Review of 113Cd production methods

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I Pre-October 2004 studies

All information in this section is based on that presented by J. Blachot in ref. [1], with additional information taken from the original reports as required. For any experiments where the original report is not cited, a citation can be found within Blachot's report.

A McGowan et. al., 1958

With incident particle energies between 2.1 and 3.3 MeV, the reaction $^{113}\mathrm{Cd}(p, p'\gamma)$ was used. Three γ-rays at energies of 300 ± 3, 582 ± 6 and 675 ± 7 were recorded for an incident particle energy of 3.0 MeV [2].

B Jolly et. al., 1962

The process $^{113}\mathrm{Cd}(d, d')$ was used with an incident beam energy of 15 MeV, but very few levels were ultimately seen [3].

C Koike, 1967

Koike used the beam and emitted particle combinations of (p, p') and $(p, p'\gamma)$ with a proton beam energy of 14.240 MeV on ^{113}Cd, resulting in observation of a small number of energy levels between 0 and 1986 MeV [4].

D Goldman et. al., 1969

The reaction used was $^{112}\mathrm{Cd}(d, p)^{113}\mathrm{Cd}$ with the deuteron energy set to 13 MeV. Essentially all states up to 2.8 MeV were observed, with the spins, parities and spectroscopic factors for each determined using distorted-wave Born approximation calculations. These researchers also ran a (d, t) reaction on ^{114}Cd in order to aid the determination of j values of nuclear states in ^{113}Cd, with an incident deuteron energy of 17 MeV [5].

E Andreev et. al., 1972

Two different pathways were used in this study to produce ^{113}Cd. These were ^{113}Cd$(\alpha, \alpha'\gamma)$ (with beam energy 12.4 MeV) and ^{113}Cd(^{12}C, ^{12}C$'\gamma$) (with energies of 35.3 and 41.1 MeV). The full text was unable to be located so comment the recorded results could not be described.

F Ohya et. al., 1980

On a metallic foil of ^{114}Cd that had been enriched to 99%, a (γ, p) reaction was used to produce a ^{113}Ag source, the decay of which strongly populated the $3/2^-$ state at 1194.6 keV in ^{113}Cd. This state is above the isomeric level at 263.6 keV and it also feeds into it through a γ-ray cascade. These researchers were trying to measure lifetimes of particular states in ^{113}Cd and ^{115}Cd so no results in the form of a set of identified levels was presented here.

G Baskova et. al. (1987) and Nemeth (1991)

Baskova et. al. used the process ^{113}Cd$(n, n'\gamma)$ with an enriched (96%) target. Nemeth re-analysed the data that Baskova et. al. produced, following which excited states up to $\approx$ 2760 keV were observed [1].

H Kroll, 1991

Here the process ^{113}Cd(^{197}Au, ^{197}Au$', \gamma$) was used with an energy of around 4.5 MeV and an enriched ^{113}Cd target. Energy levels between 0 and 1513 keV were seen.

I Geiger et. al., 1994

Here Bremsstrahlung radiation with endpoint energies of 3.16 ± 0.05 and 4.20 ± 0.05 MeV was used in the reaction ^{113}Cd(γ, γ'). Excited states were recorded between around 1800 and 4000 keV, but limited spin-parity assignments were made [6].

J Warr et. al., 1997

This study used the reaction ^{110}Pd$(\alpha, \mathrm{n}\gamma)^{113}$Cd to extend the level scheme of ^{113}Cd, using $\gamma\gamma$-coincidences and five Compton-suppressed Ge detectors. The target 10 mg/cm^2 foil had been enriched to 98.9% in ^{110}Pd. The beam energies used were 12.2, 14.9, 16.2 and 18.0 MeV, with the optimum energy for producing ^{113}Cd from ^{110}Pd found to be $\approx$16 MeV. The highest excited energy level these researchers observed was 2219.64 keV, but they were not able to assign spins and parities for most of the higher-lying states [7].

K Fotiades et. al., 2000

A fusion-evaporation reaction of the form ^{173}Yb(^{24}Mg, $F\gamma$) was used with an energy of 134.5 MeV in this study, conducted at GAMMASPHERE. F here denotes unspecified fusion products. Energy levels up to around 4200 keV were observed [8].

L Buforn et. al., 2000

In this paper the authors describe using the reaction ^{176}Yb(^{28}Si, $F\gamma$) with a beam energy of 145 MeV. They also recorded energy levels up to around 4200 keV.

II Studies between October 2004 and May 2009

The research described below was sourced from Blachot's 2009 evaluation of the Nuclear Data Sheets for A=113 [9], ignoring anything already covered in the preceding section. Additional details are taken from the original papers where required.

A Bucurescu et. al. 2005

This work performed high energy resolution studies of ^{113}Cd using polarized beams with the (d,p) and (d,t) reactions, in one-neutron transfer reaction experiments. In both reactions, a large number of levels (about 80) were observed up to excitation energies of 2.6 MeV. For many of them unambiguous spin and parity assignment were made. According to the authors of this report, "together with previous data from other experiments, the level scheme has probably become essentially complete up to this energy" [10]. As stated by the authors, the use of "polarised projectiles allows unambiguous spin-parity assignments".

For the ^{114}Cd$(d,t)^{113}$Cd (or ^{114}Cd(pol $d,t)^{113}$Cd) reaction, the beam energy used was 25.0 MeV (beam current around 150 nA), the target was enriched to 99.1% ^{114}Cd and the FWHM (resolution) achieved was ≈5 keV. They observed 98 excited states of ^{113}Cd below an excitation energy of 2.63 MeV.

For the ^{112}Cd(pol $d,p)^{113}$Cd reaction, the beam energy used was 22.0 MeV (beam current around 100 nA), the target was enriched to 98.6% ^{112}Cd and the resolution achieved was again FWHM ≈5 keV. Below an excitation energy of 2.63 MeV they observed 75 excited states of ^{113}Cd with the (d,p) reaction.

Overall, up to an excitation energy of 2.6 MeV, about 80 levels were observed in both of the above reactions, with spin, parities and spectroscopic factors determined for many of them.

A.1 Previous nuclear reactions used to study ^{113}Cd

All of the following (historical) reactions and studies are mentioned by Bucurescu et. al. [10]. This list gives a nice summary of some significant achievements made using a few different reactions.

- The ^{113}Cd$(n, n'\gamma)$ study, which evidenced a large number of levels up to about 2.3 MeV in the spin window 1/2 to 7/2 (Nemeth et. al. 1994)
- The ^{110}Pd(α, nγ)^{113}Cd reaction study, which mainly populated levels in a wide region above the yrast band, up to spin of about 15/2 [7].
- Heavy-ion fusion reaction studies, such as ^{173}Yb(^{24}Mg, $F\gamma$) carried out in [8], enabled determination of high spin states (such as the νh11/2 sequence)

A.2 Further noteworthy points

- Once formed from the β-decay of ^{113}Ag, ^{113}Cd decays either to the ground state, or to the 11/2- isomer at 263 keV, which leads to the population of ^{114}Cd (by thermal neutron capture from the g.s.) and of ^{113}In (by β-decay of the isomer) respectively.
- The obtained experimental angular distributions were compared with the predictions of distorted-wave Born approximation (DWBA) calculations in order to determine the values of the transferred angular momentum (l) and spin (j) for each level.
- Many (3/2-) states were observed in the excitation region 2.1–2.6 MeV, and the authors suggested, by similarity with the tellurium isotopes, that they play an important role in the population of the 11/2- isomeric state through the (γ,γ') reaction.
- The observation of many $l = 1$ transitions above 2 MeV excitation energy gives a clue to the way by which the 11/2- isomeric state can be populated in the (n, γ) and (γ,γ') (which starts at the ground state) reactions, through a series of many negative parity low-spin states. The logic that Bucurescu et. al. present for this is as follows.
  - Above 2 MeV, nine excited states with energies of 2174, 2320, 2327, 2381, 2424, 2477, 2488, 2556 and 2591 keV were observed and all assigned as $3/2^-$ states in ^{113}Cd.
  - The distribution of the 3p$_{3/2}$ orbital in which these lie (within ^{113}Cd) appears rather similar to that observed in the Te isotopes 123, 125 and 129 through the (d, p) and (n, γ) reactions [11].

- In ^{113}Cd the γ-ray decay for only the two lowest $3/2^-$ states is known: they preferentially decay to the $5/2^-_1$ state.
- However, the similarity with the afore-mentioned Te isotopes is good enough for it to be assumed that the behaviour of the higher lying $3/2^-$ states is similar. This assumption means that these states will also favour decay towards the same $5/2^-_1$ state.
- The $5/2^-_1$ states mainly decay to the $7/2^-_1$ state which then primarily decays to the $11/2^-_1$ isomer.
- Hence, the observed $3/2^-$ states are probable candidates for a "gateway" level in the (γ, γ') process. So, through their decay to the $5/2^-_1$ "funnel" state (at 855 keV), it is likely that strong population of the $11/2^-$ isomeric state can occur.

III Post-May 2009 studies

Hereafter studies not covered by the most recent evaluation of the $A = 113$ data sheet by Blachot are described.

A Karamian et. al., 2015

This work focuses on producing a range of isotopes and isomers (like $^{113\text{m}}$Cd) and measuring yield ratios rather than improving level schemes. Here 23 MeV electron beams were used to generate bremsstrahlung, which was used to irradiate a ^{113}Cd target (among others like ^{114}Cd and $^{\text{nat}}$ Cd) for 10 hours. From the $^{114}\text{Cd}(\gamma, n)$ reaction, $^{113\text{m}}$Cd was produced with a yield of 0.12(1). Similarly, from a $^{\text{nat}}$Cd target, the process $^{114}\text{Cd}(\gamma, n)^{113\text{m}}\text{Cd}$ had a yield of 0.125(18) [12].

B Hayakawa et. al., 2016

These researchers tried to measure the isomer production ratio for the reaction $^{112}\text{Cd}(n, \gamma)^{113}\text{Cd}$ using neutron beams. They found that excited states with low spin in ^{113}Cd are populated following neutron capture reactions on the $J^\pi = 0^+$ ground state of ^{112}Cd. These excited states then decay away to the $11/2^-$ isomer or the $1/2^+$ ground state via γ-ray emission.

This team also found that the isomer branching ratio increases with increasing spins of the state populated following the neutron capture, but this ratio appears to remain constant (at an unknown value) as a function of energy below 5 keV [13].

C Gicking et. al., 2019

Radiative neutron capture cross-sections were measured for the stable isotopes of Cd (mass number A = 106, 108, 110, 112, 114 and 116) through observation of the decays of the eight radioisotopes produced as a result of neutron capture. The capture process ^{112}Cd $\rightarrow$ ^{113m}Cd was observed in a sample that was enriched to be $\sim$98% 112Cd, with the 263.7 keV γ-ray recorded at a branching ratio of 0.01839 (presumably this ratio refers to branching from whichever level of ^{113m}Cd was populated following neutron capture) [14].

After the work of Hayakawa et. al. [13], Gicking et. al. state values of the ratio of the capture cross section leading to formation of the isomer to the total neutron capture cross section as 0.012(3) and 0.095(8), results that were obtained using thermal cross-sections and resonance integrals respectively. In their words, the "small cross sections for isomer formation [reflect] the relative smaller probability of a γ-ray cascade leading from the low-spin capture state to the 11/2 isomer as opposed to the 1/2 ground state".

D Ryvkin and Skachkov, 2019

Bremsstrahlung of accelerator electrons used to irradiate a cadmium plate, leading to the formation of $^{113\mathrm{m}}$Cd [15].

E Artun 2019

The article at the following link was unable to be accessed in full. From the abstract and title, this work describes the investigation of a range of radioisotopes (including $^{113\mathrm{m}}$Cd) for use in nuclear batteries through phenomenological and microscopic level density models. In particular, the abstract mentions three parts:

(i) Investigation of the production of some radioisotopes that could be used in nuclear battery technology with neutron-induced reaction processes

(ii) Estimation of the cross-section curves of (n,γ) reactions for astrophysical processes in the energy region between 1 eV and 1 MeV

(iii) Determination of suitable level density models for the (n,γ) reaction processes.

IV Break-up vs. fusion

Brief summaries of studies that explore the ideas of break-up and fusion suppression in nuclear reactions.

A Dasgupta et. al., 1999

Key points made by Dasgupta et. al. in their report on their observations of significant fusion suppression when ^{208}Pb is exposed to a ^{9}Be beam [16].

- The large cross-sections observed for incomplete fusion products support the interpretation that this suppression of fusion is caused by ^{9}Be breaking up into charged fragments before reaching the fusion barrier.
- Breakup into charged fragments affects fusion very significantly.
- Reactions with ^{9}Be therefore offer an excellent opportunity to study breakup and its effect on fusion.
- The complete fusion of ^{9}Be is suppressed compared with the fusion of more tightly bound nuclei.
- ^{9}Be has a large probability of breaking up into two helium nuclei (specifically ^{4}He and ^{5}He), which would suppress the complete fusion yield.
- Breakup of the stable ^{9}Be appears to be more significant than breakup of the unstable ^{10,11}Be in influencing the fusion product yields. This conclusion is favourable for using fusion with radioactive beams at near–barrier energies to form new, neutron-rich nuclei.

B Diaz-Torres et. al., 2007

Key points made by Diaz-Torres et. al. in their write-up regarding their three-dimensional classical model for low energy reactions of weakly-bound nuclei. Their model demonstrates the importance of the breakup probability function, accessible from experiments at sub-barrier energies, to predictions of complete and incomplete fusion yields of weakly-bound projectiles at energies above the Coulomb barrier [17].

- Breakup of weakly bound nuclei is an important process in their collisions with other nuclei.
- A major consequence of breakup is that not all the resulting breakup fragments might be captured by the target, termed incomplete fusion (ICF); capture of the entire projectile by the target is called complete fusion (CF).

- ICF processes can dramatically change the nature of the reaction products, as for the stable weakly-bound nuclei ^{9}Be and ^{6,7}Li. There, at energies above the fusion barrier, CF yields were found to be only $\sim$2/3 of those expected, the remaining 1/3 being in ICF products.

- Elastic or no-capture breakup: when the projectile breaks up and none of the fragments are captured. According to Diaz-Torres et. al., this provides an important diagnostic of the reaction dynamics.

C Kozub et. al., 1984

Using γ-particle coincidence analysis (once that is up and running), performing an "inverted" heavy ion reaction (e.g. ^{7}Li beam on a ^{110}Pd target) might be worth considering. The key points made in the above report are as follows [18].

- Coincidence data acquisition using two Ge detectors is often very slow, owing primarily to low photon detection efficiency

- Particle-γ coincidence data can generally be acquired at a higher rate than γ-γ data because particles incident on a detector can be detected with essentially 100% efficiency, if their energies are above some threshold value.

- The overall system (the system being the detection of particles and γ-rays) efficiency is further enhanced in the case of "inverted" heavy ion reactions, i.e., reactions in which the projectile is more massive than the target nucleus.

V Potential plans for us

Based on the work of Warr et. al. [7], making use of the reaction $^{110}\mathrm{Pd}(\alpha, \mathrm{n}\gamma)^{113}\mathrm{Cd}$ with a beam energy of around 16 MeV might be a good way to study the level scheme of ^{113}Cd. However, instead of a beam of α-particles, a beam of Li-7 or Be-9 could be used in order to take advantage of the documented phenomenon of break-up and incomplete fusion [16, 17]. Regardless, the low energy ($\approx$16 MeV) used is important because it means that the (α, n) process dominates over other reactions like (α, xn) with $x > 1$ that will produce cadmium isotopes other than ^{113}Cd. This is also why having a highly enriched target matters.

We have the capability to use either a Li-7 or Be-9 beam to mimic the $^{110}\mathrm{Pd}(\alpha, \mathrm{n}\gamma)^{113}\mathrm{Cd}$ reaction. Hopefully soon we will also have the ability to detect (light) particles in coincidence with γ-rays, which we could use to identify which nuclides were produced in coincidence (setting an appropriate timescale Δt) with which gammas using knowledge of the beam and target used.

^{6,7}Li can be thought of as a system comprising a weakly bound α-particle and a ^{2,3}H nucleus (deuterium nucleus/deuteron and tritium nucleus/triton respectively). As an example, possible break-up reactions for Li-7 (that may produce ^{113}Cd) are

- $^7\mathrm{Li} \rightarrow {}^6\mathrm{Li} + n \rightarrow (\alpha, d)$ where the α-particle would go on to fuse with ^{110}Pd in order to form ^{113}Cd as above.
- $^7\mathrm{Li} \rightarrow F$ where F is a complete fusion product with the target, followed by the evaporation of n, $2n$ or $3n$ from the compound nucleus that is formed.
- $^7\mathrm{Li} \rightarrow (\alpha, nt)$ where an α is absorbed and a triton t emitted (as well as a neutron). The triton can then be detected using a charged particle detector.
- $^7\mathrm{Li} \rightarrow (t, n\alpha)$ where a t is absorbed and an α emitted (as well as a neutron). The α-particle can then be detected using a charged particle detector.

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