

Shell-Model Half-Lives for $N = 82$ Nuclei and Their Implications for the r Process

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We have performed large-scale shell-model calculations of the half-lives and neutron-branching probabilities of the r -process waiting-point nuclei at the magic neutron number $N = 82$. We find good agreement with the measured half-lives of ^{129}Ag and ^{130}Cd . Our shell-model half-lives are noticeably shorter than those currently adopted in r process simulations. Our calculation suggests that ^{130}Cd is not produced in β -flow equilibrium with the other $N = 82$ isotones on the r -process path.

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About half of the elements heavier than mass number $A = 60$ are produced in the astrophysical r process, a sequence of neutron capture and beta decay processes [1–4]. The r process is associated with an environment of relatively high temperatures ($T \approx 10^9$ K) and very high neutron densities ($>10^{20}$ neutrons/cm³) such that the intervals between neutron captures are generally much smaller than the β lifetimes, i.e., $\tau_n \ll \tau_\beta$ in the r process. Thus, nuclei are quickly transmuted into neutron-richer isotopes, decreasing the neutron separation energy S_n . This series of successive neutron captures comes to a stop when the (n, γ) capture rate for an isotope equals the rate of the destructive (γ, n) photodisintegration rate. Then the r process has to wait for the most neutron-rich nuclei to β decay. Under the typical conditions expected for the r process, the $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium is achieved at neutron separation energies, $S_n \approx 2$ MeV [5]. This condition mainly determines the r -process path, which is located about 15–20 units away from the valley of stability. The r -process path reaches the neutron shell closures at $N = 50, 82,$ and 126 at such low Z values that S_n is too small to allow the formation of still more neutron-rich isotopes; the isotopes then have to β decay. To overcome the shell gap at the magic neutron numbers and produce heavier nuclei, the material has to undergo a series of alternating β decays and neutron captures before it reaches a nucleus close enough to stability to have S_n large enough to allow for the continuation of the sequence of neutron capture reactions. Noting that the β -decay half-lives are relatively long at the magic neutron numbers, the r -process network waits long enough at these neutron numbers to build up abundance peaks related to the mass numbers $A \approx 80, 130,$ and 195 . Furthermore, the duration of the r process, i.e., the minimal time required to transmute, at one site, seed nuclei into nuclei around $A \approx 200$, is dominantly given by the sum of the half-lives of the r -process nuclei at the three magic neutron numbers. It appears as if the required minimal time is longer than the duration of the favorable r -process conditions in the neutrino-driven wind from type II supernovae [6], which is the currently most favored r -process site.

Simulations of the r process require a knowledge of nuclear properties far from the valley of stability. As

the relevant nuclei are not experimentally accessible, theoretical predictions for the relevant quantities (i.e., neutron separation energies and half-lives) are needed. This Letter is concerned with the calculation of β decays of r -process nuclei at the magic neutron number $N = 82$. These β decays are determined by the weak low-energy tails of the Gamow-Teller strength distribution, mediated by the operator $\sigma\tau_-$, and provide quite a challenge to theoretical modeling as they are not constrained by sum rules. Previous estimates have been based on semiempirical global models, quasiparticle random phase approximation, or, very recently, the Hartree-Fock-Bogoliubov method. But the method of choice to calculate Gamow-Teller transitions is the interacting nuclear shell-model, and decisive progress in programming and hardware make now reliable shell-model calculations of the half-lives of the $N = 82$ r -process waiting-point nuclei feasible.

Our shell-model calculations have been performed with the code ANTOINE developed by Caurier [7]. As model space we chose the $0g_{7/2}, 1d_{3/2,5/2}, 2s_{1/2}, 0h_{11/2}$ orbitals outside the $N = 50$ core for neutrons, thus assuming a closed $N = 82$ shell configuration in the parent nucleus. For protons our model space was spanned by the $1p_{1/2}, 0g_{9/2,7/2}, 1d_{3/2,5/2}, 2s_{1/2}$ orbitals where a maximum of two (three) protons were allowed to be excited from the $1p_{1/2}, 0g_{9/2}$ orbitals to the rest of the orbitals in the parent (daughter) nucleus. The $0g_{9/2}$ neutron orbit and the $0h_{11/2}$ proton orbit have been excluded from our model space to remove spurious center of mass configurations. Therefore, we do not allow for Gamow-Teller transitions from the $0g_{9/2}$ and $h_{11/2}$ neutron orbitals, which should, however, not contribute significantly to the low-energy decays we are interested in here. The $1p_{1/2}$ proton orbit has been included to describe the $1/2^-$ isomeric state seen in ^{131}In and expected in the other $N = 82$ odd- A isotones, but does not play any role in the decay of the ground states. The residual interaction can be split into a monopole part and a renormalized G -matrix component which can be derived from the nucleon-nucleon potential. We use the interaction of Ref. [8] for the $gdsh_{11/2}$ orbits and the Kahama-Lee-Scott interaction [9] for the interaction between the previous orbits with the $1p_{1/2}$ orbit. To derive the appropriate

monopole part, we followed the prescription given by Zuker [10], and fine tuned the monopoles to reproduce known spectra of nuclei around the $N = 82$ shell closure. As shell-model studies overestimate the Gamow-Teller (GT) strength by a universal factor, we have scaled our results by the appropriate factor $(0.74)^2$ [11].

The Q_β values have been taken either from experiment (^{131}In) or from the mass compilation of Duflo and Zuker [12]. Note that the extended Thomas-Fermi with Strutinsky integral (ETFSI) approach [13] and the finite-range droplet model (FRDM) of Möller [14] give very similar Q_β values (with typical uncertainties of 250 keV for $Q_\beta \approx 10$ MeV) so that the associated uncertainty in the half-lives is small.

The shell-model half-lives are summarized in Table I and are compared to other theoretical predictions in Fig. 1. For $Z = 47-49$, the half-lives are known experimentally [15,16] and our shell-model values are slightly faster. This, however, is expected as our still truncated model space will miss some correlations and, hence, slightly overestimates the Gamow-Teller matrix elements.

Our shell-model half-lives show significant and important differences to those calculated in the FRDM [14] and the ETFSI approach [13], which have been typically used in r -process simulations. Although the latter predicts a Z dependence of the half-lives in the $N = 82$ isotones very similar to the present results, the ETFSI half-lives are longer on average by factors 4–5 indicating that the method fails to shift enough GT strength to low energies [13]. The FRDM half-lives show a very pronounced odd-even dependence which is predicted neither by ETFSI nor shell model. While the FRDM half-lives for odd- A $N = 82$ isotones approximately agree with the shell-model results (within a factor of 2) and the experimental values for ^{131}In and ^{129}Ag , they overestimate the half-lives for even isotones by an order of magnitude. As such an odd-even dependence is not present in the experimental half-lives (nor in the r -process abundances); it is probably an artifact of the FRDM model. The absence of

odd-even effects can be understood considering that the main contribution to the half-life comes from transitions from a $g_{7/2}$ neutron to a $g_{9/2}$ proton due to the energy gap between the $g_{9/2}$ and the other orbits. Therefore, neither the GT matrix elements nor the half-lives show a strong odd-even dependence along the $N = 82$ isotonic line. Noting that the Q_β values in the FRDM model are very similar to the ones used and that the main difference with our results appears when the final nuclei is odd-odd, we conclude that the odd-even effect must stem from the treatment of the pn interaction in the FRDM approach. Very recently, Engel *et al.* have performed half-life calculations of r process nuclei within the Hartree-Fock-Bogoliubov (HFB) model [17]. Unfortunately their studies are yet restricted to even-even nuclei only, but they obtain results which, except for a factor of 2, closely resemble the present shell-model results. Reference [17] points out that the half-lives of the $N = 82$ waiting-point nuclei are noticeably shorter than currently assumed in r -process simulations, in support of our findings.

Odd- A nuclei in this mass range usually exhibit a low-lying $1/2^-$ isomeric state which can be related to a proton hole in the $p_{1/2}$ orbital. These isomeric states can affect the r -process half-lives in two different ways: (i) If low enough in energy, the isomeric state can be populated thermally; (ii) in a nonequilibrium picture the isomeric state can be fed by the preceding neutron capture on the $N = 81$ nucleus. The half-life of the isomeric state has been measured in ^{131}In (350 ms), very similar to the ground state half-life (280 ms). We have calculated the energy positions and half-lives of the isomeric states within our shell-model approach. We find that the excitation energy of the isomeric state slowly decreases within the $N = 82$ isotones when moving from ^{123}Nb ($E^* = 500$ keV) to ^{131}In (375 keV) where

TABLE I. Comparison of the shell-model half-lives for the ground and isomeric state with experiment [16,18]. All half-lives are in ms.

Nucleus	Ground state		Isomeric state	
	Expt.	Theor.	Expt.	Theor.
^{131}In	280 ± 30	177	350 ± 50	274
^{130}Cd	195 ± 35	146		
^{129}Ag	46 ± 9	35.1		39.5
^{128}Pd		27.3		
^{127}Rh		11.8		12.4
^{126}Ru		9.6		
^{125}Tc		4.3		4.2
^{124}Mo		3.5		
^{123}Nb		1.8		1.7
^{122}Zr		1.5		

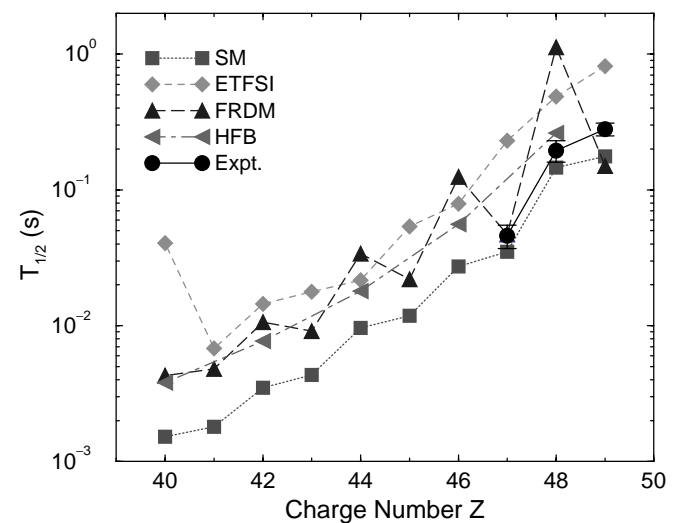


FIG. 1. Comparison of half-lives of the $N = 82$ isotones as calculated in the FRDM, HFB, ETFSI, and the present shell-model approaches with data.

experimentally only the isomeric state in ^{131}In is known (at 360 keV). Importantly, our calculation predicts the half-lives of the isomeric states to be comparable to the ground state half-lives in all cases (see Table I). Thus, the effective r -process half-lives will be very close to the ground state half-lives. We note that the isomeric state in ^{131}In dominantly decays by first-forbidden transitions, as the approximately closed $g_{9/2}$ proton configuration in this state strongly suppresses low-energy GT transitions. We calculate a half-life of the isomeric state of 274 ms due to first-forbidden decay, about 30% faster than the experimental value (350 ms). For the $N = 82$ nuclei with $Z \leq 47$, the $g_{9/2}$ orbital is not anymore closed for the isomeric state allowing for GT transitions at low energy. Consequently, these nuclei decay by GT transitions rather than first-forbidden ones.

An interesting, but yet open, question is whether the r process proceeds in β -flow equilibrium also at the waiting points related to magic neutron numbers [18]. If so, the duration of the r process has to be larger than the sum of the beta half-lives of the nuclei in β -flow equilibrium. In this appealing picture, the observed r -process abundances scale as the respective β -decay half-lives, if the former are corrected for β -delayed neutron emissions during their decays from the r -process paths towards the stable nuclei which are observed as r process abundances. Using our shell-model β -strength functions, we have calculated the probability P_{1n} that the β decay is accompanied by the emission of a neutron, defined as the relative probability of the β -decay rate above the neutron emission threshold, S_n . For consistency we adopted the S_n values from Duflo and Zuker (DZ), which, for a mild parity effect, gives similar results than the ETFSI model, while the FRDM model predicts a significantly slower decrease of S_n with decreasing Z . As the P_{1n} values are rather sensitive to the neutron separation energies we have accounted for the differences between the ETFSI and the DZ predictions by assigning an uncertainty of 500 keV to the DZ S_n values. In this way we have calculated an equally probable range for the shell-model P_{1n} values as shown in Fig. 2. We find rather small neutron emission probabilities for $Z = 46-49$ (which will only slightly be increased if the $1h$ -proton orbitals were included); for the smaller Z -values our results approximately resembles the FRDM values, also showing a noticeable odd-even dependence.

Using the solar r -process abundances [19] and the shell-model neutron emission probabilities P_{1n} , we have determined the abundances of the $N = 82$ progenitor nuclei, $n(Z)$, on the r -process path by one-step iteration; we have checked that second-order branchings change the results only insignificantly. If β -flow equilibrium at the waiting points is indeed achieved, one has $n(Z) \sim \tau(Z)$. Thus, up to a constant $n(Z)$ can be expressed as the so-called β -flow half-life $T_{\beta f}$. Fixing the constant appropriately, Fig. 3 shows that β -flow equilibrium can be attained for the $N = 82$ isotones with $Z = 44-47$,

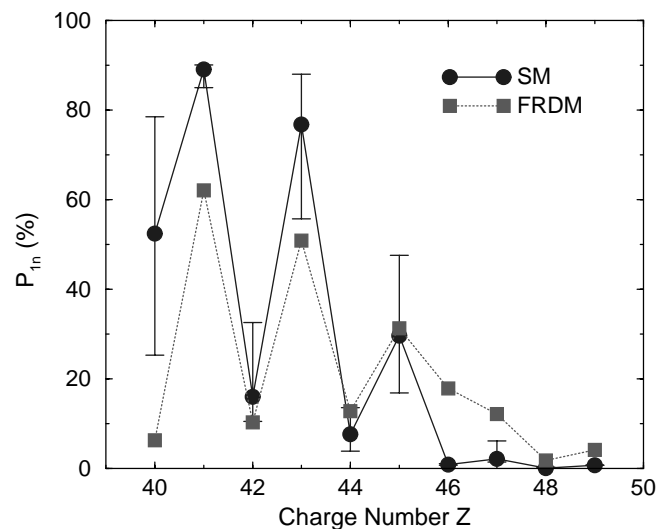


FIG. 2. Comparison of neutron emission probabilities P_{1n} as calculated in the FRDM and the present shell-model approach.

but fails by more than a factor of 4 for ^{130}Cd and 10 for ^{131}In . (The factor for indium will be slightly reduced if ^{133}In is included in the r -process path [18].) As the systematic of neutron separation energies put ^{130}Cd on the r process path, our results suggest that the conditions which allow one to build the $N = 82$ r -process abundance peak do not last long enough to achieve β -flow equilibrium for this nucleus. This is consistent with the expectation that the r -process peaks at $N = 82$ and $N = 126$ are made under different conditions [5,20,21]. Recent observations also indicate that the nuclides in the $N = 82$ and 126 abundance peaks are produced at different sites [22]. Furthermore, the assumption of β -flow equilibrium,

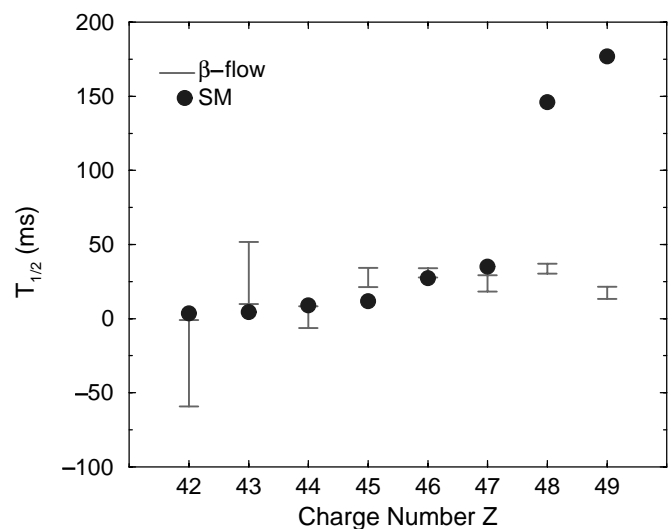


FIG. 3. Test of β -flow equilibrium by comparing the shell-model half-lives for the $N = 82$ r -process waiting-point nuclei with the β -flow half-lives. The error bars in the latter reflect the errors in the P_{1n} and in the solar r -process abundances.

which on the r -process path should be fulfilled better the shorter the half-life, leads to unphysical (negative) $T_{\beta f}$ values for $Z < 43$, indicating that these nuclei are not on the r -process path. However, a firm conclusion here can be reached only after reducing the uncertainties in the P_{1n} values for all nuclei in the decay sequence to stability.

So far we have discussed the r process as a sequence of competing neutron capture and β -decay processes. If the r -process site is indeed the neutrino-driven wind above a newly born neutron star, then it occurs in a very strong neutrino flux and charged-current (ν_e, e) reactions can substitute for β decays; in this case the picture of β -flow equilibrium has to be extended to “weak-flow” equilibrium. McLaughlin and Fuller [23] have shown that weak steady flow equilibrium at the $N = 82$ waiting point normally cannot be attained in the neutrino-driven wind model. However, their study adopted β half-lives taken from [18] which predict a Z dependence of the half-lives in disagreement with the recent theoretical studies (including the present) and the data. Nevertheless, when we reinvestigate this question using the present shell-model β -decay rates and the charge current neutrino rates of [24,25], we find that ^{129}Ag and ^{130}Cd cannot be produced in β -flow equilibrium within the neutrino-driven wind model in agreement with the conclusions reached in Ref. [23].

In conclusion, we have calculated shell-model half-lives and neutron emission probabilities for the $N = 82$ waiting-point nuclei in the r process, finding good agreement with the experimentally known half-lives for the $Z = 47\text{--}49$ nuclei. Our half-lives are significantly shorter than the ETFSI and FRDM half-lives, which are frequently used in r -process simulations. Our results indicate that ^{129}Ag is produced in β -flow equilibrium together with the lighter isotones at the $N = 82$ waiting point. r -process simulations usually include ^{130}Cd and even ^{131}In in the r -process path at freeze-out. If so, they will not be synthesized in β -flow equilibrium. That fact together with the shorter half-lives implies a shorter waiting time at $N = 82$. This is quite welcome to remove possible conflicts between the required duration time for the r process and the expansion time scale of the neutrino-driven wind scenario which requires the r process to occur in a fraction of a second.

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