Isospin mixing in ^{54}Co super-allowed beta decay : shell model results

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Introduction

The concept of isospin quantum number was introduced by W. Heisenberg [1] to distinguish between proton and neutron, as the two different charge states of the same particle 'nucleon'(N). From the mirror symmetry and the isobaric multiplet symmetry in the spectra of nuclei, the charge symmetry and charge independence, respectively, of the strong nucleon-nucleon interaction potential V(NN) were established. Introducing nuclear isospin quantum number T and its z-component T_z, representing the identity of the nucleus, corresponding to charge independence and charge symmetries, respectively, one can label a nuclear state, for example, by $|E, J^{\pi}, T, T_z>$, where J^{π} is the total angular momentum and parity of the state and E is the energy of the state.

Isospin symmetry is a very useful concept in nuclear and particle physics. However, as is well known, this symmetry is approximately only, broken, in a nucleus, by the neutron-proton mass difference, coulomb, and charge-dependent nuclear part of the nucleon-nucleon (NN) interactions. Precise knowledge of isospin mixing in nuclear states is important for fundamental interaction processes and nuclear astrophysics [2]. Violation of isospin symmetry leads to various phenomena, such as split of isobaric analog state (IAS) [3], [4], and Gamow-Teller strength (GT) [4], [5], [6], isospin-forbidden electromagnetic transitions [7] to occur. Observations and measurements of these phenomena, in turn, allow the determination of isospin mixing probability.

In this work, we have calculated isospin mixing probability for a number of N=Z nuclei using super-allowed Fermi β^+-decay, but for brevity discuss only the super-allowed decay of ^{54}Co. The ^{54}Co ground state ($|J^{\pi} = 0^+, T = 1>$) decays to the ground state (g.s.) of ^{54}Fe ($|J^{\pi} = 0^+, T = 1>$) (Fig. 1), the isobaric analogue state (IAS). Because no T=0 state can occur in ^{54}Fe, so it's g.s. should be a pure T=1 state. No experimental T=0 state has yet been reported [8] in ^{54}Co. However, from shell model calculation we find around 9 MeV, a (0^+, T=0) state in it. So, the g.s. of ^{54}Co can mix with this state and form an isospin mixed doublet.

The half-life corresponding to β^+ branch (I_{β}^{+}= 99.8932%) is 193.487 ms. The Q-value of the decay is 8244.55 keV. The calculated phase-space factor is 16069.4 corresponds to $(ft)_{Z=0}$ = 3109.22 s.

The Method

We shall consider only two-level mixing, the mixing of pure T = 1 and T = 0 states in ^{54}Co (Fig. 1). This is justified since other T = 0 levels are lying high in energy and have negligible mixing with T = 1 ground state as indicated by the first order perturbation theory. One can write for the wave functions of observed mixed doublet in terms of unperturbed wave functions $|J^{\pi}, T = 1>$ and $|J^{\pi}, T = 0>$, as

$$\begin{bmatrix} |E_1, J^{\pi}> \\ |E_2, J^{\pi}> \end{bmatrix} = \begin{bmatrix} \sqrt{1-b^2} & -|b| \\ |b| & \sqrt{1-b^2} \end{bmatrix} \times \begin{bmatrix} |J^{\pi}, T = 1> \\ |J^{\pi}, T = 0> \end{bmatrix} \quad (1)$$

Here $|b|$ is the isospin mixing amplitude. We have assumed $|E_1, J^{\pi}>$ as the lower

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eigenvalue and $|b|$ as the smaller amplitude. Thus $|E_1, J^\pi >$ is predominantly T =1 and $|E_2, J^\pi >$ is predominantly T = 0. The wave function of the isobaric analog state, the 0^+, T = 1 ground state of ^{54}Fe will be denoted by $|^{54}$Fe, $J = 0, T = 1 >$

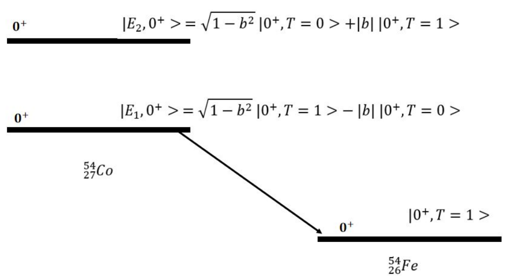

FIG. 1: Two level isospin mixing.

The Fermi-strength, $b(F) =$

$$|\langle ^{54}Fe, T = 1|T^+|^{54}Co, T = 1; g.s.\rangle|^2 \qquad (2)$$

$$b(F) = \frac{[T(T+1) - T_{iz}T_{fz}]}{2J_i + 1}(1 - b^2) \qquad (3)$$

The isospin related factor in the numerator has a value 2 in this case. The b(F) value extracted from $(ft)_{Z=0}$ = C(Z=0)/b(F) = 6170/b(F) can not be used directly since it will lead to negative value of b^2. So corrections are needed for ft value.

Shell model calculations, Results and Discussions

Shell model calculations with certain truncation have been performed with the OXBASH [9] and NuShellX code [10] using kb3gpn and fpd6npn Hamiltonians with the codes. The energy eigenvalues of the low-lying levels agree reasonably with the experimental level sequence with both interactions. The log ft values for the two interactions are 3.51 and 3.568 , respectively, which compare well with the experimental value 3.4846. The resulting b(F) values are 1.911 and 1.671, give isospin mixing probability, using Eq(3) and a Z^{-2} scaling (from hydrodynamic model (HM) consideration), 0.0061(%) and 0.0226(%), respectively. The HM based model prediction is about 0.003. We have also found b^2 from $\bar{F}t = f^R$t(1-b^2) [11], where, average $\bar{F}t$ value is the universal ft-value, same for all super-allowed decays considered and f^R is radiative correction included phase space factor. The isospin mixing probability turns out to be about 1%.

Conclusion

In conclusion, it can be pointed out that the shell model predictions for isospin mixing probability calculated in shell model compares well with the other estimates.

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