# THE SPIN DEPENDENCE OF Λ WEAK INTERACTION IN THE DECAY OF HYPERNUCLEI

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## Abstract

From an analysis of 468 hypernuclei (HFs) with ranges > 120 $\mu$m, the non-mesic to $\pi^-$-mesic ratio ($Q^-$) for $_\Lambda$He and $_\Lambda He^5$ HFs was found to be $1\cdot37 \pm 0\cdot17$ and $1\cdot58 \pm 0\cdot20$ respectively. This data, together with results on $_\Lambda He^4$ and heavy hypernuclei, has been used to deduce spin dependences for $\Lambda n$ and $\Lambda p$ weak interactions in decay of hypernuclei. It is found that the rates for triplet and singlet interactions between $\Lambda$ and neutron are $22\,\Gamma_\Lambda$ and $11\,\Gamma_\Lambda$ and for $\Lambda$ and proton are $8\cdot2\,\Gamma_\Lambda$ and $5\cdot5\,\Gamma_\Lambda$ respectively, where $\Gamma_\Lambda$ is the decay rate of $\Lambda$. The total decay rates for $_\Lambda He^4$ and $_\Lambda He^5$ are $1\cdot28\,\Gamma_\Lambda$ and $0\cdot99\,\Gamma_\Lambda$ and the non-mesic decay rates are $0\cdot17\,\Gamma_\Lambda$ and $0\cdot51\,\Gamma_\Lambda$ respectively.

## 1. Introduction

Very little is known concerning $\Lambda N \rightarrow NN$ weak interaction. The properties of interest in this interaction are: (*a*) its charge dependence and (*b*) its spin dependence. Information on these points could be obtained from the following experimentally determined parameters in decays of hypernuclei (HFs):

(i) $Q^-$, the ratio of non-mesic to $\pi^-$-mesic decay of HFs and

(ii) R, the ratio of proton to neutron stimulation of the $\Lambda$ ($\Lambda p/\Lambda n$) in non-mesic decay of HFs.

Normally, if a "fast" proton of energy $\geqslant$30 MeV is associated with the decay of a HF it is taken to be due to the stimulation of the $\Lambda$ by

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proton. It is assumed that the contribution of evaporation protons is negligible in this energy region. The absence of such a fast proton in the non-mesic decay of HFs is taken to be a signature for the neutron-stimulated decay of the Λ.

Dalitz[1] had investigated the relations connecting the parameters $Q^-$ and R with transition rates, $R_{NS}$, in ΛN weak interactions for certain species of HFs. Here $R_{NS}$ refers to the transition rate $\Lambda N \rightarrow NN$, when N is in a *s*-state of total spin S and the density of nucleons of type N is unity at the Λ position. For convenience in discussion later we give some of the pertinent relations in Table I. In Table I $\Gamma_{\pi^-}({}_\Lambda He^4)$ and $\Gamma_{\pi^-}({}_\Lambda He^5)$ refer to $\pi^-$ decay rates for ${}_\Lambda He^4$ and ${}_\Lambda He^5$ respectively and $1/\Gamma_\Lambda$ is the lifetime of the free Λ hyperon; $\rho_3$ and $\rho_4$ refer to nucleon densities for $He^3$ and $He^4$ respectively.

TABLE I

*Theoretical estimates for stimulation and transition rates of* ${}_\Lambda He^4$, ${}_\Lambda He^5$ *and heavy HFs*

| Species of HFs | $\Lambda p/\Lambda n$ stimulation ratio R | Mean transition rate $R = \langle R_{NS} \rangle$ |
|---|---|---|
| ${}_\Lambda He^4$ | $\frac{3R_{p1} + R_{p0}}{2R_{n0}}$ | $\frac{1}{6}(3R_{p1} + R_{p0} + 2R_{n0})$<br>$= \frac{Q^-({}_\Lambda He^4)\,\Gamma_{\pi^-}({}_\Lambda He^4)\,\Gamma_\Lambda}{\rho_3}$ |
| ${}_\Lambda He^5$ | $\frac{3R_{p1} + R_{p0}}{3R_{n1} + R_{n0}}$ | $\frac{1}{8}(3R_{p1} + R_{p0} + 3R_{n1} + R_{n0})$<br>$= \frac{Q^-({}_\Lambda He^5)\,\Gamma_{\pi^-}({}_\Lambda He^5)\,\Gamma_\Lambda}{\rho_4}$ |
| Heavy HFs | $\frac{3R_{p1} + R_{p0}}{3R_{n1} + R_{n0}}$ | |

Earlier attempts to determine $Q^-$ and R, using nuclear emulsion technique, were based on poor statistics; in addition there were experimental biases in the charge resolution of HFs. Recent measurements of $Q^-$ for ${}_\Lambda He$ HFs by Miller *et al.*[2] and Chaudhari *et al.*[3] were definite improvements over earlier attempts. Miller *et al.*[2] using HFs of range $\geqslant 50\,\mu m$ obtained good resolution in separating charges 1 and 2 HFs by the method of track width measurements, whereas Chaudhari *et al.*[3] achieved good charge resolution for all HFs with ranges $\geqslant 5\,\mu$m using a statistical method based on the shapes of range spectra for HFs of different charges.

In this investigation we have used only HFs of range $> 120\,\mu$m, because among this sample (i) HFs of $Z \geqslant 4$ are zero, (ii) $_{\Lambda}$Li forms a minor contribution, and (iii) there are no $_{\Lambda}$H HFs in the non-mesic events as $N_h \geqslant 2$. From such a sample we report results on $Q^-$ and R for $_{\Lambda}$He HFs and use them to deduce similar values for $_{\Lambda}He^5$. We also give an upper limit for the ratio of proton-stimulated decay to $\pi^-$-mesic decay for $_{\Lambda}H^4$. Finally the data presented here, together with the results on heavy HFs and $_{\Lambda}He^4$, obtained by other workers, have been utilized to discuss ΛN weak interactions in the decay of HFs.

## 2.0. EXPERIMENTAL RESULTS

2994 HFs of range $\geqslant 5\,\mu$m were obtained in an emulsion stack, exposed to a slow $K^-$ beam of the proton synchrotron at CERN. Details of the stack, procedures for scanning and selection criteria for HFs and their analysis are described elsewhere.[4] The numbers of $\pi^-$-mesic and non-mesic HFs in the range groups $5\,\mu$m to $120\,\mu$m and $> 120\,\mu$m are given in Table II.

TABLE II

*Details of mesic and non-mesic HFs*

| Range of HFs in $\mu$m | $\pi^-$-mesic decay mode | non $\pi^-$-mesic decay mode | Total |
|---|---|---|---|
| 5–120 | 977 | 1549 | 2526 |
| $> 120$ | 296 | 172 | 468 |
| Total $\geqslant 5\,\mu$m | 1273 | 1721 | 2994 |

Only those non-mesic HFs which have two or more decay prongs are included in the data given in Table II. From a comparison of range spectra of uniquely charge-identified HFs produced by $K^-$ captures in emulsion, Chaudhari *et al.*[3] concluded that the contribution of charge $\geqslant 4$ HFs in the range group $> 120\,\mu$m is zero whereas the contribution of charge 3 HFs in this range group is only about 2% of the charge 3 HFs in the 5–120 $\mu$m range group. Therefore, we conclude that $\pi^-$-mesic HFs with ranges $> 120\,\mu$m are HFs of charges 1, 2 and 3 whereas non-mesic HFs of similar range have charges 2 and 3. Results concerning the charge split of mesic and non-mesic HFs of ranges $> 120\,\mu$m are described in the following Sections.

## 2.1. *Charge Splitting of Mesic HFs*

The 296 mesic HFs were analysed for unique identification on a CDC 3600 computer from binding energy consideration as described by Chaudhari *et al.*[4] By this procedure 273 events were uniquely charge-identified; the numbers for $_\Lambda$H, $_\Lambda$He, and $_\Lambda$Li are 162, 110 and 1 respectively. The rest of the 23 events were charge split into $_\Lambda$H, $_\Lambda$He and $_\Lambda$Li in relative proportions same as those found for uniquely charge identified HFs with ranges $> 120\,\mu$m; their distribution was found to be 13 ± 3, 9 ± 2 and 1 ± 1 respectively. Thus the total number of $_\Lambda$He HFs in the mesic sample of 296 is 119 ± 11. Taking the ratio of $_\Lambda\text{He}^4$ to $_\Lambda\text{He}^5$ for uniquely identified mesic HFs to be 1/4 and assuming the same ratio in these 119 $_\Lambda$He events the numbers of mesic $_\Lambda\text{He}^4$ and $_\Lambda\text{He}^5$ in this sample are 24 and 95 respectively.

## 2.2. *Charge Splitting of Non-mesic HFs*

This group of 172 events are due to $_\Lambda$He and $_\Lambda$Li HFs. The decay vertices of these events were examined with care under high magnification (1500 ×) to detect the presence of blobs or short tracks. In this way the number of 3 prong events was found to be nine and the remaining 163 events were of the 2 prong type. The former nine events were certainly $_\Lambda$Li HFs.

The number of $_\Lambda$Li events in this sample can also be estimated from the corresponding number of $_\Lambda$Li events in the range interval 5 to 120 $\mu$m. The number of $_\Lambda$Li events in this interval was found to be 475 by Chaudhari *et al.*[3] From this number and from the results quoted in Section 2·0 we estimate that the number of $_\Lambda$Li events in our non-mesic sample of 172 HFs is 9 ± 3. As 9 events of the three prong type were observed, we attribute the rest 163 two prong type events to $_\Lambda$He HFs. The number of $_\Lambda$Li events amongst the two prong type of events is estimated to be less than 5, which, being a small number, will not affect our final results and hence may be neglected. This number of 163 $_\Lambda$He HFs represents their non-mesic as well as $\pi^\circ$ decay modes. The number of $\pi^\circ$ decay modes had to be calculated and subtracted from the $_\Lambda$He non-mesic events. In addition, $_\Lambda$He non-mesic events with $N_h = 0$ and 1 have to be added to obtain the true number of $_{\Lambda}$He events in this sample. These two corrections were of opposite signs and it has been shown by Chaudhari *et al.*[3] that the magnitudes of the corrections are equal. Hence we conclude that the number 163±13 represents the true number of non-mesic $_{\Lambda}$He events in the sample.

### 2·3. *$Q^-$ in $_{\Lambda}He^4$ and $_{\Lambda}He^5$*

From results given in Sections 2.1 and 2.2 the $Q^-$ value for $_{\Lambda}$He is found to be $1·37 \pm 0·17$ $(163 \pm 13/119 \pm 11)$. $Q^-$ for $_{\Lambda}He^4$ was determined by Block *et al.*[5] to be $0·52 \pm 0·10$. Using this $Q^-$ value, the number of non-mesic $_{\Lambda}He^4$ in this sample of 163 $_{\Lambda}$He events was calculated to be 13. Therefore the value of $Q^-$ for $_{\Lambda}He^5$ is $1·58 \pm 0·20$ $(150 \pm 13/95 \pm 10)$.

### 2.4. *Ratio, R, of Proton to Neutron Stimulation in $_{\Lambda}He$*

The decay products from the 163 $_{\Lambda}$He events were followed in the stack and their energies were determined from their residual ranges assuming them to be protons. The values of the ratio, R, have been calculated using various energy cut-offs (from 15 to 50 MeV at 5 MeV intervals) and the results are given in Table III.

TABLE III

*Stimulation ratio as a function of cut-off energy of proton*

| Cut-off energy of fast protons in MeV | Number of $_{\Lambda}$He events with a fast proton | Number of $_{\Lambda}$He events without a fast proton | R ($_{\Lambda}$He) = $\frac{\Lambda p}{\Lambda n}$ |
|---|---|---|---|
| 15 | 116 | 47 | 2·47 |
| 20 | 108 | 55 | 1·96 |
| 25 | 104 | 59 | 1·76 |
| 30 | 97 | 66 | 1·47 |
| 35 | 93 | 70 | 1·33 |
| 40 | 90 | 73 | 1·23 |
| 45 | 81 | 82 | 0·99 |
| 50 | 74 | 89 | 0·83 |

Assuming a momentum cut-off of 250 MeV/c for fast protons, Block *et al.*[5] determined the value of R to be $2 \cdot 2 \pm 0 \cdot 8$ for ${}_{\Lambda}He^4$.

As can be seen from Table III, the values of R (${}_{\Lambda}He$) are sensitive to energy cut-off used for fast protons. This cut-off value of energy has to be inferred from the momentum distribution of nucleons in the core nuclei of HFs. When the mass number of nuclei is large, Fermi momentum distribution will enable us to set a lower limit for the energy of fast protons ; however, Fermi distributions cannot certainly be applied to as light a nucleus as $He^3$ or $He^4$. A possible lower limit for the energy of fast protons in ${}_{\Lambda}He$ HFs can be inferred from other considerations as discussed in Section 3.2.

### 2.5. *Ratio of $\Lambda p$ Stimulation to $\pi^-$-Mesic Rate in ${}_{\Lambda}H^4$*

In addition to what is presented in Table II, we observed events with a single prong associated with the ends of tracks from $K^-$ stars. In addition to being due to HFs such events could also be due to $\pi^-$ or $\Sigma^-$ captures or scattering of fast tracks. To reduce this bias to a minimum, we set the following criteria for classifying 1 prong decays as HFs:

(i) The range of the connecting track is $> 120\,\mu$m; to a large extent this enables us to distinguish between the various possibilities mentioned above.

(ii) The range of the secondary track should be greater than 2 mm.; this will enable us to eliminate possible low energy scattering events and interaction-in-flight events.

Thus it is clear from the criteria set up that the events thus found should either be non-mesic decays of ${}_{\Lambda}H$ HFs or absorptions of $\Sigma^-$ hyperons in heavy emulsion nuclei (Ag, Br) leading to the formation of cryptofragments which subsequently decay by the emission of a fast proton.

In our sample of $K^-$ stars 8 events satisfying these criteria were found. About 20% of all $K^-$ stars were re-examined by an independent observer and no new events were found. From this we estimate that the efficiency to detect 1 prong type of events with the criteria laid down by us is more than 85%. The energies of the protons for these eight cases are 23·4, 27·1, 33·8, 34·5, 35·6, 39·9, 56·8 and 76·5 MeV. If these events are due to decay of cryptofragments formed by $\Sigma^-$ captures in heavy emulsion nuclei we expect an Auger electron or blob to be associated with about 4 decay vertices. However, none of these eight events was associated with an

Auger electron or blob; the decay centers are clean and only fast protons were seen associated with the decay vertices. We are therefore led to the conclusion that most of the events represent the non-mesic decay mode of $_{\Lambda}$H HFs. If we set a lower limit of 30 MeV for the energy of fast protons, 6 events represent an upper limit of $_{\Lambda}$H non-mesic decays by proton stimulation in our sample. We have also looked into the possibility of scattering measurements on the HF tracks for mass estimation by using P 0·7 μm constant sagitta scheme. Only two events were favourable for measurements and the masses obtained are 3976 ± 1200 and 3725 ± 1300 MeV; these are consistent with the mass of $_{\Lambda}$H.

From Section 2.1, we obtain 175 $_{\Lambda}$H HFs (of range ≥ 120 μm) which decayed by $\pi^-$-mesic mode; again from the work of Chaudhari *et al.*[4] we estimate that 136 of the 175 events are due to $_{\Lambda}H^4$ (assuming the $_{\Lambda}H^3$:$_{\Lambda}H^4$ ratio to be the same as in the uniquely identified sample of events). If we assume all 6 events to represent non-mesic decay of $_{\Lambda}H^4$ then an upper limit on the ratio of proton-stimulated decay to $\pi^-$-mesic decay of Λ in $_{\Lambda}H^4$ would be 6/136.

## 3.0 DISCUSSION OF THE RESULTS

### 3.1. *Experimental Comparison*

A survey of $Q^-$ values for $_{\Lambda}$He was given by Chaudhari *et al.*[6]; the values of $Q^-$ show large variations mainly because of small samples used by various authors. Miller *et al.*[2] determined the value of $Q$ for $_{\Lambda}$He to be 1·02 ± 0·12 using a sample of 93 mesic and non-mesic HFs of range ≥ 50 μm. Recently, Chaudhari *et al.*[3] using a statistical method for charge separation on a total sample of 2994 HFs (of charges 1, 2, 3 and ≥ 4) determined the value of $Q$ for $_{\Lambda}$He to be 1·01 ± 0·12 based on 1313 $_{\Lambda}$He events.

In the present investigation, a value of $Q^-$ for $_{\Lambda}$He HFs was found to be 1·37 ± 0·17 using 468 HFs of range ≥ 120 μm. Our value appears to be a little high but not inconsistent with the earlier observations of Miller *et al.*[2] and Chaudhari *et al.*[3] For further discussion we adopt the present value of $Q$.

### 3.2. *Theoretical Considerations*

To determine the values of $R_{NS}$ it is essential to know the value of the decay rates of $_{\Lambda}He^4$ and $_{\Lambda}He^5$. Assuming the total decay rate for each to be the sum of $\pi^-$-mesic, $\pi^1$-mesic and non-mesic decay rates and assuming a ratio of 1 : 4 for ${}_{\Lambda}\mathrm{He}^4$ : ${}_{\Lambda}\mathrm{He}^5$ the total decay rate of ${}_{\Lambda}\mathrm{He}$ may be written as

$$\Gamma({}_{\Lambda}\mathrm{He}) = \frac{1}{\tau}({}_{\Lambda}\mathrm{He}) = 0\cdot 8\, \Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^5) + \Gamma_{\pi^\circ}({}_{\Lambda}\mathrm{He}^5) + \Gamma_{nm}({}_{\Lambda}\mathrm{He}^5)$$

$$+ 0\cdot 2\, \Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^4) + \Gamma_{\pi^\circ}({}_{\Lambda}\mathrm{He}^4) + \Gamma_{nm}({}_{\Lambda}\mathrm{He}^4)$$

whare $\tau({}_{\Lambda}\mathrm{He})$ is the lifetime for ${}_{\Lambda}\mathrm{He}$ HFs and $\Gamma({}_{\Lambda}\mathrm{He}^4)$ and $\Gamma({}_{\Lambda}\mathrm{He}^5)$ correspond to decay rates of ${}_{\Lambda}\mathrm{He}^4$ and ${}_{\Lambda}\mathrm{He}^5$ respectively. Recently, Phillips and Schneps[7] obtained a value of $2\cdot 43^{+0\cdot 6}_{-0\cdot 4} \times 10^{-10}$ sec. for $\tau({}_{\Lambda}\mathrm{He})$; this value will be utilized by us for calculating $\Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^4)$. The $\tau_{\Lambda}$ for free $\Lambda$ decay was measured to be $2\cdot 535 \pm 0\cdot 035 \times 10^{-10}$ sec. by Grimm.[8] The following relations were also adopted:

(i) $\Gamma_{\pi^\circ}({}_{\Lambda}\mathrm{He}^4) = 1\cdot 49\, \Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^4)$ from Block *et al.*[5];
(ii) $\Gamma_{\pi^\circ}({}_{\Lambda}\mathrm{He}^5) = 0\cdot 5\, \Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^5)$ from $\triangle \mathrm{I} = \frac{1}{2}$ rule;
(iii) $\rho_3 = 0\cdot 019\, f^{-3}$; and
(iv) $\rho_4 = 0\cdot 038\, f^{-3}$.

Using the completeness relation, Dalitz[9] has shown that the value of the ratio $\Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^5)/\Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^4)$ should be close to unity. Assuming $\Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^5) = \Gamma_{\pi^-}({}_{\Lambda}\mathrm{He}^4)$ and using the above data we find $\Gamma_{\pi}({}_{\Lambda}\mathrm{He}^4) = 0\cdot 32\, \Gamma_{\Lambda}$.

From the values of $Q^-$ for ${}_{\Lambda}\mathrm{He}^4$ and ${}_{\Lambda}\mathrm{He}^5$ obtained by Block *et al.*[5] and in this investigation respectively, we obtain the following:

$$3\mathrm{R}_{p1} + \mathrm{R}_{p0} + 3\mathrm{R}_{n1} + \mathrm{R}_{n0} = 106 \pm 13\, \Gamma_{\Lambda}$$
$$3\mathrm{R}_{p1} + \mathrm{R}_{p0} + 2\mathrm{R}_{n0} = 52 \pm 10\, \Gamma_{\Lambda}.$$

The $\Lambda p/\Lambda n$ ratios for ${}_{\Lambda}\mathrm{He}^4$ and ${}_{\Lambda}\mathrm{He}^5$ could not be accurately determined for lack of knowledge of the correct energy cut-off for fast protons. However, for heavy HFs the well-known Fermi momentum distribution will enable one to obtain the spread in proton energy spectrum in the decay of HFs. Further, the evaporation spectrum for de-excitation of heavy nuclei is well understood. Thus using a cut-off energy of 30 MeV for fast protons, Beniston,[10] Lagnaux[11] and Ganguli and Swami[12] determined $\Lambda p/\Lambda n$ ratio in decay of heavy HFs. The values of the ratios obtained by these authors agree well with one another and the mean of the values is found to be $0\cdot 4 \pm 0\cdot 1$. Thus we may write

$$(\Lambda p/\Lambda n)\ \text{heavy HFs} = (3R_{p1} + R_{p0})/(3R_{n1} + R_{n0})$$
$$= 0{\cdot}4 \pm 0{\cdot}1.$$

From the data presented above, we get

$$3R_{n1} + R_{n0} = 76 \pm 7\ \Gamma_\Lambda$$
$$R_{n0} = 11 \pm 2\ \Gamma_\Lambda$$
$$R_{n1} = 22 \pm 4\ \Gamma_\Lambda$$
$$R_{n1}/R_{n0} = 2{\cdot}0 \pm 0{\cdot}5$$
$$3R_{p1} + R_{p0} = 30 \pm 8\ \Gamma_\Lambda.$$

An upper limit on $R_{p0}$ could be obtained from the data presented in Section 2.5 for ${}_\Lambda H^4$ HFs. We have

$$(\Lambda p/\pi^-)\ {}_\Lambda H^4 = 6/136 = 2R_{p0}\,\rho_3/6\ \Gamma_{\pi^-}({}_\Lambda H^4).$$

$\Gamma_{\pi^-}({}_\Lambda H^4)$ was calculated by Dalitz and Liu[13] to be $0{\cdot}77\ \Gamma_\Lambda$. Therefore from the above relation, $R_{p0} \le 5{\cdot}3\ \Gamma_\Lambda$. The values of $R_{p1}$ and $R_{p0}$ may also be obtained from relations between transition rates and $\Delta I = \frac{1}{2}$ rule; the relations are: $R_{p0} = \frac{1}{2} R_{n0}$ and $R_{p1} = \frac{1}{2} R_{n1}$. Thus the values of $R_{p1}$ and $R_{p0}$ were found to be $8{\cdot}2\ \Gamma_\Lambda$ and $5{\cdot}5\ \Gamma_\Lambda$ respectively. These values of $R_{p1}$ and $R_{p0}$ are consistent with the upper limits obtained from experiment. The ratio $R_{p1}/R_{p0}$ is found to be $1{\cdot}5$. These values for transition rates could now be utilized to estimate $\Lambda p/\Lambda n$ ratios for ${}_\Lambda He^4$ and ${}_\Lambda He^5$ HFs; the ratios respectively are $1{\cdot}4 \pm 0{\cdot}4$ and $0{\cdot}4 \pm 0{\cdot}13$. The value $\Lambda p/\Lambda n$ for ${}_\Lambda He^4$ obtained by Block *et al.*[5] was $2{\cdot}2 \pm 0{\cdot}8$, which is not inconsistent with the expected values. However, the values presented in Table III for ${}_\Lambda He$ could be made consistent with expected values only when we assume a cut-off value much above the nominal value of 30 MeV normally chosen for such purposes.

It is also possible to derive the total and non-mesic decay rates of ${}_\Lambda He^4$ and ${}_\Lambda He^5$. The values obtained are

$$\Gamma({}_\Lambda He^4) = 1{\cdot}28\ \Gamma_\Lambda$$
$$\Gamma({}_\Lambda He^5) = 0{\cdot}99\ \Gamma_\Lambda$$
$$\Gamma_{nm}({}_\Lambda He^4) = 0{\cdot}17\ \Gamma_\Lambda$$
$$\Gamma_{nm}({}_\Lambda He^5) = 0{\cdot}51\ \Gamma_\Lambda.$$

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