

## Halflife of $^{56}\text{Ni}$ in cosmic rays

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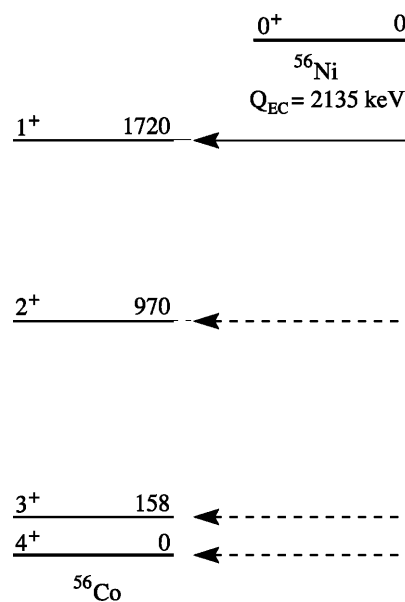
**Abstract.** A measurement of the  $^{56}\text{Ni}$  cosmic ray abundance has been discussed as a possible tool to determine the acceleration time scale of relativistic particles in cosmic rays. This conjecture will depend on the halflife of totally ionized  $^{56}\text{Ni}$  which can only decay by higher-order forbidden transitions. We have calculated this halflife within large-scale shell model calculations and find  $t_{1/2} \approx 4 \times 10^4$  years, only slightly larger than the currently available experimental lower limit, but too short for  $^{56}\text{Ni}$  to serve as a cosmic ray chronometer.

**PACS.** 23.40.-s Beta decay; double beta decay; electron and muon capture – 23.40.Hc Relation with nuclear matrix elements and nuclear structure – 21.60.Cs Shell model – 27.40.+z  $39 \leq A \leq 58$  – 98.70.Sa Cosmic rays

In the laboratory  $^{56}\text{Ni}$  decays by electron capture to the  $1^+$  state in  $^{56}\text{Co}$  at 1.72 MeV ( $\approx 100\%$  branch) with a halflife of  $t_{1/2} = 6.075 \pm 0.020$  days [1]. If  $^{56}\text{Ni}$  is, however, stripped of its electrons, this transition is no longer energetically allowed (see Fig. 1), and the decay is assumed to occur to the  $3^+$  state at 158 keV via a second forbidden unique transition. Currently only a lower limit for the halflife of totally ionized  $^{56}\text{Ni}$  could be established ( $2.9 \times 10^4$  y) [2], but from systematics of similar decays in other nuclei it has been argued that the halflife can be as large as  $5.4 \times 10^6$  y [2].

The drastic change in halflife, if stripped of electrons, makes  $^{56}\text{Ni}$  a potential chronometer for cosmic rays. It is generally believed that supernovae are the site for the acceleration of relativistic particles found in cosmic rays; during this acceleration the nuclei are stripped of electrons.  $^{56}\text{Ni}$  is very abundantly produced in supernovae and its decay (with  $t_{1/2} = 6$  days) powers the early supernova lightcurve. However, if supernovae are the site for the acceleration of relativistic cosmic-ray particles and if the associated acceleration timescale is short enough, some of the  $^{56}\text{Ni}$  will survive in cosmic rays (now being totally ionized and hence having a significantly larger halflife), thus making a future measurement of the  $^{56}\text{Ni}$  abundance in cosmic rays a potential chronometer for this process. Nevertheless, the  $^{56}\text{Ni}$  cosmic ray abundance will also depend on the survival rate of the nucleus after acceleration. As the time the cosmic rays stay in our galaxy is in the range 10–20 Myr [3], a halflife of totally ionized  $^{56}\text{Ni}$  shorter than this timescale would lead to a further depletion of the  $^{56}\text{Ni}$  cosmic ray abundance.

It is the aim of this note to calculate the halflife of totally ionized  $^{56}\text{Ni}$ . As weak interaction transitions in



**Fig. 1.** Level scheme of  $^{56}\text{Co}$  relevant for the decay of totally ionized  $^{56}\text{Ni}$ . The solid line indicates the decay of  $^{56}\text{Ni}$  under laboratory conditions, while the dashed lines show the decay branches for fully ionized  $^{56}\text{Ni}$

general are sensitive to nuclear correlations, our method of choice is the interacting shell model. Shell model diagonalization approaches have made significant progress in recent years and, combined with improved computer technologies, basically allow now for complete  $pf$  shell calculations in the mass  $A = 56$  mass range, e.g. [4]. For example, using the KB3 interaction [5] one calculates the (labora-

**Table 1.** Partial half-lives (in years) for fully stripped  $^{56}\text{Ni}$ . The calculations have been performed with the KB3 interaction and its recently modified version [14] and employing harmonic oscillator (harm. osc.) and Woods-Saxon (WS) radial wave functions

final state	HO		WS	
	KB3	mod. KB3	KB3	mod. KB3
$4^+$	$2.6 \times 10^{12}$	$3.2 \times 10^{12}$	$4.1 \times 10^{12}$	$5.0 \times 10^{12}$
$3^+$	$3.8 \times 10^4$	$3.7 \times 10^4$	$4.2 \times 10^4$	$3.9 \times 10^4$
$2^+$	$5.6 \times 10^7$	$1.1 \times 10^8$	$1.2 \times 10^8$	$3.3 \times 10^8$

tory) half-life of  $^{56}\text{Ni}$  against electron capture as 6.7 d [6], which is in good agreement with experiment.

As the theory for nuclear beta decay is well developed and the respective formulae for allowed and forbidden transitions can be found in many textbooks, e.g. [7], it is not necessary to repeat it here. Just short of a complete calculation in the  $pf$  shell we have performed large-scale shell model calculations for the  $^{56}\text{Ni}$  ground state and the 3 lowest states in  $^{56}\text{Co}$  in a model space which allowed a maximum of 6 particles to be excited from the energetically favored  $f_{7/2}$  orbit to the rest of the  $pf$  shell in the final nucleus. We expect that the transition matrix elements are converged at this level of truncation (for an example see Fig. 2 of [4]). The decay to the  $3^+$  state in  $^{56}\text{Co}$  is a unique second-forbidden transition, while those to the  $4^+$  ground state and the  $2^+$  state at 970 keV are non-unique fourth-forbidden and non-unique second-forbidden transitions [7], respectively. Shell model codes solve the many-body problem in Fock space. Thus the calculation of the transition matrix elements requires assumptions about the single particle wave functions. Here we have assumed harmonic oscillator wave functions with an oscillator parameter,  $b = 1.99$  fm, determined from the  $^{56}\text{Ni}$  charge radius [8] using the prescription of [9]; but we have also considered Woods-Saxon radial wave functions derived from a potential which includes spin-orbit and Coulomb terms [10]. For the Gamow-Teller strength to be reproduced in complete  $0\hbar\omega$  calculations it is necessary to renormalize the spin operators by a universal factor  $(0.74)^2$  [11–13]. But such a renormalization has not been established for forbidden transitions and we thus assume no quenching.

We have performed the shell model calculations with two different residual interactions. At first we used the KB3 interaction, but we also performed calculations with a new version of this force in which some slight monopole deficiencies have been corrected [14]. Our calculations reproduce the  $^{56}\text{Co}$  level scheme rather well as we place the excited  $3^+$  and  $2^+$  states at 216 (237) keV and 1.03 (1.06) MeV, respectively (the energies in parenthesis refer to the KB3 interaction). In the calculation of the various partial half-lives for totally ionized  $^{56}\text{Ni}$  we, however, used the experimental energies. Our results for the various beta decays are summarized in Table 1.

As expected [2] totally ionized  $^{56}\text{Ni}$  decays preferably to the  $3^+$  state at 158 keV. The other possible second-

forbidden transition is disfavored by phase space due to the significantly smaller Q-value, while the transition to the ground state is strongly suppressed as it is of fourth order. For the dominating decay all four shell model calculations are in close agreement. We just find a half-life of totally ionized  $^{56}\text{Ni}$  of  $4 \times 10^4$  y, which is only slightly larger than the current lower limit ( $2.9 \times 10^4$  y, [2]) and thus might be in experimental reach.

We like to add two short remarks concerning the other transitions. First, we note that all formfactors of the type  ${}^V F_{KK-11}$  (in the notation of [7]) are identical zero for harmonic oscillator wave functions, but not for Woods-Saxon single particle states. In our case this applies to the  ${}^V F_{211}$  and  ${}^V F_{431}$  in the calculations of the non-unique second and fourth transitions respectively. It turns out that the contributions of these formfactors are not negligible and cause the differences observed in the partial half-lives of these two transitions calculated with Woods-Saxon and harmonic oscillator wave functions. Second, the differences observed between the two interactions in the decay to the ground state and the  $2^+$  excited state are due to cancellations in the calculations of the  ${}^A F_{KK1}$ -type matrix elements using the KB3 interaction. Such a cancellation is absent for the modified interaction. Such a case does not occur for the dominating decay to the  $3^+$  state and thus the shell model half-life should be rather reliable.

Can  $^{56}\text{Ni}$  serve as a chronometer for cosmic rays? The answer implied from our study is unfortunately negative, as the calculated half-life is significantly shorter than the time relativistic particles need to escape from our galaxy ( $> 10^7$  y). Thus, even  $^{56}\text{Ni}$ , originally accelerated from a supernova remnant into the cosmic rays, will be depleted too fast to serve as cosmic ray chronometer. This conclusion is not expected to change, even if forbidden transitions require a renormalization of the spin operator. If we assume the same universal renormalization factor like for Gamow-Teller transitions, the lifetime of totally ionized  $^{56}\text{Ni}$  increases to  $7.3 \cdot 10^4$  y, but is still much too small for  $^{56}\text{Ni}$  to substantially survive in cosmic rays.

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