d), experiments with different sources had to be carried out in order to achieve a sufficient statistical accuracy for each of the γ-lines. The effective cross section \( \sigma_{res} \) corresponding to the 778.3 keV level in \(^{96}\)Mo has been accurately measured with each of the different sources prepared in the course of this experiment. These different results were in excellent agreement with each other, with deviations not larger than expected from the statistical error of 1 to 2%. This shows that the different sources had identical properties.

For an evaluation of the data the angular correlation function \( W(\theta) \) which enters into the geometrical factor, has to be known. For transitions with pure multipolarity \( W(\theta) \) can be calculated without ambiguity. The 820.6 keV \( M1-E2 \) transition has a mixing parameter of \( \delta^2 = 5 \times 10^{-3} \) (Table 3). Therefore, for the calculation of \( W(\theta) \) this transition can be regarded as being of pure \( M1 \) multipolarity. In case of the 765.8 keV transition use has been made of the fact that this transition is also predominantly of \( M1 \) multipolarity [1, 3]. Then \( A_4 \) can be neglected and we have \( W(125°) = 1 \). The effective cross section listed in Column 3 of Table 1 for the 765.8 keV transition has been measured at \( \theta = 125° \). In order to determine \( A_4 \), an additional experiment has been carried out using \( \theta = 110° \). The two experiments have been analysed in terms of \( \frac{d\sigma}{d\Omega} = \sigma_0 (1 + A_2 P_2 (\cos \theta)) \) yielding \( A_2 = 0.34 \pm 0.15 \) which is in good agreement with \( A_2 = 0.54 \pm 0.2 \) obtained by Langhoff et al. [3]. The mixing parameter corresponding to our \( A_2 \) is \( \delta = 0.14 \pm 0.08 \), where the sign convention of Rose and Brink [5] has been used. In case of the 1074.0 keV transition the average scattering angle was \( \theta = 110° \), which proved to be most favourable for the majority of the transitions as far as the size of the geometrical factor was concerned. \( W(\theta) \) has been calculated using \( \delta = 0.72 \pm 0.11 \) [1]. A different \( \delta \) would result in a \( \sigma_{res} \) differing by a factor of \( a \approx W(110°) \) from the value given in Table 1.

### 3. Line Profiles

From the effective cross section for resonance scattering \( \sigma_{res} \) the total width of the level \( \Gamma \) can be calculated by the relation

\[
\sigma_{res} = N(E_0) g \pi^2 \hbar^2 \Gamma \frac{\Gamma_0^2}{\Gamma}
\]