PROCEEDINGS OF SCIENCE

Theoretical description of β-delayed proton emission of some proton rich sd- and pf- shell nuclei*

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The study of β-delayed decay of nuclei near the proton drip line provides a powerful tool to understand the role of isospin-symmetry breaking in the structure of proton-rich nuclei. A β-delayed process involves first a β-decay of a precursor, with a large superallowed branch populating the isobaric analogue state (IAS), followed by emission of charged particles (protons, diprotons, alpha particles, clusters) or gamma radiation. The typical Q value systematics of these decays is such that the second-stage proton (or multi-particle) emission from the IAS is isospin-forbidden, whereas decay from Gamow-Teller populated states is consistent with the isospin-symmetry limit. The experimental data on isospin-forbidden proton-emission branching ratios provides a stringent test for charge-dependent terms of the nuclear Hamiltonian. In this contribution, we present a shell-model study of the partial-decay schemes of some recently measured very neutron deficient silicone isotopes, e.g., ^{23}Si, ^{24}Si, ^{25}Si, as well as a pf-shell precursor, ^{53}Ni. We use a microscopic isospin-nonconserving (INC) Hamiltonian which allows us to account for the isospin-symmetry breaking consistently in all physics processes involved in the whole β-delayed decay scheme, namely, β-decay, proton emission and electromagnetic de-excitation. Our shell-model results successfully, though not fully, match with the key features of these experimental partial-decay schemes.

The 26th International Nuclear Physics Conference
11-16 September, 2016
Adelaide, Australia

*The work was carried out under the auspices of the Ministry of Foreign Affairs and International Development of France in the framework of PHC Xu GuangQi 2015 under project No. 34457VA.

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‡The author is supported by the Talented Young Scientist Program of Ministry of Science and Technology of China and the China Postdoctoral Science Foundation under Grant No. 2014M562481.

§The author appreciates the research grant of CFT (IN2P3/CNRS, France), AP théorie 2015–2016.

PoS(INPC2016)042

1. Introduction

The study of β-delayed decay of proton-rich nuclei opens interesting ways to perceive the role of isospin-symmetry breaking in a quantum many-body system [1]. In particular, often the most intense β-decay branch populates the isobaric analogue state (IAS) of the precursor's ground state, which may further decay by gamma (γ) ray and isospin-forbidden (multi)particle emission. The measured branching ratio of isospin-forbidden proton-emission represents a sensitive probe to charge-dependent term of a nuclear Hamiltonian.

We performed a systematic study of partial-decay schemes of some very neutron deficient *sd*- and *pf*-shell precursors using our recently constructed INC Hamiltonians with the aid of NuShellX@MSU [2] and ANTOINE [3] shell-model codes. The selected INC Hamiltonian of *sd*-shell nuclei [4] is a combination of an isospin-conserving Hamiltonian (USD [5], or USDB [6]), a two-body Coulomb potential accounting for the short-range correlations withing the unitary correlation operator method [7], isovector single particle energies (IVSPEs) describing the differences of proton and neutron single particle energies, and a phenomenological charge-dependent term expressing the isospin-symmetry breaking of the effective nucleon-nucleon interaction. All strength parameters scaling the charge-dependent terms in the INC Hamiltonian were determined by a least-squares fit to reproduce the recently compiled experimental isovector and isotensor coefficients of the quadratic isobaric-multiplet-mass equation (IMME) [8] in *sd* shell. The INC Hamiltonian of *pf*-shell nuclei only includes an isospin conserving Hamiltonian, which is either GXPF1a [9], or KB3G [10], a set of two-body Coulomb potential and respective IVSPEs [11] with scaling factor $\sim \sqrt{\hbar\omega_A}$ deduced from experimental data [4]. For the moment, we neglect other charge-dependent two-body terms. All INC Hamiltonians based on the respective isospin conserving Hamiltonian are labeled with a prefix "cd", e.g. cdUSDB, cdGXPF1a, etc. For each precursor, we used the respective INC Hamiltonian consistently in all physics processes within the whole β-delayed partial-decay scheme, i.e., β-decay, proton emission and electromagnetic de-excitation.

2. Proton widths and Gamow-Teller transition strengths

We deduced the one-proton-emission width [12], $\Gamma_p = \sum_{nlj} C^2S(nlj)\,\Gamma_{sp}(nlj)$, of which $C^2S(nlj)$ is a corresponding spectroscopic factor, and Γ_{sp} is a single-particle proton width for emitting a proton from an (nlj) quantum orbital. The Γ_{sp} can be estimated using the proton-scattering cross section based on a Woods-Saxon potential by matching the potential depth to obtain the known proton energy [13]. The other option is to calculate Γ_{sp} from the Coulomb-barrier penetration [12], $\Gamma_{sp} = \left(3\hbar^2/\mu R^2\right) P_\ell(E)$, where the nuclear channel radius, $R = r_0(1+A_D)^{1/3}$ fm, A_D is the daughter nucleus, and P_ℓ is the Coulomb penetration factor. The single-particle widths computed by these two methods may not be exactly similar, but such differences do not qualitatively alter the branching ratios of proton emission from the IAS. Theoretical reduced Gamow-Teller (GT) transition strength, $B(\mathrm{GT})$, is calculated as $B(\mathrm{GT}) = q_F^2\,(g_A/g_V)^2\,\langle f\|\sum_k \sigma^k t_+^k\,\|i\rangle^2/(2J_i+1)$, of which we assumed the quenching factor, $q_F = 0.77$ for *sd*-shell [14], and $q_F = 0.7$ for *pf* shell. All level schemes presented in Figures of this contribution are based on the respective experiments and/or NNDC data [15].

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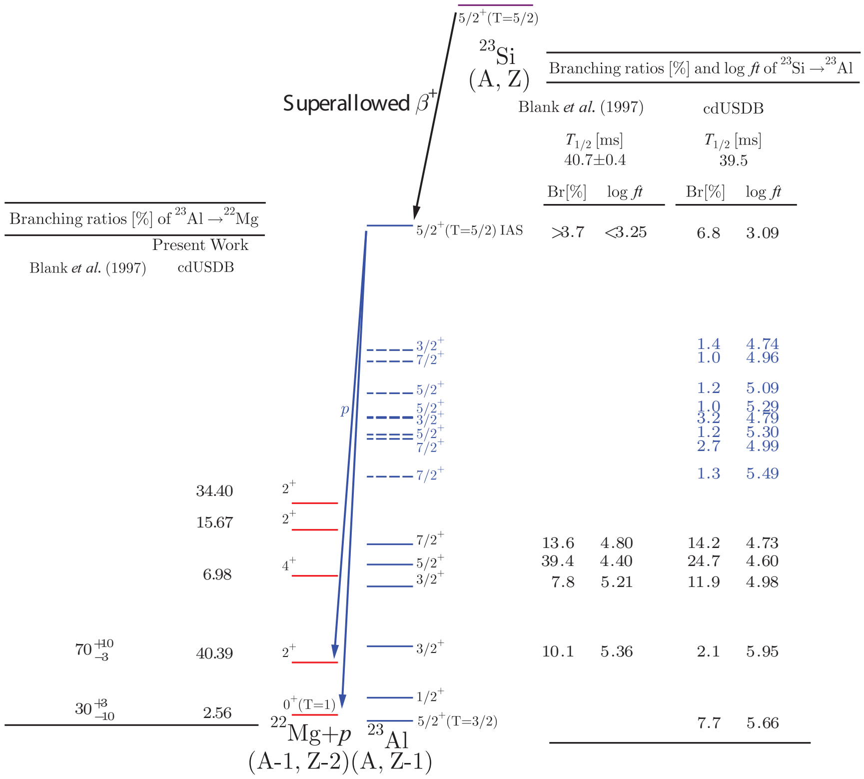


Figure 1: Partial-decay scheme of ^{23}Si.

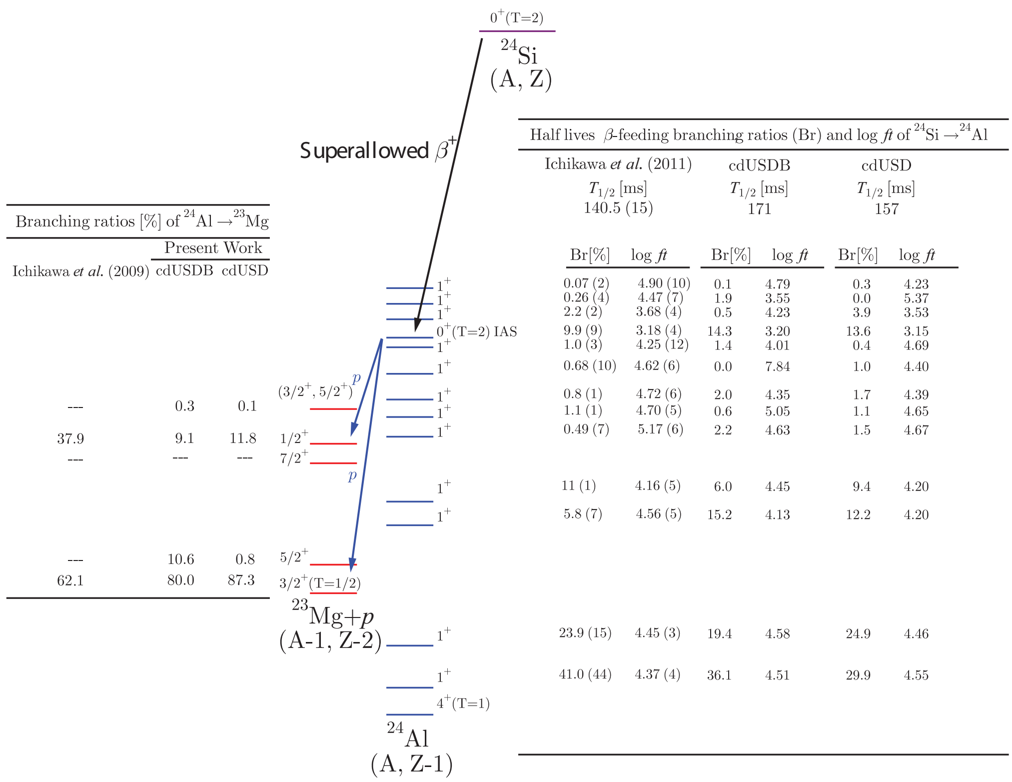
3. Partial-decay schemes

Partial-decay scheme of ^{23}Si. The latest measurement was done by Blank *et al.* [16]. The cdUSDB successfully reconstructs the half life of ^{23}Si and the measured β-decay branching ratios which matches with the experimentally proposed range. In particular, the two major branches populate the $5/2^+$ and $7/2^+$ states at 3.7 MeV and 4.2 MeV, respectively. Some discrepancy is observed for the feeding of the first $3/2^+$ state. This may be due to a high probability occupation of the weakly-bound proton $1s_{1/2}$ state (the so-called Thomas-Ehrman effect). The present charge-dependent interaction still lacks a proper description of loosely bound state. In particular, the theoretical excitation energy of this state is about 300 keV larger than the experimental value. Further analysis will be presented elsewhere [17].

Experimentally, only branching ratios for the proton emission from the $5/2^+$, IAS, in ^{23}Al to the two lowest states in ^{22}Mg have been measured. Those two branches are qualitatively reproduced. Further experimental information is required to have a more stringent test for the theory.

Partial-decay scheme of ^{24}Si. In spite of numerous previous studies [18, 19, 20], the most complete information comes from the recent measurement done by Ichikawa *et al.* [21, 22] which included β-γ coincidences. This was crucial in finding the β feeding of the two lowest 1^+ states of ^{24}Al. Importantly, from comparison with the β decay of ^{24}Si and of ^{24}Ne, they discovered a mirror asymmetry of B(GT)$^+$ to B(GT)$^-$ populating 1^+_2 states in daughter nuclei, ^{24}Al and ^{24}Na, respectively. This asymmetry should be related again to a weakly bound nature of the $1s_{1/2}$ orbital contributing to the structure of 1_2^+ states. In the present work we study how charge-dependent Hamiltonians overall describe the decay modes. As seen from the table given in Fig. 2, both cdUSDB and cdUSD reproduce the general features of the partial decay scheme. The present cdUSDB Hamiltonian shows a bit better agreement with the experimental branching ratio to the 1_1^+ state in ^{24}Al and the proton-emission branching ratio from the IAS to the ground state of ^{23}Mg. At the same time it finds a large mirror asymmetry of B(GT)$^+$ to B(GT)$^-$ for the transitions to the first 1^+ state, which is not confirmed experimentally [22]. The other Hamiltonian, cdUSD, predicts closer the B(GT) ratios of transitions to the two lowest 1^+ states in ^{24}Al and ^{24}Na. More detailed analysis of the mirror asymmetry will be published elsewhere [17].

Partial-decay scheme of ^{25}Si. Figure 3 depicts the decay scheme of ^{25}Si which includes an extension of the theoretical work of Ref. [23]. The level scheme of ^{25}Al is quoted from the experimental data of Thomas *et al.* [24]. First, we compared the level schemes produced from USD Hamiltonian and OBUSD Hamiltonian from Ref. [11] with experimental and theoretical levels in Ref. [24]. Then, we associated in a similar manner our theoretical levels produced from cdUSDB to the experiment Ref. [24]. Basically, the key features of the β decay of ^{25}Si→^{25}Al is reproduced in our current preliminary work, especially, the branching ratios of the first few low-lying states of ^{25}Al and the IAS. Furthermore, our cdUSDB Hamiltonian can also qualitatively reproduce the branching ratios of the proton emission from ^{25}Al$(5/2^+, \mathrm{IAS})$. We remark that those proton-emission branching ratios cannot be qualitatively reproduced by OBUSDB Hamiltonian, which relies on the USDB plus a charge-dependent term parametrized as in Ref. [11]. This shows importance of a



Branching ratios [%] of ^{24}Al → ^{23}Mg

	Ichikawa *et al.* (2009)	Present Work cdUSDB	Present Work cdUSD
$(3/2^+, 5/2^+)$	---	0.3	0.1
$1/2^+$	37.9	9.1	11.8
$7/2^+$	---	---	---
$5/2^+$	---	10.6	0.8
$3/2^+$(T=1/2)	62.1	80.0	87.3

Half lives β-feeding branching ratios (Br) and log *ft* of ^{24}Si → ^{24}Al

	Ichikawa *et al.* (2011) $T_{1/2}$ [ms] 140.5 (15)		cdUSDB $T_{1/2}$ [ms] 171		cdUSD $T_{1/2}$ [ms] 157	
State	Br[%]	log *ft*	Br[%]	log *ft*	Br[%]	log *ft*
1^+	0.07 (2)	4.90 (10)	0.1	4.79	0.3	4.23
1^+	0.26 (4)	4.47 (7)	1.9	3.55	0.0	5.37
1^+	2.2 (2)	3.68 (4)	0.5	4.23	3.9	3.53
0^+(T=2) IAS	9.9 (9)	3.18 (4)	14.3	3.20	13.6	3.15
1^+	1.0 (3)	4.25 (12)	1.4	4.01	0.4	4.69
1^+	0.68 (10)	4.62 (6)	0.0	7.84	1.0	4.40
1^+	0.8 (1)	4.72 (6)	2.0	4.35	1.7	4.39
1^+	1.1 (1)	4.70 (5)	0.6	5.05	1.1	4.65
1^+	0.49 (7)	5.17 (6)	2.2	4.63	1.5	4.67
1^+	11 (1)	4.16 (5)	6.0	4.45	9.4	4.20
1^+	5.8 (7)	4.56 (5)	15.2	4.13	12.2	4.20
1^+	23.9 (15)	4.45 (3)	19.4	4.58	24.9	4.46
1^+	41.0 (44)	4.37 (4)	36.1	4.51	29.9	4.55

Figure 2: Partial-decay scheme of ^{24}Si.

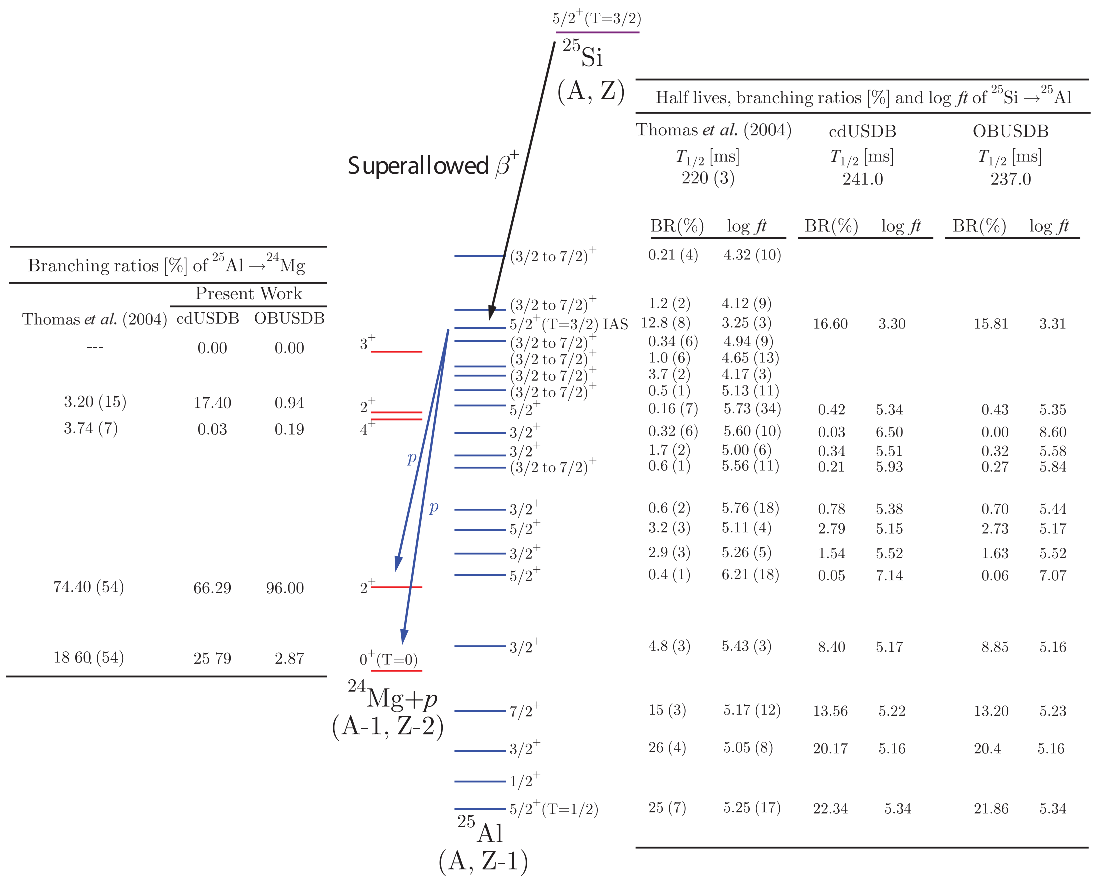


Figure 3: Partial-decay scheme of ^{25}Si.

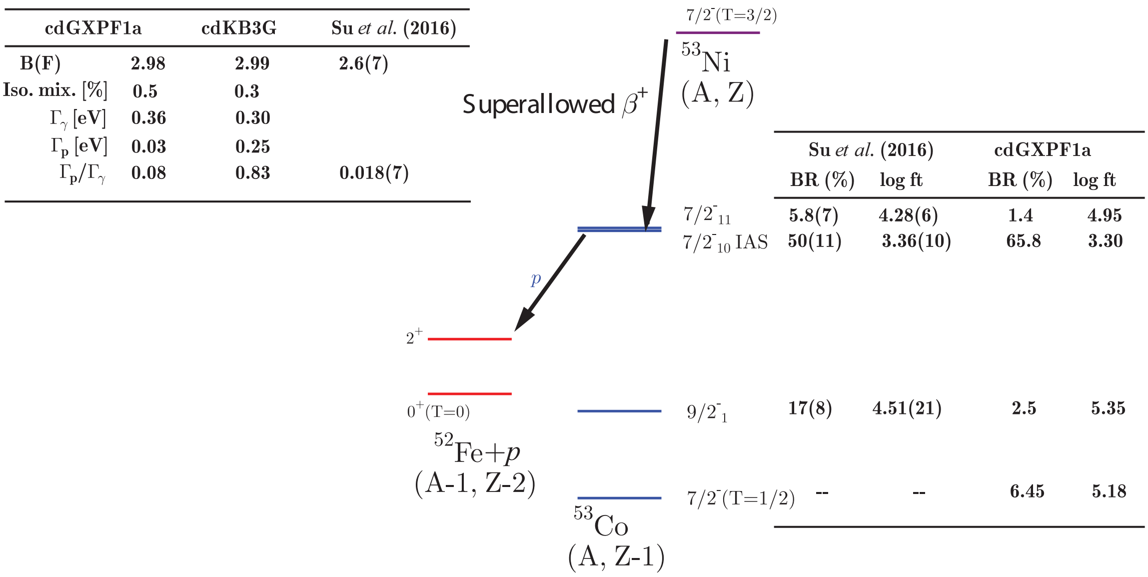


Figure 4: Partial-decay scheme of ^{53}Ni.

consistent and updated fit of strength parameters and implemented SRC schemes of Ref. [4]. More detailed analysis will be published elsewhere [17].

Partial-decay scheme of ^{53}*Ni.* IMME was found invalid for $A = 53, T = 3/2$ multiplet by MacCormick and Audi [25] based on Dossat *et al.* [26] work. To confirm the breakdown of IMME for this multiplet, Su *et al.* [27] performed a measurement of the β-delayed proton emission of ^{53}Ni with the consideration of β-γ coincidence. Our shell-model with pf-shell INC Hamiltonian (cdGXPF1a) predicts that there is an adjacent $7/2^-, T = 1/2$ state close to (below) the ^{53}Co ($7/2^-, T = 3/2$, IAS), see Fig. 4 for the newly proposed partial-decay scheme of ^{53}Ni. In spite of a small energy difference between the two states, the isospin-mixing matrix element appears to be very small and the respective isospin quantum numbers stay very pure. This adjacent state with the mentioned above properties was discovered to be about 60 keV above the ^{53}Co($7/2^-$, IAS) with β-γ coincidence in the work of Su *et al.* [27]. Moreover, the prediction of our shell-model calculation with cdGXPF1a Hamiltonian about the decay of the ^{53}Co($7/2^-$, IAS) favoring γ transitions instead of one-proton emission matches with the finding of Su *et al.* [27], see the top-left table in Fig. 4. The retardation of the proton emission from the IAS is due to a very small isospin mixing with only up to a maximum of 0.26 %. Using the newly assigned IAS, the IMME of the $A = 53, T = 3/2$ multiplet is revalidated.

In conclusion, our recently constructed INC Hamiltonians exhibit a strong predictive power and successfully, though not wholly, reproduced experimental partial-decay schemes of proton-rich silicone isotopes and some pf-shell precursors. We stress that the respective INC Hamiltonians used in the analysis of partial-decay schemes are consistent for all involved physics processes, i.e., β-decay, proton emission and electromagnetic de-excitation. According to these few comprehensively studied examples, the proton-emission branching ratios of IAS are sensitive to the details of an INC Hamiltonian. In particular, the study of the decay of light Si isotopes clearly shows a necessity of taking into account a weakly-bound nature of the $s_{1/2}$ orbital. Further investigation is required to fine-tune the interactions and to improve the descriptive power of the models.

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