

Impossibility to Measure the Total Neutron- and Proton-Induced Nonmesonic Decays for ${}^3_{\Lambda}\text{H}$

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Based on realistic calculations for the nonmesonic decay rate of ${}^3_{\Lambda}\text{H}$ we demonstrate that, in principle, it is not possible to measure the total n - and p -induced decay rates and as a consequence Γ_n/Γ_p for that lightest hypernucleus. The calculations are performed with modern YN forces based on various meson exchanges and taking the final state interaction among the three nucleons fully into account. Our findings might have consequences also for the interpretation of experimental Γ_n/Γ_p ratios for heavier hypernuclei where severe discrepancies exist to theoretical Γ_n/Γ_p ratios.

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Nonmesonic decays in hypernuclei require that a meson emitted in a weak decay of the hyperon is reabsorbed inside the nucleus. We assume that in the reabsorption process only one other nucleon is involved, which is generally considered to be the dominant mechanism, but absorption on two nucleons has also been regarded recently [1]. The meson can be absorbed by a neutron or a proton and one speaks of a neutron or proton induced decay.

There is a long-standing discrepancy between the theoretical ratio of the total neutron-induced nonmesonic decay rate Γ_n to Γ_p (the proton-induced one) for various hypernuclei and the experimental data [1]. The experimental values are typically around 1 except for the very light hypernucleus ${}^4_{\Lambda}\text{He}$ [2,3], while theoretical evaluations lead to 0.05–0.2. The experimental value for Γ_n is estimated either from neutron measurements and/or deduced from the measured values of the total nonmesonic decay rate Γ_{nm} and of Γ_p as $\Gamma_n \equiv \Gamma_{nm} - \Gamma_p$. At first sight this relation is questionable due to interferences. The quantity Γ_p is determined experimentally from measuring single proton spectra and correcting for those protons coming from the neutron-induced decay via final state interactions through intranuclear cascade models [4–6]. These Monte Carlo studies involving cross sections are not full quantum mechanical calculations with all interference effects built in.

On the theoretical side one faces the nuclear many-body problem. Rigorous solutions based on realistic modern baryon-baryon forces are not in sight. Therefore shell model pictures supplemented by Jastrow-type two-body correlations are typically being used and final state interactions are established by optical potentials. It appears difficult to estimate quantitatively the uncertainty of the theoretical predictions. In such a situation a view on very light systems is of increasing interest. In the three-baryon system bound and scattering states can be rigorously calculated based on modern realistic baryon-baryon forces [7]. Therefore uncertainties about the quality of the hypernucleus wave function and final state interactions are absent. In the four-body system first rigorous solutions

for bound states (${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$) already appeared [8]. The mesonic and nonmesonic decays of ${}^3_{\Lambda}\text{H}$ have been calculated [7,9], but there are only a few data to compare with. Some data for mesonic decay rates for ${}^3_{\Lambda}\text{H}$ agree rather well with that theory. Though there are state of the art calculations no data are available for the very small nonmesonic decay rates of ${}^3_{\Lambda}\text{H}$. We use that theoretical insight to throw light on the questionable issues mentioned above. In [7] we found that the nonmesonic decays of ${}^3_{\Lambda}\text{H}$ leading to a final deuteron and a neutron are suppressed by about a factor of 10 with respect to the full breakup processes. Therefore we shall neglect those two-body fragmentation decay channels of ${}^3_{\Lambda}\text{H}$ in the following—except for pointing out that there a separation of n - and p -induced decays is impossible. This is evident from the fact that $\Gamma_n^{n+d} + \Gamma_p^{n+d} = 0.39 \times 10^7 \text{ s}^{-1}$, whereas the total $n + d$ decay rate $\Gamma^{n+d} = 0.66 \times 10^7 \text{ s}^{-1}$. There is a strong interference between the n - and p -induced decays.

For the exclusive differential $n + n + p$ decay rate we have shown in [7] that there are regions in phase space that are populated by n - and p -induced decays and therefore an experimental separation for those contributions is impossible. But there are also regions in phase space which are rather cleanly populated by either n - or p -induced processes. Therefore one has to be satisfied with certain fractions of Γ_n and Γ_p , defined by integrations over certain subregions of the total phase space. Only in this manner one can measure n - and p -induced processes separately. Now we demonstrate that necessarily problems occur in the approach to Γ_p which is being used for heavier hypernuclei [1]. There one investigates the semiexclusive decay process in which only one proton is detected. We shall study in this Letter the single differential decay rate $d\Gamma/dE_p$, which is a measure of events (no matter from which mechanism) that have a proton with energy between E_p and $E_p + dE_p$ and in addition also $d\Gamma/dE_n$ (defined analogously) and investigate whether they can be separated into n - and p -induced contributions and whether certain energy ranges are

dominated by one or the other process. In the following we denote the part of $d\Gamma/dE_p$ which is induced by a proton (neutron) by $d\Gamma_p/dE_p$ ($d\Gamma_n/dE_p$). The corresponding notation for measured neutrons will be $d\Gamma_p/dE_n$ and $d\Gamma_n/dE_n$.

Our results are based on rigorous solutions of the Faddeev equations for ${}^3_\Lambda\text{H}$ and the $3N$ final scattering states. We use the YN Nijmegen potential [10] which includes Λ - Σ conversion. It turned out that this potential produces the experimental ${}^3_\Lambda\text{H}$ binding energy without further adjustment [11]. For the NN forces we used the Nijm93 potential [12]. We expect no dependence on the choice among the most modern NN potentials. For the hypertriton this has been verified. The importance of the final state interaction (FSI) is demonstrated by also presenting results where the $3N$ scattering state in the nuclear matrix element is replaced by $3N$ plane wave states. This extreme approximation will, as in [7], be denoted by symmetrized plane wave impulse approximation (PWIAS), whereas the calculation with final state interaction will be called "FULL." In Fig. 1 we show $d\Gamma/dE_n$, $d\Gamma_n/dE_n$, and $d\Gamma_p/dE_n$ in PWIAS. The quantity $d\Gamma/dE_n$ has two peaks, one at very low neutron energies and one close to the maximal possible neutron energy. The peak at the higher energy is fed by the n - and p -induced processes as is obvious from the corresponding peaks in $d\Gamma_n/dE_n$ and $d\Gamma_p/dE_n$. Clearly in both processes a high energetic neutron is produced. Surprisingly for us $d\Gamma_n/dE_n + d\Gamma_p/dE_n$ sum up to $d\Gamma/dE_n$ with an error smaller than 5%. The interference terms are therefore numerically very small. For very small neutron energies $d\Gamma_n/dE_n$ dies out, since the n -induced process creates mostly high energetic neutrons. The p -induced process, however, $d\Gamma_p/dE_n$, exhibits a strong peak at very low neutron energies, which is caused by the (spectator) momentum distribution of the neutron in ${}^3_\Lambda\text{H}$. Clearly a measurement of the decay rate $d\Gamma/dE_n$ as a function of

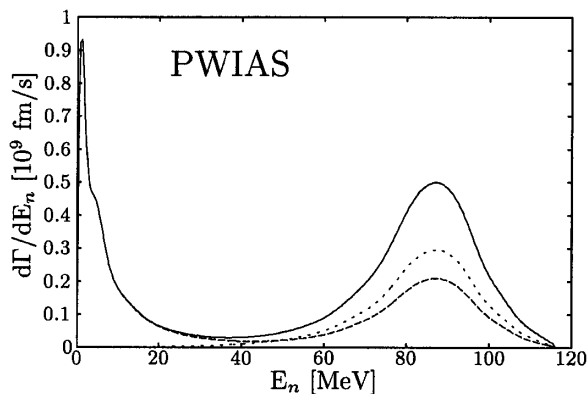


FIG. 1. The single neutron decay rates $d\Gamma/dE_n$ (solid line), $d\Gamma_n/dE_n$ (dotted line), and $d\Gamma_p/dE_n$ (dashed line) in PWIAS as a function of the neutron energy E_n . A separation in n - and p -induced processes is not possible. The peak at very low E_n 's shows directly the momentum distribution of the neutron in ${}^3_\Lambda\text{H}$.

the neutron energy will not allow to separate the n - and p -induced processes—except at very low neutron energies, where the energy distribution of the neutrons, however, is not determined by the Λ -decay process. That picture does not change qualitatively if one turns on the final state interaction as can be seen in Fig. 2. Quantitatively, however, the rates are quite different. We can see a reduction factor of about 2 and the neglect of FSI would be disastrous in a quantitative analysis of data. Now the sum $d\Gamma_n/dE_n + d\Gamma_p/dE_n$ equals $d\Gamma/dE_n$ only within about 12%.

The situation for a separation of n - and p -induced processes appears somewhat more favorable if one regards the single particle decay rates as a function of the proton energy. Our results are shown in Fig. 3 for PWIAS and Fig. 4 for the FULL calculation. For large proton energies nearly all protons result from the p -induced process: $d\Gamma/dE_p \approx d\Gamma_p/dE_p$ in the case of PWIAS. The quantity $d\Gamma_n/dE_p$ cannot produce high energetic protons except due to FSI and this is indeed visible by comparing Figs. 3 and 4. $d\Gamma_n/dE_p$ exhibits, however, the very low energetic proton peak from the spectator proton in ${}^3_\Lambda\text{H}$. Also note again the reduction factor of about 2 caused by FSI.

Let us now quantify the question, whether integrated proton distributions can provide a good estimate for Γ_p . Clearly the very low energetic peak should be excluded and one has to start integrating $d\Gamma/dE_p$ from the highest possible proton energy E_p^{\max} , downwards. Thus we compare the integrals

$$\Gamma(E_p) \equiv \int_{E_p}^{E_p^{\max}} dE'_p \frac{d\Gamma}{dE'_p} \quad (1)$$

and corresponding ones, $\Gamma_p(E_p)$ and $\Gamma_n(E_p)$, where $\frac{d\Gamma}{dE'_p}$ is replaced by $\frac{d\Gamma_p}{dE'_p}$ and $\frac{d\Gamma_n}{dE'_p}$, respectively, as functions of E_p . The results are displayed in Figs. 5 and 6 for PWIAS and FULL. We see that in the case of PWIAS down to about $E_p \approx 50$ MeV the two curves $\Gamma(E_p)$ and $\Gamma_p(E_p)$ are close to each other within less than 5%

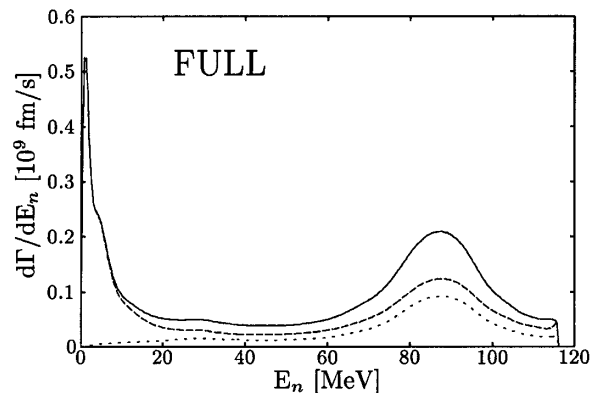


FIG. 2. The same as in Fig. 1 for the FULL calculation. The peak at very low E_n 's is now also influenced by final state interactions.

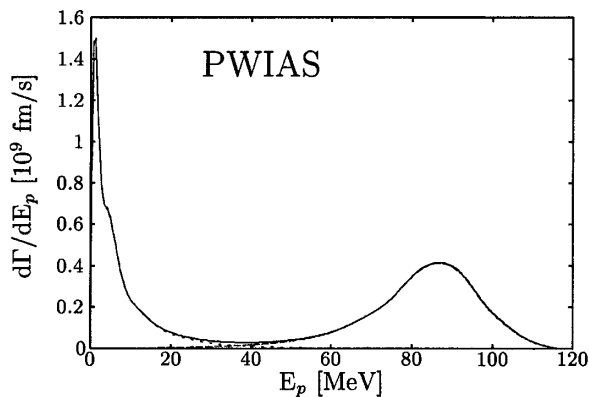


FIG. 3. The single proton decay rates $d\Gamma/dE_p$ (solid line), $d\Gamma_n/dE_p$ (dotted line), and $d\Gamma_p/dE_p$ (dashed line) in PWIAS as a function of the proton energy E_p . Now a separation in n - and p -induced processes would be possible for E_p larger than about 50 MeV. The peak at very low E_p 's shows directly the momentum distribution of the proton in ${}^3_\Lambda\text{H}$.

and only then start to deviate strongly. While $\Gamma_p(E_p)$ flattens out and approaches $\Gamma_p = \Gamma_p(E_p = 0)$, $\Gamma(E_p)$ receives contributions from the n -induced process. The situation is not so favorable, however, for the case FULL. Around $E_p = 60$ MeV the relative deviation $|\Gamma_p(E_p) - \Gamma(E_p)|/\Gamma_p(E_p)$ is about 10% and increases to about 20% around $E_p = 15$ MeV. Below that the deviation increases up to 30%. Note also the relative factor of about 2 between PWIAS and FULL. We have to conclude that an estimate for Γ_p from $d\Gamma/dE_p$ is possible only within an error of about 30%. If one is satisfied with a fraction of Γ_p the error can be reduced to about 10%.

Now we address the question of whether Γ_n can be found as $\Gamma_{nm} - \Gamma_p$ in the case of ${}^3_\Lambda\text{H}$. This is a pure theoretical issue since, as we just demonstrated, Γ_p cannot be measured for ${}^3_\Lambda\text{H}$. Surprisingly this relation is valid. As seen from Table V in [7] we have $\Gamma_n^{\text{FULL}} = 0.17 \times 10^8 \text{ s}^{-1}$, $\Gamma_p^{\text{FULL}} = 0.39 \times 10^8 \text{ s}^{-1}$, and thus

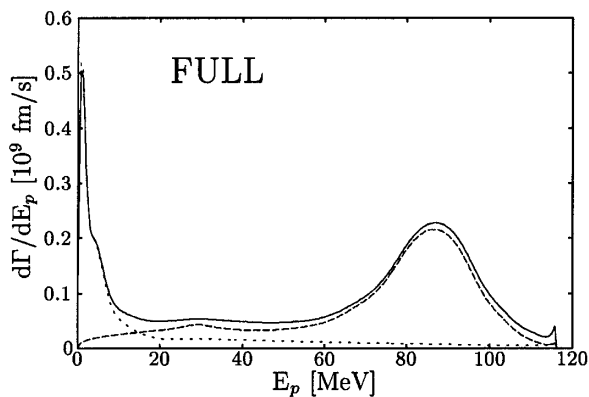


FIG. 4. The same as in Fig. 3 for the FULL calculation. The final state interaction causes now small contributions of high energetic protons resulting from the n -induced decay. Also the peak at very low E_p 's is now influenced by final state interactions.

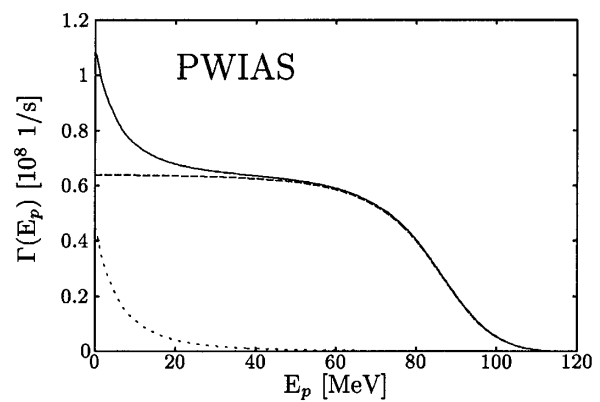


FIG. 5. The integrated single proton decay rates according to Eq. (1) (see text) for PWIAS; $\Gamma_n(E_p)$ (dotted line), $\Gamma_p(E_p)$ (dashed line), $\Gamma(E_p)$ (solid line). For $E_p \geq 50$ MeV $\Gamma_p(E_p) \approx \Gamma(E_p)$.

$\Gamma_n^{\text{FULL}} + \Gamma_p^{\text{FULL}} = 0.56 \times 10^8 \text{ s}^{-1}$, which agrees nicely with $\Gamma^{\text{FULL}} = 0.57 \times 10^8 \text{ s}^{-1}$. The latter value is due to the full process treated correctly as a coherent sum of the n - and p -induced decays. Finally we note that our theoretical result for the ratio of the total n - and p -induced decay rates in the case of ${}^3_\Lambda\text{H}$ is $\Gamma_n/\Gamma_p = 0.44$.

Let us now add a remark on an approximate treatment of FSI. We assume as is usually done in shell model-type studies that only the two outgoing nucleons involved in the decay undergo a final state interaction. According to Eqs. (13), (19), and (20) of [7] this amounts to keeping only the first term in Eq. (20) which is linear in the NN t matrix t . Even more one should also drop the permutation operator P in that first term, which antisymmetrizes the final state properly. We shall discuss both results, with and without antisymmetrization in the final state. They will be denoted by FSI' and FSI'', respectively. In Fig. 7 FSI' is displayed. For the convenience of the reader $d\Gamma/dE_p$ from Fig. 4 is also included, which is based on the full FSI including antisymmetrization. We see that the restricted

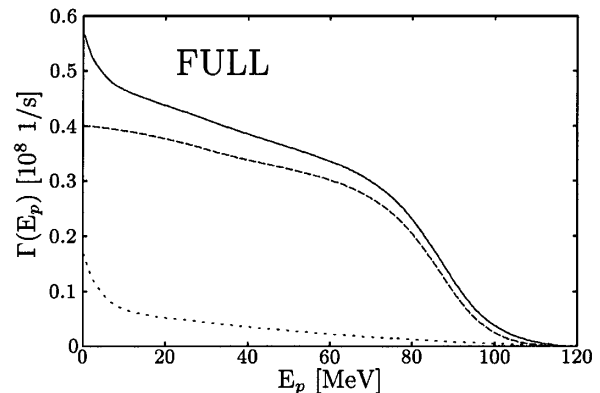


FIG. 6. The same as in Fig. 5 for FULL. Now the influence of the n -induced decay does not allow one to estimate $\Gamma_p(E_p)$ by $\Gamma(E_p)$.

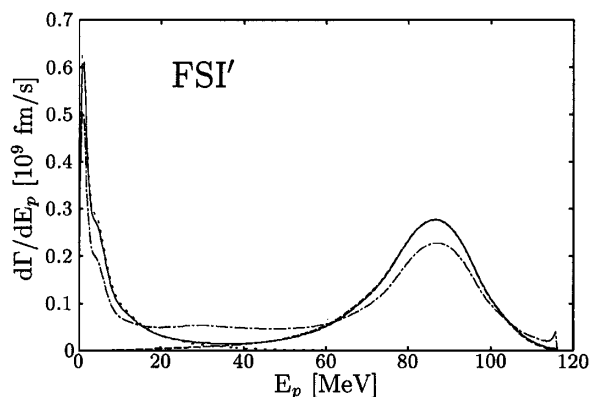


FIG. 7. The same as in Fig. 3 but now allowing the two outgoing nucleons involved in the decay to undergo a final state interaction. Antisymmetrization in the final state is neglected. For comparison the FULL calculation from Fig. 4 (dash-dotted line) is also included.

FSI calculation overestimates $d\Gamma/dE_p$ in the maximum by about 21% and underestimates it around 30 MeV by about 68%. Including antisymmetrization (FSIS') leads to a strong enhancement for smaller proton energies, which overshoots the correct result by about a factor of 2.

The curve corresponding to Fig. 6 is displayed in Fig. 8. There we neglect antisymmetrization and find unsatisfactory deviations from the correct result (about 16% around $E_p = 60$ MeV). If we include antisymmetrization the deviations from the correct result are much worse. For instance at 40 MeV one is about 36% above the correct result. We have to conclude that the approximation usually carried through in shell model studies would be unsatisfactory for the hypertriton.

Since Γ_p in the case of ${}^3_\Lambda\text{H}$ cannot be measured, it appears advisable to concentrate directly on $d\Gamma/dE_p$ and $d\Gamma/dE_n$ and compare those distributions to theory. This is an alternative to the above mentioned exclusive processes. While measurements of the nonmesonic decay of ${}^3_\Lambda\text{H}$ appear to be far away, data for the four-body hypernuclei already exist [2,3] and theoretical predictions can be expected to come up in the near future. This will then allow interesting tests of the nonmesonic decay matrix elements, which will be based on realistic four-body wave functions and various meson-exchange operators [7,13], which drive the nonmesonic decay process.

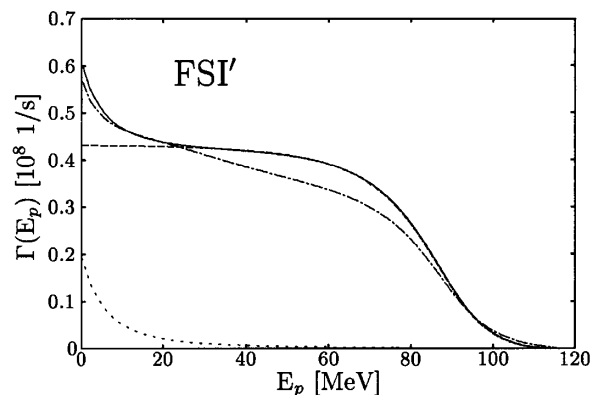


FIG. 8. The same as in Fig. 6 with an approximate treatment of FSI (see text) and without antisymmetrization. For comparison the FULL calculation from Fig. 6 (dash-dotted line) is also included.

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