Proposal to the INTC Committee

Beta-decay study of very neutron-rich Cd isotopes with a chemically selective laser ion source


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Abstract

Following our test measurements of N=82–84 Cd isotopes with a specifically developed laser ion source (CERN/ISC 97–16, ISC/I 22), we now propose detailed spectroscopic studies of the decay of $^{130}$Cd to $^{132}$Cd, and at least the determination of some gross properties of the new N=85–86 nuclides $^{133}$Cd and $^{134}$Cd. The main nuclear-structure objective of this experiment is the identification of the energies of the single-hole (SH) proton states in $^{131}$In. Nearly all of the other single-nucleon shell-model basis energies around doubly magic $^{132}$Sn are known by now, except those $\pi$SH in Z=49 $^{131}$In. Theoretical agreement on these values has not been achieved so far. Of particular interest is the depth of the $\pi f_{5/2}$ hole and the $p_{3/2} - p_{1/2}$ spin-orbit splitting. A second important goal is the determination of the position of the lowest-energy $1^+$ level in $^{130}$In predominantly populated in the Gamow-Teller (GT) decay of N=82 $^{130}$Cd. Apart from the intrinsic shell-model importance, especially the even-mass isotopes $^{130}$Cd, $^{132}$Cd and $^{134}$Cd are also of astrophysical interest as r-process “waiting-point” nuclei for different neutron-density regimes.

1. Introduction

With regard to the single-particle (SP) structure far from stability, the doubly closed-shell nucleus $^{132}$Sn itself together with its nearest-neighbor SP ($^{133}$Sb$_{82}$ and $^{135}$Sb$_{83}$) and SII ($^{131}$In$_{82}$ and $^{133}$Sn$_{81}$) nuclides play an essential role in testing the shell model, and serve as input for any reliable microscopic nuclear-structure extrapolations towards the neutron drip-line. In the past, spectroscopic studies of $\beta$-decays at on-line mass-separator facilities have been the most efficient tool to investigate such exotic nuclei. Today, the $\nu$-hole structure of $^{131}$Sn [1], four of the five $\pi$-particle states in $^{133}$Sb [2], and the lowest $\nu$-particle levels in $^{133}$Sn [3] are fairly well known. The only missing information is the
π-hole structure in $^{131}\text{In}$, where so far only the energy of the lowest-lying πSH isomeric state is known within ±25 keV [1,4]. The full set of l=1 and l=3 πSH levels can in principle be studied through $\beta$-decay of the N=83, $I^*=7/2^-$ nucleus $^{131}\text{Cd}$ or via $\beta$-delayed neutron ($\beta\text{dn}$) decay of N=84, $I^*=3^+$ isotope $^{132}\text{Cd}$.

Also in the context of studying details of the r-process nucleosynthesis in the A≈130 region, experimental information on nuclear quantities such as masses, $\beta$-decay properties and general shell-structure features in the vicinity of the classical, neutron-magic "waiting-point" nuclei below $^{132}\text{Sn}$ is of special interest [5,6]. In the Cd isotopic chain, both the rather long half-life (T$_{1/2}$≈165 ms) of N=82 $^{130}\text{Cd}$ and the low neutron separation energy (S$_n$≈2 MeV) in N=83 $^{131}\text{Cd}$ will slow down the r-matter flow through the A≈130 mass region for neutron-density and temperature conditions of n$_n$≈10$^{20}$–10$^{22}$ cm$^{-3}$ and T≈10$^8$ K. This is mirrored by the top of the peak in the solar-system r-abundance distribution (N$_{r,\odot}$). For higher neutron densities, the r-process in Cd chain will break through N=82, and 97 ms N=84 $^{132}\text{Cd}$ and the so far unknown N=86 $^{134}\text{Cd}$ will become the waiting-points. Consequently, the N>82 Cd isotopes will to a large extent determine the N$_{r,\odot}$ peak shape and total duration of the "main" r-process component [7].

2. Results from theoretical measurements

After having faced severe experimental problems with the first identification of $^{130}\text{Cd}$ at the old SC-ISOLDE using a chemically non-selective plasma ion source, further progress in the study of neutron-rich Cd isotopes only became possible during recent years through the application of element-selective resonance ionization laser ion sources (RILIS). First experiments to find a well-suited excitation scheme for resonance ionization of Cd were carried out in Mainz [13], and later adapted to the PSB-ISOLDE. At the General Purpose Separator (GPS), $\beta\text{dn}$-multiscaling measurements were performed at masses A=130 to 132 to determine half-lives and P$_n$ values. The results have been published recently in some detail [8-11]; therefore, in the following we briefly summarize the main outcome.

In Fig. 1 are shown the $\beta\text{dn}$-multiscaling curves obtained for A=130 to 132, when operating the ion source in two different modes, i.e. in surface-ionization ("laser-off") and in laser-ionization ("laser-on") mode. The "laser-off" decay curves represent half-life mixtures of the known $^{129}\text{In}$ to $^{132}\text{In}$ isomers, each [12]. The "laser-on" $\beta\text{dn}$-curves clearly show a shorter-lived component on top of the respective In activity, which can be attributed to the decay of laser-ionized Cd. For the classical N=82 waiting-point nucleus $^{130}\text{Cd}$, we have obtained a T$_{1/2}=(162±7)$ ms, which is more precise than our earlier value of (195±35) ms from 1986 [13]. Also its $\beta$-branch of P$_n=(3.6±1)$ % is in agreement with our old estimate. For the new isotope N=83 $^{131}\text{Cd}$, a T$_{1/2}=(68±3)$ ms has been determined. This half-life is unanticipatedly short when compared to current global-model predictions for GT-decay (e.g. T$_{1/2}(\text{GT})=943$ ms from the QRPA of [14]). Also the P$_n=(3.4±1)$ % is surprisingly low when considering the large (Q$_{\beta-S_n}$) window of about 5.8 MeV for $\beta\text{dn}$-emission. Möller et al. [14] predict, for example, P$_n(\text{GT})=99$ %. A somewhat similar picture arises for the second new isotope, N=84 $^{132}\text{Cd}$. Its T$_{1/2}=(97±10)$ ms is again considerably shorter than the T$_{1/2}(\text{GT})=633$ ms from [14]. However, in this case, the
large experimental $P_n = (60 \pm 15)$ % is at least in qualitative agreement with the predicted $P_n(GT) = 100$ %.

In trying to understand the shell structure responsible for the above decay properties of the $N \geq 82$ Cd isotopes, three quantities are of interest: (i) the Q-value for $\beta$-decay, (ii) the log(ft) values for the main GT and first-forbidden (f) transitions to states in the In daughters, and (iii) the energies of these states. A detailed discussion about the "required" features to reproduce our experimental data is given in [8]. Here, we summarize our arguments at the example of $N=83\ ^{131}\text{Cd}$ decay (see Fig. 2). The left part contains the straight-forward predictions of Möller et al. [14] for pure GT-decay with $Q_\beta = 11.6$ MeV from the FRDM mass model [15]. This QRPA is an admitted simple, but global SP model, within which several nuclear quantities ($Q_\beta, S_n, \epsilon_2, E_{QP}, J^\pi, \log(ft), T_{1/2}, P_n$) of thousands of isotopes (spherical or deformed) can be calculated in a selfconsistent way.

An advantage of this model is its flexibility, allowing detailed nuclear-parameter studies for local fine-tuning. Following this concept, the right part of Fig. 2 shows an improved prediction considering GT- and f-decay properties, guided by experimental observations in the $^{132}\text{Sn}$ region, with $Q_\beta = 12.6$ MeV from the ETFSI-Q mass model [16]. It is interesting to point out here, that these predictions are in good overall agreement with the very recent local shell-model approach of Brown et al. [17]. These authors use the OXBASH code with a renormalized G-matrix to calculate in a selfconsistent way $Q_\beta$ and $S_n$ values, level energies, $\beta$-branching ratios, $T_{1/2}$ and $P_n$ values. They apply a set of effective renormalized GT matrix elements, and rank 0 and 1 f-transition operator matrix elements chosen to fit experimentally known transition strengths in the $^{132}\text{Sn}$ region. For the decay of $^{131}\text{Cd}$,
for example, they confirm (i) the high $Q_\beta$ value expected from the Audi et al. mass evaluation [18] and predicted by "quenched" mass models [16,19], (ii) the importance of the $ff$-strength at $N \approx 82$, and (iii) the location of the lowest $\nu g_{7/2} \rightarrow \pi g_{9/2}$ GT-transition to the $[\nu f^{1+} / g_{7/2}^{-1} \pi g_{9/2}^{-1}]$ 3QP level below $S_n$. With this, Brown et al. [17] calculate a $T_{1/2}=93.5$ ms and a $P_n=2.74\%$. We consider this work of particular importance, also for astrophysical applications, because consistently good overall agreement has been obtained for all other known exotic isotopes in the whole region around $^{132}\text{Sn}$.

3. Proposed experiments

In these experiments, we now wish to extend the studies of gross $\beta$-decay properties to heavier Cd isotopes, $N=83\ ^{133}\text{Cd}$ and $N=84\ ^{134}\text{Cd}$, and to identify the $\gamma$-rays from decay of $^{130-132}\text{Cd}$ in order to determine the $\pi$SH structure of the $^{130}\text{In}$ nuclides in the region of the $N=82$ closed neutron shell. Particular emphasis will be placed on the structure of the isotope $^{131}\text{In}$ which has a single proton hole in the double magic nucleus $^{132}\text{Sn}$. These data would then provide a full set of SP levels for the nearest neighbors surrounding $^{133}\text{Sn}$. The levels of $^{131}\text{In}$ can be studied in two ways. They are populated directly in the decay of $J^\pi=7/2^-\ ^{131}\text{Cd}$ as shown in Figure 2. In this case, mainly high-spin states will be reached. In addition, $^{131}\text{In}$ levels can be populated in the $\beta dn$-decay of $J^\pi=0^+\ ^{132}\text{Cd}$. Thus, the use of $n\gamma$-coincidences for the study of $^{132}\text{Cd}$ decay offers a second path to a different, mainly low-lying, low-spin set of levels in $^{131}\text{In}$. The second important goal is the identification of the lowest $1^+$ state and other levels in one-$\pi$-hole – one-$\nu$-hole nucleus $^{130}\text{In}$ that are expected to be populated in the decay of $N=82\ ^{130}\text{Cd}$. Finally, we would also seek new data for the level structure of $^{132}\text{In}$, the one-$\pi$-hole – one-$\nu$-particle, odd-odd nuclide adjacent to $^{132}\text{Sn}$. As we can study $\beta dn$-decay of isotopes 3 masses heavier than the mass under study in the $\gamma$-ray beam line, we would simultaneously seek new $\beta dn$-data for $^{133,134}\text{Cd}$ during the $\gamma$-measurements of $^{130,131}\text{Cd}$ decays.

For these experiments, two moving tape collector (MTC) stations would be used, one to study $\gamma$-rays and one to study $\beta dn$-decay. At the $\gamma$-ray station, three large, BGO-shielded Ge detectors from the Strahlenphysik Stuttgart will be mounted in close geometry to the MTC. Beta-gating and anti-gating will be accomplished through the use of 5 large-area PIN detectors mounted just outside of the tape station vacuum chamber. The high-efficiency, three-ring Mainz $^3\text{He}$ neutron detector will be mounted on the other MTC. In addition, a Ge detector will be placed in position to detect $n\gamma$-coincidences.

The study of the $\beta dn$-decay of $^{133,134}\text{Cd}$ will be more difficult than the previous study of the decay of $^{131,132}\text{Cd}$ as the daughter nuclides $^{133,134}\text{In}$ (with half-lives of 180 and 140 ms, respectively) have large $P_n$ values. Since In isotopes are expected to be ionized via surface ionization, the selectivity achieved by RILIS at the GPS may not be enough to permit unambiguous observation of the decay of these Cd nuclides. On the other hand, comparison of "laser-on" with "laser-off" data, along with microgating of the beam, are powerful tools for the identification of the decay of weakly produced isobars, as was achieved for $^{128}\text{Ag}$ decay, for example.
Figure 2: Predicted level scheme of the N=82, πSH nucleus $^{131}$In populated in β-decay of N=83 $^{131}$Cd. In the left part, QRPA calculations for pure GT-decay are shown using a Folded-Yukawa potential with Lipkin-Nogami pairing [14] and the mass parameters of the global FRDM model [15]. In the left part, calculations for GT- and ff-decay are depicted, now using a Nilsson potential with reduced I²-term, as suggested in [20,21], and BCS pairing, together with the mass parameters of the "quenched" ETFSI-Q model [16]. It is clearly seen from this figure, that the experimentally observed short $T_{1/2}$=68 ms and the low $P_{\alpha}$=3.5 % only be reproduced with (i) a high $Q_{\beta}$ value, (ii) the inclusion of ff-branches – in particular the $\nu_{I/2}^{T/2} \rightarrow \pi g_{9/2}$ ground-state to ground-state transition, and (iii) a shift of the lowest 3QP state strongly fed in GT-decay below $S_{\alpha}$≈6.3 MeV.
4. Nuclear-physics considerations

The evolution of SP structure plays a crucial role in all calculations of the structure of nuclides, especially those far from stability where no experimental data are available. Usually, near $\beta$-stability, these are determined for nuclides adjacent to double and single magic isotopes. Such studies for nuclides near $^{40,48}$Ca and $^{208}$Pb have been the foundation of both shell-model and other model calculations for many years. In contrast, the single-proton levels for the region between $^{78}$Ni and $^{132}$Sn are not at all well established. No data are now available for excited states in $^{79}$Cu and $^{90}$In, and only an estimate exists for the location of the $\pi_p_{1/2}$ level in $^{131}$In. Because the ground states (g.s.) of both $^{90}$In and $^{131}$In are $\pi g_{9/2}$ levels, in-beam data will be unlikely to prove new information for a more precise location for the $\pi p_{1/2}$ level in either nuclide, nor for the $\pi p_{3/2}$ and $\pi f_{5/2}$ levels that comprise the $\pi$-orbitals for $28 \leq Z \leq 50$. Data are available for how the respective $\nu$-orbitals evolve between $^{57}$Ni and $^{89}$Zr. However, these nuclides are in a region where $N \simeq Z$, whereas for $^{131}$In $N = 1.67\cdot Z$. Recent studies suggest that in high N/Z regions, low-spin orbitals for both protons and neutrons will be depressed relative to higher-spin orbitals. In addition, variations in the spin-orbit splitting are not firmly established. Hence, the location of the $\pi p_{1/2}$, $\pi p_{3/2}$ and $\pi f_{5/2}$ levels in $^{131}$In will answer a number of important questions.

As can be deduced from the proposed decay pattern of $J^p = 7/2^-$ $^{131}$Cd shown in Figure 2, in agreement with the shell-model calculations of Brown et al. [17], GT- and ff-decays are expected to populate 5/2, 7/2 and 9/2 3QP levels just below $S_\alpha \simeq 6.3$ MeV. The individual decay pattern of these levels is quite important to the final determination of the low-energy $\pi$SP levels. For example, the 5/2$^-$ levels cannot populate the 9/2$^+$ g.s., but should show decay to the low-lying 1/2$^-$, 3/2$^-$, and 5/2$^-$ levels. In contrast, the 7/2$^-$ and 9/2$^-$ levels cannot populate the $p_{1/2}$ state, but should populate the 5/2$^-$ and 9/2$^+$ levels. Taken together, these decays should permit determination of the location of all three negative-parity ($l=1$ and $l=3$) levels with respect to the expected $\pi g_{9/2}$ g.s.

From the experimental perspective, the situation is quite hopeful. The most serious isobaric interferences in this mass region come from In, Cs, and Ba nuclides. In this case, the half-lives of the three $^{131}$In isomers lie in the range $\sim 260-300$ ms, $^{131}$Cs has no $\gamma$-rays, and the $\gamma$-rays from 11-d $^{131}$Ba are all at low energy. Hence, the combination of "laser-on", "laser-off" and time dependent-spectra should permit the ready identification of the 68-ms $\gamma$-rays from $^{131}$Cd decay.

In contrast, the 60% $\beta$dn-decay of $J^p = 0^+$ $^{131}$Cd is likely to populate predominantly the low-lying $\pi p_{1/2}$, $\pi p_{3/2}$, and $\pi f_{5/2}$ levels. Thus, the strongest lines in the $\pi\gamma$-coincidence spectra would be just those expected from the decay of the $\pi p_{3/2}$ and $\pi f_{5/2}$ levels. The predicted decay pattern of $^{132}$Cd is shown in Fig. 3. Because of the spins involved and the low $S_\alpha \simeq 2.7$ MeV in the $\beta$-decay daughter, we expect only few low-energy $\gamma$-rays. The main $\beta$-feeding will lead to neutron-unbound states with $J^p = 1^+$ (GT-decay) and $J^p = 1^-$ (ff-decay) between $\sim 5$ and 6 MeV in $^{132}$In. From these levels, $l=1$ and $l=0,2$ neutron emission will occur to the $\pi p_{1/2}$, $\pi p_{3/2}$ and $\pi f_{5/2}$ levels in the $\beta$dn-final nucleus $^{131}$In, in competition with $l=4$ and $l=3$ decay to the $\pi g_{9/2}$ g.s.. The $\gamma$-rays from 2-d $^{132}$Cs are few in number, and the $\gamma$-lines from $\sim 200$ ms $^{132}$In decay are well-known. Hence, some identification of
Figure 3: Proposed decay scheme of $N=84$ $^{132}$Cd. Most of the GT- and ff-strength goes to neutron-unbound states, from which low-$l_n$ neutron emission is expected to populate the $\pi p_{1/2}$, $\pi p_{3/2}$ and $\pi f_{5/2}$ levels in the $\beta$dn-final nucleus $^{131}$In. For further discussion, see [8].
γ-rays in $^{132}$In populated in $^{132}$Cd decay may also be possible. There is little theoretical agreement for the energy differences expected for the negative parity π-levels. For example, Rutz et al. [22], suggest a spin-orbit splitting of $\sim 1$ MeV for the $p_{1/2} - p_{3/2}$ gap. Leander et al. [23], summarized a number of approaches to these energies. They reached a consensus of 1.4 MeV for the spin-orbit $p_{1/2} - p_{3/2}$ splitting and obtained a $p_{1/2} - f_{5/2}$ energy difference of $\sim 2.6$ MeV. Earlier, Heyde et al. [24], had used values of 0.6 and 1.3 MeV for the $p_{1/2} - p_{3/2}$ and $p_{1/2} - f_{5/2}$ energy splitting, respectively. The recent SKX shell-model calculations of Brown et al. [17,25] predict a $l=1$ spin-orbit splitting of $\sim 1.1$ MeV and a $p_{1/2} - f_{5/2}$ energy difference of roughly 2.6 MeV. Our QRPA calculations, using a Folded-Yukawa potential and Lipkin-Nogami pairing (see left part of Fig. 2), predict a spin-orbit splitting of the two $l=1$ states of $\sim 1.3$ MeV, and a $p_{1/2} - f_{5/2}$ energy difference of $\sim 2.4$ MeV. Our version with a modified Nilsson potential and BCS pairing (see right part of Fig. 2) would suggest similar energy gaps, but a general shift towards lower excitation energies in $^{131}$In. Indeed, the wide differences among these calculations are the main reason for this experiment, as these low-lying π-states are a crucial part of any attempt to calculate level structures of nuclides further from stability that lie in the r-process path.

For the decay of N=82 $^{130}$Cd, all our QRPA calculations agree that the two main GT-branches populate two J$^*$=1$^+$ 2QP [$\pi_g7/2\pi_f9/2$] states below S$_0$≈5 MeV. Depending on the model parameters used (potential: Folded-Yukawa, Woods-Saxon, different Nilsson parametrizations; pairing: Lipkin-Nogami, BCS), the lowest 1$^+$ state is predicted to lie between 1.2 MeV and 2.5 MeV with a log(tf) varying between 4.1 and 4.4, corresponding to β-feedings between 60 and 90 %. The recent local shell-model calculations of Brown et al. [17] predict this 1$^+$ state at 1.325 MeV with a log(tf)=4.17. Using a $Q_β$ value of 8.5 MeV from the latest NUBASE-evaluation [18], our QRPA predicts the $P_β$ value between 2 % and 11 %, and the $T_{1/2}$(GT) between 100 ms and 260 ms. Both gross properties are in satisfactory agreement with our experimental findings. Hence, the main properties of the GT-decay of $^{130}$Cd seem to be reasonably well understood. Nevertheless, the position of the lowest 2QP 1$^+$ state and its β-feeding (log(tf) value) remain important quantities to be measured.

5. Astrophysics considerations

Already since the late 1950's [5,26] it is consensus among astrophysicists and cosmochemists that the neutron shell closures at N=20, 82 and 126 are important for the time-scale of the fast neutron-capture nucleosynthesis and the "r-process pile-up" at the bromine (A≈80), xenon (A≈1300) and platinum (A≈195) peaks of Suess and Urey's so-called "cosmic abundances".

Focussing on the N=82 shell, already B$^2$FH [5] explain how the r-process "climbs a staircase with Z and A (from Z=41, A=123) both increasing by unity at each step", and define Z=49, A=131 (i.e. $^{131}$In) as the "break-through" from N=82 to N≥83 at the A=130 r-abundanced peak. Within this classical picture, $^{130}$Cd is thus the heaviest N=82 "waiting-
Figure 4: "Static" calculations of $N \geq 82$ isotopic abundances of $^{48}$Pd to $^{49}$Cd within the nuclear Saha equation as a function of neutron density. Left part: mass model FRDM [15] with strong $N=82$ shell-closure; right part: mass model HFB/SkP [19] with quenched $N=82$ shell far from stability.
point nucleus”. In those days, however, several simplified assumptions were made, such as a constant neutron density \( n_n \) and constant \( S_n \approx 2\ MeV \) values at \( N=82 \) up to \( Z=48 \).

Today, with improved nuclear-physics knowledge and more realistic \( r \)-process scenarios, we know that \( S_n(Z) \) is not constant at \( N_{magic} \) and that an \( r \)-process requires a range of neutron densities of several orders of magnitude. This changes the original waiting-point picture and makes the \((Z,A)\) break-through value a function of \( n_n \). This is shown in Fig. 4 as a "static" snapshot (not time-dependent) for the \( N=82 \) isotones \(^{128}\text{Pd}, \(^{129}\text{Ag} \) and \(^{130}\text{Cd} \) for two different mass models, the FRDM [15] with a classical, strong \( N=82 \) shell-closure, and the HFB/SkP [19] which predicts a considerably quenched \( N=82 \) shell far from stability. When comparing the two figures, it is evident that (i) the \( N=82 \) isotones of the three elements act as waiting-points within different \( n_n \)-ranges, and (ii) the respective break-through from \( N=82 \) to \( N=83 \) occurs at lower \( n_n \) values for the quenched mass model.

Focussing on HFB/SkP and the Cd isotopes considered in this proposal, we see that up to \( n_n \approx 5 \times 10^{20} \ cm^{-3} \) all three \( N=82 \) isotones, \(^{130}\text{Cd}, \(^{129}\text{Ag} \) and \(^{128}\text{Pd} \) act as waiting-points. When increasing \( n_n \) by one order of magnitude \((n_n \approx 5 \times 10^{21} \ cm^{-3})\), still \(^{129}\text{Ag} \) and \(^{128}\text{Pd} \) are waiting-points, whereas in the Cd isotopic chain the break-through to the \( N=84 \) isotope \(^{130}\text{Cd} \) has occurred. At \( n_n \approx 5 \times 10^{22} \ cm^{-3} \) the break-through in the Ag chain takes place, and in the Cd chain \( N=86 \) \(^{134}\text{Cd} \) becomes the new waiting-point.

Summarizing, in order to understand in detail the build-up of the \( A \approx 130 \) \( r \)-abundance peak and its bottle-neck behavior for the \( r \)-matter flow through \( N=82 \), experimental nuclear data not only of the classical neutron-magic waiting-point nuclei (here \(^{130}\text{Cd} \)) are of importance, but also for the next heavier isotopes (here mainly \(^{132}\text{Cd} \) and \(^{134}\text{Cd} \)).

6. Beam-time request

We are requesting a total of 18 shifts for these studies. As noted above, the ability to establish the positions of the 4 \( \pi SH \)-levels in \(^{131}\text{In} \) will depend on considerable detail in the observed \( \gamma \)-spectra taken at \( A=131 \) and the \( n\gamma \)-spectra taken at \( A=132 \). Hence, we are asking for 12 shifts for these measurements. At the same time, we would be seeking to identify the \( \beta \text{dn-decay of } ^{134}\text{Cd} \). To the direct study of the \( \gamma \)-decay of \(^{132}\text{Cd} \) we would devote 3 shifts. Another 3 shifts would be used for the \( \gamma \)-decay study of \(^{130}\text{Cd} \), simultaneously with \( \beta \text{dn-decay of } ^{132}\text{Cd} \).

References