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Nuclear Excitation by Electronic Transition - NEET

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Abstract. Experiments seeking to demonstrate nuclear excitation induced by synchrotron radiation have been enabled by the development of intense synchrotron radiation. The phenomena has been demonstrated in ^{197}Au, while realistic upper limits for ^{189}Os have been established. A new experiment in ^{189}Os is described. The experimental claim of NEET in isomeric ^{178}Hf is not credible.

INTRODUCTION

Nuclear excitation by electronic transition (NEET) is a rare decay mode for excited atomic states resulting in nuclear excitation. (Atomic states ordinarily decay via x-ray emission and Auger emission.) NEET requirements include energy degeneracy between the atomic and nuclear states, and the same transition multipolarity between the states. The development on intense beams of synchrotron radiation has enabled experiments designed to measure the probability of NEET (P_{NEET}) induced by synchrotron radiation in nuclei where the NEET conditions are met. Rare as the phenomenon is, observation of NEET induced by synchrotron radiation has been reported by Kishimoto, et al. [1]. The focus of this manuscript is on describing the process, some recent experiments, and some ideas for future experiments.

WHAT is NEET?

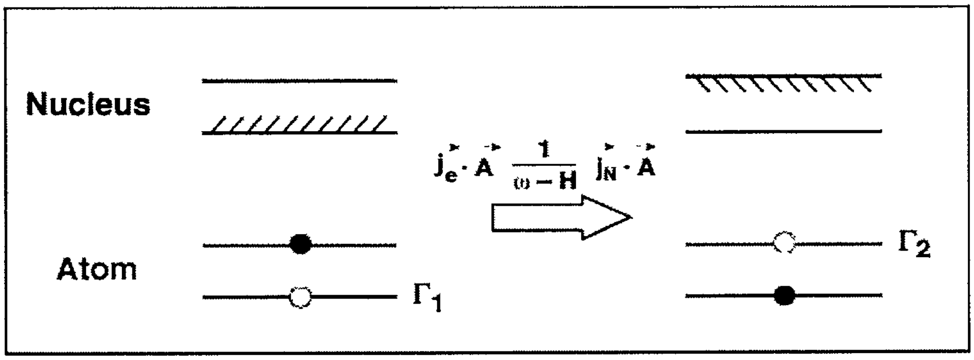
Nuclear excitation through Electronic Excitation (NEET) was discussed by Morita in 1973 [2]. The two dominant decay processes for excited atomic states are x-ray emission and Auger electron emission. Exchange of a virtual photon induces NEET, a second order effect. The NEET probability is small, many orders of magnitude less than atomic excitation loss by x-ray emission.

Fig. 1 isolates (schematically) NEET and gives the relevant formula in a self-evident notation. The matrix element is similar to the (inverse) internal conversion matrix element. Important conditions for NEET to occur include:

- An overlap of the approximately degenerate states
- Common multipolarity of the atomic and nuclear transitions
- $\Gamma_1 > \Gamma_2$ (Widths of the initial and final atomic-hole states, respectively).

The last condition allows NEET to compete with real photon emission. The width of the nuclear state is so small it is treated as zero in the expression for P_{NEET}. The formula in Fig. 1 is given in [3]. Ahmad, et al., [4] independently motivate a similar formula.

Kishimoto, et al., [1] have made a marvelous experiment and find that P_{NEET} is $(5.0 \pm 0.6) \times 10^{-8}$ of the K x-ray emission rate in ^{197}Au for the K $\rightarrow$ M_1 hole transition, while Ahmad, et al., [4] report an upper limit in ^{189}Os for the probability that a K-vacancy results in nuclear excitation of ^{189}Os (E_x = 69.5 keV), $P_{NEET} < 3 \times 10^{-10}$. These experiments take advantage of the intense monochromatic beams available from 3rd generation synchrotrons to prepare the ionized atom to optimize conditions for the observation of NEET. Both experiments are discussed below.



$$P_{NEET} = \left(1 + \frac{\Gamma_1}{\Gamma_2}\right) \times \frac{W^2}{\left(\delta^2 + \frac{(\Gamma_1 + \Gamma_2)^2}{4}\right)}$$

$$W^2 = 4\pi e^2 \frac{\omega_N^{2(L+1)}}{[(2L+1)!!]^2} < j_1 1/2\, L0 | j_2 1/2 > |M_L(\omega_N)|^2 B(ML)$$

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FIGURE 1. Schematic of NEET. The expression for the probability of NEET is given.

RECENT NEET EXPERIMENTS

NEET in ^{197}Au

Kishimoto et al., [1] recently demonstrated the NEET effect in the nucleus ^{197}Au. ^{197}Au has an (accidental) near degeneracy between the energy of the nuclear $1/2^+$ state at $E_x = 77.351$ keV and the atomic K $\rightarrow$ M_I hole transition ($1S_{1/2} \rightarrow 3S_{1/2}$), ($80.725 \rightarrow 3.425$) keV, $\Delta E_{ATOMIC} = 77.300$. The energy difference in the atomic configuration is 53 eV, and the atomic and nuclear transitions can have the same multipolarity.

Therefore, two important conditions for NEET are clearly realized: a near energy degeneracy between the nuclear and atomic transitions ($\Delta E = 51$ eV), and common multipolarity for the transitions. Kishimoto, et al., irradiated ^{197}Au with monochromatic photons ($\Delta E = 19(2)$ eV) at several energies. They measured photon absorption at the nuclear resonance energy 77.351 keV and also measured NEET at an incident photon energy E = 80.989 keV where they found the maximum yield. They report $P_{NEET} = 5.0\ (6) \times 10^{-8}$ relative to the production of K-vacancies. Measurements of both resonance absorption and of NEET allowed Kishimoto, et al., to use ratios to remove uncertainties in their report of P_{NEET}, and in particular to avoid a determination of detection efficiency. (A calculation of the K-vacancy rate is however required.) The experimental signal of excitation of the nuclear state included measuring its decay with time, $t_{1/2} = 1.9$ ns for the 77.35 keV state. The experimental result for NEET agrees with the recent calculations of Tkalya [5], who finds $P_{NEET} \sim 3.8 \times 10^{-8}$ and Harston [6], who finds $P_{NEET} \sim 3.6 \times 10^{-8}$.

NEET in ^{189}Os (I)

Ahmad, et al., [4] searched for NEET in ^{189}Os. They irradiated ^{189}Os with an intense monochromatic beam of photons delivered at the Advance Photon Source (APS), sited at Argonne National Laboratory. The incident energy was E = 98.74 keV, well above the Os K-edge at 73.9 keV. The atomic-nuclear degeneracy Ahmad, et al., attempted to take advantage of lies between the nuclear state at $E_x = 69.537$ keV ($J^{\Pi} = 5/2^-$) and the KM_I transition (70.822 keV, M1). (There are also nearby E2 atomic transitions where the energy overlap is not as good.) The NEET condition for energy degeneracy is not as well satisfied in this case as in the ^{197}Au case: ΔE (keV) = 70.822 - 69.537 = 1.285, while in ^{197}Au ΔE (keV) = 0.051. The experimental signal for NEET was not the direct decay of the 69.54 keV state, but rather the more easily observed and definitive decay of the 30.814 keV isomeric state in ^{189}Os [$J^{\pi} = 9/2^-$, $t_{1/2} \sim 5.7(1)$ h], populated in the decay of the 69.54 keV state. Ahmad, et al. did not observe NEET, reporting an upper limit $P_{NEET} < 9 \times 10^{-10}$, a limit improved in a subsequent experiment to $P_{NEET} < 3 \times 10^{-10}$ [7]. This result is consistent with the results of an independent experiment at the SPring-8 synchrotron radiation facility, where Aoki et al. [8], report $P_{NEET} < 4.1 \times 10^{-10}$. These limits are orders of magnitude below earlier experimental efforts. (See *e.g.*, [4,8] for references to the earlier work.)

What is expected for P_{NEET} in these experiments on ^{189}Os? Ahmad, et al., make use of the expression they develop to calculate P_{NEET} (M1) = 1.3×10^{-10}, a value entirely consistent with their experimental result, and consistent with the measurement of Aoki, et al. The experimental upper limits are also consistent with two recent calculated values: $P_{NEET} = 1.2 \times 10^{-10}$ [5], and $P_{NEET} = 1.1 \times 10^{-10}$ [6].

NEET in ^{189}Os (II)

An experiment planned for late summer 2002 at LLNL takes advantage of the LLNL Electron Beam Ion Trap Facility (EBIT) [9]. Ionized ^{189}Os is prepared by bombardment with a variable energy electron beam and contained within the ion trap. The energy of the electron beam is carefully controlled and tuned so that the sum of the energies of the bombarding electron beam and the L-shell ionized ^{189}Os (a free-bound transition) adds up to the excitation of the nuclear ^{189}Os level at 216.6 keV. Trapped ions are periodically gathered up and counted. The signal is the energy and decay rate of the $J^{\Pi} = 9/2^{-}$, $E_x = 30.814$ keV, $t_{1/2} = 5.7$ h state, populated in the decay of the 216.6-keV nuclear state. Observation of this experimental signal of NEET and not direct observation of the decay of the 216.6 keV level improves confidence in any observed signal. Finally, since the energy degeneracy is accomplished by tuning the incident energy of the incident electron beam, observing an experimental signal while changing the electron-beam energy gives an opportunity for observing a resonance signal and improving confidence in the measurement.

NEET in ^{178}Hf?

Collins, et al., [10] have recently irradiated isomeric ^{178}Hf ($J^{\Pi} = 16^{+}$ $E_x = 2.4$ MeV, $t_{1/2} = 31$ y) at the SPring-8 facility. Incident monochromatic ($\Delta E = 0.5$ eV) x-ray energies were tuned between 9 and 13 keV, in steps of ~ 5 eV. Enhanced γ-ray decay of the isomer near the incident x-ray energies of 11.3, 11.7, and 9.56 keV are reported and ascribed to NEET, and a value of $P_{NEET} = 2 \times 10^{-3}$ relative to L-shell photo ionization in this energy region reported. Attribution to NEET of this signal (if real) is extremely unlikely. This large magnitude of this result is clearly orders of magnitude greater than any reasonable theoretical calculation would predict for P_{NEET} (or for that matter, cross-section estimates based on photoabsorption). There is no evidence for the required nuclear level(s) completing the atomic-nuclear degeneracy with the appropriate multipolarity is completely lacking. The cross section claimed by Collins and coworkers [10] is also in complete disagreement with the experimental results of Ahmad, et al. [11], who report upper limits to the cross section for induced decay of isomeric ^{178}Hf irradiated by synchrotron radiation as a function of incident x-ray energy. Conclusion: there is no credible evidence for observation of enhanced decay of isomeric ^{178}Hf induced by synchrotron radiation.

SUMMARY

There is interesting basic physics within the atomic-nuclear interaction. Measurements and understanding require a discipline oriented study in order to identify cases and circumstances where the small, second-order interactions can be turned to advantage and the effect observed. A more thorough discussion of nuclear transitions induced by synchrotron radiation has been given by Gemmell [12], and a brief discussion of the proposed nuclear excitation of ^{189}Os using the EBIT facility has been given by Beiersdorfer, et al. [13].

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