**R-process \(^{130}\)Cd Waiting Point**

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**Abstract.** Most of the elements heavier than Fe in the universe were produced by the so-called r-process. Its mechanism is based on a rapid neutron capture by the nuclei, so that the neutron capture rates are much faster than those of \(\beta\)-decay. When r-process reaches nuclei with magic neutron numbers, the neutron separation or binding energies increase and the process slows down, it has to wait for several \(\beta\) decays to produce heavier nuclei. These magic nuclei are the waiting points. Information about r-process are still missing and it requires knowledge of the nuclear structure of the neutron rich nuclei. However, the nuclear properties of these nuclei are not sufficiently well understood due to the experimental difficulties in their production. The A=130 isobars with N=82 present one of the most interesting waiting points, because of their positions far from \(\beta\) stability and near the doubly magic \(^{132}\)Sn core, for which theoretical and experimental studies give important information about beta decay half-lives. In this context, we focus on the study of even-even \(^{130}\)Cd waiting point nuclear properties. We have performed some spectroscopic calculations for energetic spectrum, \(\beta\)-decay half-life evolution in terms of temperature, using recent experimental data, by means of Oxbash nuclear structure code. The getting spectrum is in a reasonably agreement with the available experimental data. However, the calculated \(\beta\)-decay half-life for the studied waiting point is short in comparison with the experimental one.

1. Introduction  
The nuclear physics aimed to achieve a unique theoretical model that allow to understand the observed abundances of the elements and their isotopes, and to explain their nuclear properties. Most of the existing nuclei heavier than the iron are produced by rapid neutron capture (r-process) in very rich neutron environment (\(\gtrsim 10^{20}\) cm\(^{-3}\)) and high temperatures (\(\approx 10^9\) K) [1, 2, 3]. This process continue to produce elements until it arrives at neutron magic nuclei for which neutron separation or binding energies \((S_n)\) are important [2, 4]. It has to wait for several successive \(\beta\) decays in order to achieve an isotopic chain with lower \(S_n\) \((S_n \leq 3\) MeV), this is the waiting point [2].  

Nuclei around \(^{132}\)Sn are located close to the r-process flow path. Their nuclear properties: binding energies, \(S_n\), excited states and \(\beta\) decay properties \((Q_\beta\) values, \(\beta\)-decay \(T_{1/2}\), \(\beta\)-delayed neutron emission\) are very significant amounts in nucleosynthesis and r-process calculations. The importance of this area in astrophysics comes from the fact that it consists three waiting points: A=130, 138 and 195 [4, 5].

In this work, we have focussed on the classical A=130 waiting point with Z= 48 \(^{130}\)Cd). This isotope was first produced and identified by Kratz et al. (1986) at SC-ISOLDE at CERN, in which a proton beam of 600 MeV on a uranium carbide in a graphite-cloth matrix target was
used. They measured $\beta$-decay half-life with possible fast first forbidden ground state transition [1, 6]. The measured value of $T_{1/2} = (195 \pm 35)\text{ms}$ was comparable with the RPA shell model prediction of 0.3s for Gamow-Teller $\beta$-decay [6]. In 2003, Dillmann et al. have performed first $\beta$-decay and $\beta$-spectroscopic studies for $^{130}\text{Cd}$ waiting point at CERN/ISOLDE [1]. They have found a high energy of 2.12MeV for $1^+$ state dominated by $(\pi 1g_2^2\nu 1g_2^2)$ configuration in $^{130}\text{In}$ nucleus, and a high $Q_\beta$ value of 8.34MeV. They have, also, carried out some spectroscopic calculations using Oxbash [7] shell model code for both nuclei $^{130}\text{Cd}$ and $^{130}\text{In}$ and using a residual interaction derived from CD-Bonn interaction [8].

2. r-Process vs Beta decay

$\beta$-decay half-lives of waiting point determine the needed time to transmute seed nuclei to heavy ones within r-process around $A \sim 200$ [2]. These half-lives are considerably long and therefore the waiting point nuclei have in general larger abundances in comparison with their isotopes [9].

In stellar conditions at temperature $T$, the $\beta$-decay rate of a nucleus is expressed by [10, 11]:

$$\lambda = \sum_i e^{-\frac{E_i}{kT}} \sum_j \frac{\lambda_{ij}}{Z}$$

(1)

$E_i$ and $Z = \sum_i (2I_i + 1)e^{-\frac{E_i}{kT}}$ denote, respectively, the energy of the state and the partition function of the mother nucleus. $i$ and $j$ sum over states of the mother nucleus and the daughter one, respectively. The rate of transition from the state $i$ to the state $j$, $\lambda_{ij}$, is given by:

$$\lambda_{ij} = \frac{\ln 2}{(ft)_{ij}} f_{ij}$$

(2)

$f_{ij}$ is the phase space factor for $\beta$ decay. The allowed $(ft)_{ij}$ values can be estimated using [10]:

$$\frac{1}{(ft)_{ij}} = \frac{1}{(ft)_{ij}^{GT}} + \frac{1}{(ft)_{ij}^{F}}$$

(3)

$(ft)^{GT,F}$ are the $(ft)$ values for Gamow-Teller ($GT$) and Fermi ($F$) transitions, which can be expressed in terms of the matrix elements $M_{GT}$ and $M_{F}$. These latter are used to estimate the GT and F transition probabilities $B_{GT}$ and $B_{F}$ [12],

$$B_{GT} = \frac{g_A^2}{2J_i + 1} |M_{GT}|^2$$

(4)

$$B_{F} = \frac{g_V^2}{2J_i + 1} |M_{F}|^2$$

(5)

with $g_A$ is a constant.

In this work, we have carried out some spectroscopic calculations, aimed to estimate some nuclear the $\beta$-decay half-life of the $^{130}\text{Cd}$ r-process waiting point, near $^{132}\text{Sn}$ doubly magic core, in the framework of the nuclear shell model by means of Oxbash nuclear structure code [7]. Using recent Single Hole Energies (SHEs) taken from $^{131}\text{In}$ and $^{131}\text{Sn}$ experimental spectra [13, 14, 15], mass effect consideration introduces some modifications on two body matrix elements ($TBME$s) of the original interaction $jj45apn$ derived from the $G$-Matrix for $^{132}\text{Sn}$ mass region [16]. By means of the resulting interaction $jj45pnh$ [17] some calculations are released.
3. Results and discussion

We have performed shell model calculations, using the new interaction \( jj45pnh \) [17] in \( \pi(0f_{7/2}^{-1}, 1p_{3/2}^{-1}, 1p_{1/2}^{-1} \text{ and } 0g_{9/2}^{-1})Z^{-28} \) and \( \nu(0g_{7/2}^{-1}, 1d_{5/2}^{-1}, 1d_{3/2}^{-1}, 2s_{1/2}^{-1} \text{ and } 0h_{11/2}^{-1})N^{-50} \) model space using \(^{132}Sn\) as a magic core.

![Energy spectra](image)

**Figure 1.** Calculated energetic spectra of \(^{130}Cd\) and \(^{130}In\) by means \( jj45pnh \) [17] in comparison with the experimental data [15, 18].

The modified effective interaction \( jj45pnh \) [17] lead to reproduce the experimental energetic sequence for \(^{130}Cd\) waiting point isotope Figure 1. (Left). For the excited energies, the calculated values are in a reasonably agreement with the experimental data taken from [18]. The calculations for \(^{130}In\) nucleus using \( jj45pnh \) [17] interaction, shown in Figure 1. (right), doesn’t allow to reproduce the parity and the spin of the experimental ground state \( 1^- \). However, the sequence between \( 3^+ \) and \( 1^+ \) is reproduced.

Using these calculated spectra, we have performed spectroscopic calculations in order to estimate the \( \beta \)-decay half-live for the studied waiting point. To evaluate \( (ft) \) value, \( Oxbash \) nuclear structure code use,

\[
(ft)^{GT}_{ij} \cdot (ft)^{F}_{ij} = 6177s
\]

with the factor \( \frac{g_A}{g_V} = 1.26 \). We have calculated beta decay Gamow-Teller transition probabilities for the transitions from \( 2^+ \) state in the father nucleus \(^{130}Cd\) to \( 1^+ \) and \( 3^+ \) states in the daughter \(^{130}In\), in order to estimate the \( T_{1/2} \) of the father nucleus. The obtained results are listed in the table bellow:

The obtained values are used to calculate a half-life of 4.477s, which seems very fast in comparison with the experimental value 162.000s.
Table 1. Calculated $\beta$ decay properties for $^{130}$Cd.

| $J_i$ in $^{130}$Cd | $J_f$ in $^{130}$In | $\log (ft)$ | $B_{GT}$ |
|---------------------|---------------------|-------------|--------|
| 2$^+$               | 1$^+$               | 3.778       | 0.649  |
|                     | 3$^+$               | 6.556       | 0.001  |

4. Conclusion
This study is based on the energetic spectra and beta decay properties calculations, for $^{130}$Cd r-process classical waiting point isotope and for $^{130}$In, with two hole protons and one hole proton and one hole neutron in their valence spaces, respectively. The calculations are carried out in the framework of the nuclear shell model, by means of Oxbash nuclear structure code. Using the jj45apn original interaction of the code, we realized some modifications based on the mass effect to get jj45pnh new interaction. This later lead to reproduce the experimental energetic sequence and the excited energies for the waiting point. However, it can not reproduce the spectrum of $^{130}$In nucleus. The calculated half-life fo 4.477s for the studied nucleus $^{130}$Cd is different from the experimental one 162.000s. These results are the consequence of the differences on the obtained energetic spectrum for the daughter nucleus.

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References
[1] Dillmann I et al. 2003 Phys. Rev. Lett. 91 162503
[2] Zhi Q, Caurier E, Cuenca-Garcia J J, Langanke K, Martinez-Pinedo G and Sieja K 2013 Phys. Rev. C 87 025803
[3] Panov I V 2016 Phys. Atom. Nuc. 79 159
[4] Basdevan J L, Rich J and Spiro M 2005 Fundamentals in nuclear physics from nuclear structure to cosmology (Berlin: Springer)
[5] Kratz K L, Pfeiffer B, Arndt O, Henrich S, Wohr A and ISOLDE/IS333, IS378, IS393 Collaborations 2005 Eur. Phys. J. A 25 633
[6] Kratz K L, Gabelmann H, Hillebrandt W, Pfeiffer B, Schlosser K and Thielemann F K 1986 Z. Phys. A 325 489
[7] Brown B A 2004 Oxbash for windows MSU-NSCL Report 1289
[8] Machleidt R, Sammarruca F and Song Y 1996 Phys. Rev. C 53 1483
[9] Cuenca-Garcia J J, Martinez-Pinedo G, Langanke K, Nowacki F and Borzov I N 2007 Eur. Phys. J. A 34 99
[10] Kar K, Chakravarti S and Manfredi V R 2006 Pramana -J. Phys. 67 363
[11] Sarkar S and Sarkar M S 2009 AIP Conf. Proc. 1175 182
[12] Suhonen J Theoretical and Mathematical Physics, From Nucleons to Nucleus (Berlin: Springer)
[13] Grawe H, Langanke K and Martinez-Pinedo G 2007 Rep. Prog. Phys. 70 1525
[14] Wang M, Audi G, Wapstra A H, Kondev F G, MacCormick M, Xu X and Pfeiffer B 2012 Chin. Phys. C 36 1603
[15] Sukhoruchkin S I and Soroko Z N 2013 Landolt-Brustein - Group I Elementary Particles, Nuclei and Atoms ed H Schopper (Berlin: Springer materials)
[16] Hjorth-Jensen M, Kuo T T S and Osnes E 1995 Phys. Rep. 261 125
[17] Laout N and Beurazi F Eur. Phys. J. Web of Conferences 100 01004
[18] http://www.nndc.bnl.gov/chart/