STUDIES OF OPTIMAL CONDITIONS FOR DEPLETION OF THE ^{110m}Ag ISOMER VIA NUCLEAR EXCITATION BY ELECTRON CAPTURE IN A BEAM-BASED SCENARIO*

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We have performed a theoretical study concerning the analysis of the nuclear and atomic resonance conditions for ^{110m}Ag isomer depletion through nuclear excitation by electron capture (NEEC). This analysis includes selection of the relevant fusion–evaporation reaction for ^{110m}Ag isomer production and calculation of its cross section. Moreover, using the relativistic multiconfiguration Dirac–Fock method, calculations of the dependence of the energy released by electron capture into specific atomic subshells (N, O and P) on the ^{110m}Ag ion charge state have been carried out. In addition, the potentially possible kinetic energy of the NEEC resonance and predictions of the mean equilibrium charge state for the ^{110m}Ag recoil ions as a function of its kinetic energy in the C stopping medium have been evaluated.

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1. Introduction

In the nuclear excitation by electron capture (NEEC) process, a free electron is captured into a not-fully-occupied atomic subshell and may simultaneously excite the nucleus to an energetically higher state [1–4], provided that the sum of the kinetic energy of the free electron and the magnitude of its binding energy once captured matches the nuclear energy difference between the two states. The NEEC process was predicted many years ago [1] and has been a subject of many theoretical studies [2–4]. So far there have been unsuccessful attempts to observe NEEC process, for example in ^{242}Am with an electron beam ion trap [5] or in bare ^{57}Fe ions channeling in an Si crystal [6]. It has been suggested that storage rings [7] or X-ray free-electron lasers [8] may be helpful for the NEEC process observation.

The NEEC process has been recently registered for the first time for the ^{93m}Mo isomer [9] on the world's most powerful Digital Gammasphere spectrometer, installed in the linear accelerator (ATLAS) at Argonne National Laboratory in the USA. However, theoretical investigations performed by Wu *et al.* [10] for the ATLAS NEEC experiment have shown that calculated NEEC excitation probabilities disagree with the experiment by many orders of magnitude. Therefore, further research on this and other nuclides (*e.g.* ^{110m}Ag) are necessary. The ^{110}Ag nucleus (see Fig. 1) has a 6^+ ^{110m}Ag isomer at 117.59 keV with a half-life of 249.83 d and a 3^+ intermediate state that lies 1.13 keV higher (*i.e.* at 118.72 keV). The ^{110}Ag could be produced in its metastable state (^{110m}Ag) through nuclear reactions.

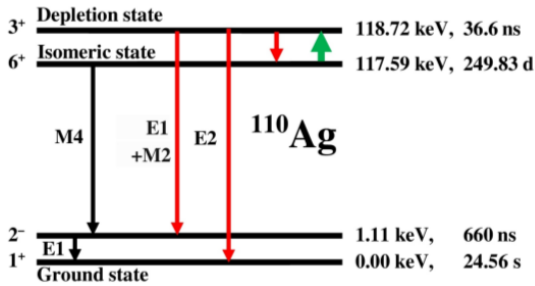

Fig. 1. Partial level scheme for ^{110}Ag nucleus (not to scale). Data are from [11].

In Fig. 2, we have presented a scheme for the ^{110m}Ag isomer production and its depletion through the NEEC process. The heavy projectiles strike a light target and, as a result of fusion–evaporation reactions, ^{110m}Ag isomers can be produced. These highly energetic isomeric recoil ^{110m}Ag ions slow down from high speed through penetration of the stopping medium and can achieve, in a specific space-time region, the suitable atomic state and energy to match nuclear and atomic conditions of the NEEC resonance.

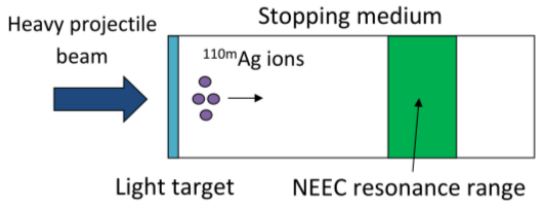

Fig. 2. The NEEC process experimental observation scheme for the ^{110m}Ag isomer (concept adapted from [12]).

2. Results

Our studies focus on performing the comprehensive analyses of the optimal conditions for a better understanding of the NEEC process for selected nuclear isomers of a few nuclides. The part of the research presented here concentrates on the NEEC process for ^{110}Ag nuclei, for which, similarly to our previous studies of the ^{93m}Mo [9, 13–15] and ^{242m}Am [16] isomers, we have determined, using the Monte Carlo fusion–evaporation GEMINI++ [17–19] and PACE4 [20, 21] codes, the cross sections of its production. We have selected the ^{110}Pd + D beam–target reaction for this purpose (see Fig. 3). The desirable ^{110}Ag nuclei are produced in the energy window from about 2.4 to about 12 MeV/nucleon (calculated by the GEMINI++ code) and in the energy window from about 3.9 to about 13 MeV/nucleon (calculated by the PACE4 code). The cross section for the ^{110}Ag isotope production reaches the maximum (about 1130 mb) for a beam energy of about 6.0 MeV/nucleon in the case of the GEMINI++ calculations and about 1390 mb using the PACE4 calculations for a beam energy of about 8.0 MeV/nucleon. The ^{110}Ag recoil ions become highly energetic because they take most of the kinetic energy from the fast ^{110}Pd projectiles.

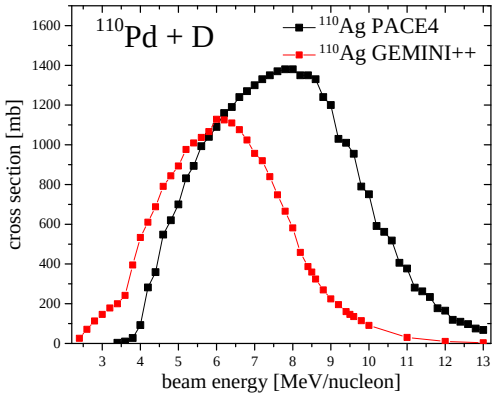

Fig. 3. Total cross sections for ^{110}Ag production in ^{110}Pd + D fusion–evaporation reactions obtained using the PACE4 and GEMINI++ codes.

In order to find to which atomic subshell of the long-lived ^{110m}Ag ion the electron capture is the most probable for observation of the NEEC process, we have performed, using the multiconfiguration Dirac–Fock (MCDF) method [22, 23], analysis of dependence of the energy released by electron capture into different N, O and P subshells on the ionization degree. As can be seen in Fig. 4, with the increase of ionization degree, the energy released by electron capture into given subshells grows considerably, but faster for N subshells than for O and P subshells. Moreover, the energy released by electron capture into N subshells is much higher than for O and P subshells, because N subshell electrons are more tightly bound with the nucleus than electrons in the O and P subshells.

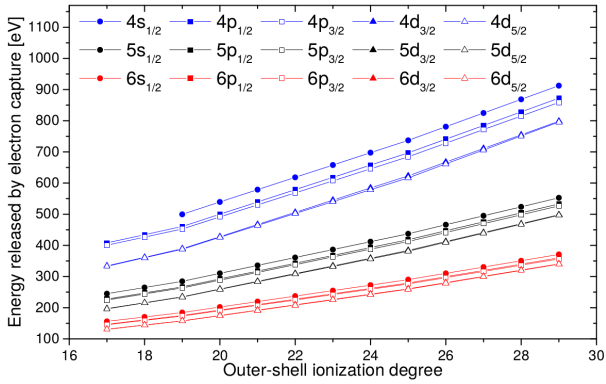

Fig. 4. Dependence of the energy released by electron capture into N ($n = 4$), O ($n = 5$) and P ($n = 6$) subshells of ^{110m}Ag isomer on the outer-shell ionization degree.

Figure 5 presents potential positions of the NEEC-resonance kinetic energy of the ^{110m}Ag ion for electron capture into the N, O and P subshells in the range of charge state from $q = 17$ to $q = 29$. This energy has been evaluated as the difference between the energy needed for occurrence of the NEEC process (1.13 keV) and the energy that has been released by electron capture into the N, O or P subshells (see Fig. 4), multiplied by the ratio of the nucleon to electron mass. The vertical bars in Fig. 5 represent the energies of the resonances, which can mostly be achieved for electron capture into: N subshells for q between 22 and 26, O subshells for q from 24 to 28, and P subshells from $q = 25$ to $q = 29$. These may occur when the bar tops in Fig. 5 reach the region between the two dashed (red) lines, $q_{\min}$ and $q_{\max}$, which describe a deviation of the experimental values ($q = \pm 3.0$). The dependence of the mean equilibrium charge state (q_{mean}), solid (green) line, for ^{110m}Ag ions on their kinetic energy during penetration of the C solid targets have been calculated using the Schiwietz and Grande formulas [24].

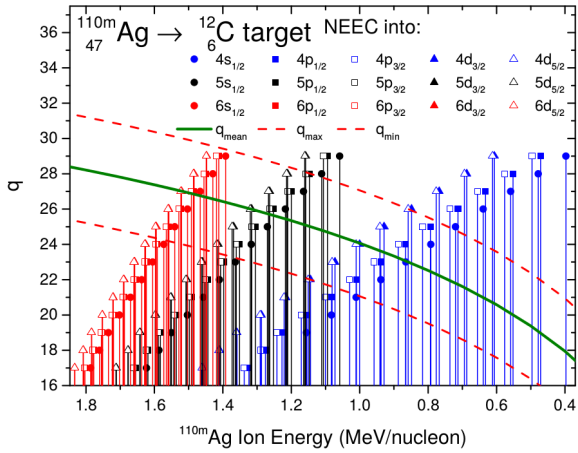

Fig. 5. (Colour on-line) The q_{mean} of the ^{110m}Ag ion as a function of its kinetic energy for a ^{12}C (solid green line) stopping medium. The vertical bars show the potential positions of the ^{110m}Ag ion NEEC resonance kinetic energies for $n = 4$ (grey/blue bars), $n = 5$ (black bars) and $n = 6$ (light grey/red bars) subshells, which can appear for the charge states, between $q = 17$ and $q = 29$, indicated by symbols at the tops of the bars.

3. Summary

We have presented analysis of optimal nuclear and atomic conditions for the occurrence of the NEEC process in the ^{110m}Ag isomer for a beam-based experiment. We have chosen the ^{110}Pd + D reaction in order to find the highest cross section for the ^{110}Ag isotope production. The maximum cross section is about 1130 mb for a beam energy of about 6.0 MeV/nucleon for the GEMINI++ and about 1390 mb for the PACE4 calculations at an energy of about 8.0 MeV/nucleon. Moreover, comprehensive MCDF calculations allow us to find the dependence of the energy released by electron capture into different atomic subshells of the ^{110m}Ag isomer as a function of the outer-shell ionization degree. This analysis has shown that, when ionization degree increases, the energy released by electron capture into certain subshells grows significantly, faster for N subshells than for O and P subshells. In addition, this energy for the N subshell is much higher than for O and P subshells. The dependence of q_{mean} for ^{110}Ag ions on their kinetic energy while passing through a C solid target has also been found. The potential positions of the ^{110m}Ag-ion NEEC-resonance kinetic energies may mainly be achieved for electron capture into N ($22 \leq q \leq 26$), O ($24 \leq q \leq 28$), and P ($25 \leq q \leq 29$) subshells.

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