



Dick Dalitz (1925–2006)

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Exchange reactions with Dick Dalitz

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Abstract. An account is given of the close collaboration of Dick Dalitz with the European K^- Collaboration over many decades in many aspects of hypernuclear physics. In particular, emphasis is given to the topics of double hypernuclei and the discovery and resolution of p -wave Λ strangeness exchange states.

PACS. 21.80.+a Hypernuclei – 01.65.+g History of science

1 Introduction

This is a personal account of a career of 50 years which strongly overlapped with two of the many of Dick Dalitz's interests, hypernuclei and the low energy $\bar{K}N$ system.

As a new graduate student, I first met Dick about 50 years ago when he gave a seminar on the low energy $\bar{K}N$ system, a preview of the subsequent Dalitz and Tuan paper [1].

My first publication [2] concerned the observation of a Σ^+ hyperon decaying into a proton with an associated Dalitz pair [3], a mere verification of what was already well known; one decay mode of the Σ^+ was to $\pi^0 p$.

In 1961 I joined Levi Setti's emulsion group in Chicago, the hub of hypernuclear physics at that time, and got to know Dick very well. While there, we made the first direct experimental estimate of the Λ nuclear potential well-depth, D_Λ , from the decays of heavy spallation hypernuclei [4]. Our value, of a little less than 30 MeV, agreed well with Dick's value of 26.5 ± 2.5 MeV [5] obtained by extrapolating from the then known binding energy of $^{13}\Lambda$ C. However, it should be remarked that at this time various theoretical estimates using ΛN potentials derived from the B_Λ values of the s -shell hypernuclei all gave values nearer to 60 MeV. Also at this time was the determination of the spin of $^8\Lambda$ Li [6, 7].

I returned to London to rejoin the European K^- Emulsion Collaboration and Dick came to England shortly afterwards, first to Cambridge and then permanently to Oxford to join up again with his old mentor, Rudolf Peierls.

There began a long, symbiotic, and fruitful collaboration between Dick and us. We benefited greatly from his advice, encouragement and theoretical input, and he knew of our results well before publication. He was invited and came to many of our meetings, not only those in London, but sometimes to those in Brussels and CERN as well.

In the sixties and early seventies we worked on such topics as the B_Λ values of p -shell hypernuclei [8], spins of

$^8\Lambda$ Li [9] and $^{12}\Lambda$ B [10], π^+ decays of hypernuclei [11], charge symmetry breaking in the $^4\Lambda$ He, $^4\Lambda$ H mirror doublet [12] and many others, always in close collaboration with Dick.

However, I would like to concentrate on two long-running sagas in which Dick played a pivotal role, those of double hypernuclei and the proton-emitting p -wave hypernuclear states.

2 Double hypernuclei versus the H

The first double hypernucleus, an example of $^{10}\Lambda\Lambda$ Be, was found by our collaborators in Warsaw in 1962 [13] and Dick was among the first to glean properties of the $\Lambda\Lambda$ interaction from it [14]. A second event, an example of $^{10}\Lambda\Lambda$ He, was reported by Prowse in 1966 [15] and then, for a long time, nothing. Prowse died in 1971 and Pniewski began to express doubts about the authenticity of the Prowse event. In 1977, Jaffe predicted the existence of the H particle, a deeply bound six quark system (u, u, d, d, s, s), the quark content of two Λ hyperons. I well remember questioning Jan de Swart at the Jablonna Conference in 1979, that was it not difficult to reconcile the existence of double hypernuclei with that of the H particle? His reply, which was echoed in many subsequent reviews by proponents of the H , was that there were only two events reported in emulsions and perhaps they had been wrongly interpreted.

Dick asked me at the end of the eighties if we could possibly remeasure the event in order to allay these doubts. I told him that this was not possible as the emulsion pell-mell containing the event no longer existed. However, I did have in my possession copies of unpublished photomicrographs taken of the event by P. Fowler *et al.* in Bristol some 25 years earlier.

It should be noted that the three vertices of the event, the Ξ^- capture and the double and single hypernuclear decays were all contained in a cube of side length 3 microns. Moreover, nuclear emulsion is approximately one

half silver bromide crystals by volume and, as a consequence, a pellicle shrinks in height by a factor a little more than two on processing. In order to achieve greater resolution for photography, the emulsion was swelled by soaking it in a saturated sugar solution made from Tate and Lyle's golden syrup, since water has the wrong optical properties, to 3.5 times its processed thickness. Unfortunately for Dick's request, the sugar ultimately crystallised and the emulsion was destroyed. The photomicrographs and an independent analysis of the event made during its photographing were published in the Royal Society paper of 1989 [16].

Every attempt was made to elicit further details of the Prowse event but without success. However, one significant fact did emerge which persuaded me that Pniewski was right to doubt the event. Although Prowse had moved to Wyoming and published the event from there, his emulsion work had remained in UCLA and where at that time Ticho, Schlein and Slater, all erstwhile hypernuclear emulsion physicists, were based. All were contacted, but none had any recollection of having seen the event!

There now exists the tightly constrained $^{11}_\Lambda$ He [17] with a $\Delta B_{\Lambda\Lambda} \approx 1.0$ MeV, completely at odds with the Prowse event, and for that matter with the original $^{10}_\Lambda$ Be event also. For the $^{10}_\Lambda$ Be event, as was stated in a footnote to a table in the paper of 1963, 'It should be noted that the value of $B_{\Lambda\Lambda}(\Lambda\Lambda Z)$, and hence $\Delta B_{\Lambda\Lambda}$, may be overestimated if the ordinary hyperfragment is produced in an excited state', and should the decay have occurred to a now known state of $^9_\Lambda$ Be at ~ 3.0 MeV [18], the $\Delta B_{\Lambda\Lambda}$ would become ~ 1.3 MeV, well compatible with the Nagaoka event [17]. No such escape clause exists for the Prowse $^{11}_\Lambda$ He event [15].

And still there is no H !

3 Strangeness-exchange states

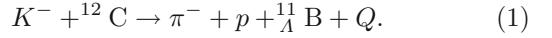
Around the late sixties we were attempting to determine the B_A values of p -shell hypernuclei. There were many possible examples of $^{11}_\Lambda$ B decays to π^- $^{11}_\Lambda$ C but see Table 1.

With range straggling of the pions of about 3%, the three hypernuclei in Table 1 cannot be separated from decay kinematics alone. It was noted that many of the $^{11}_\Lambda$ B candidates had K^- at rest production topologies of hyperfragment + π + one baryonic track. The azimuthal and dip angles of all three tracks were measured, as were the ranges of the hyperfragment and assumed proton (the pion invariably left the emulsion before stopping).

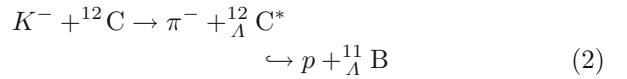
Table 1. Competing two-body decay characteristics.

	pion range (μm)	recoil range (μm)	recoil
$^{11}_\Lambda$ B $\rightarrow \pi^-$ $^{11}_\Lambda$ C	20700	1.0	β^+
$^{10}_\Lambda$ Be $\rightarrow \pi^-$ $^{10}_\Lambda$ B	19800	1.1	stable
$^7_\Lambda$ Li $\rightarrow \pi^-$ $^7_\Lambda$ Be	21600	1.8	E.C.

Assuming the K^- capture is on a light nucleus of the emulsion, in this case ^{12}C , the proposed reaction is



The range of the proton determines both T_p and p_p . With the Q value known, an iterative procedure was used to determine the value of the pion's energy. Starting with a value of $T_{HF} = 0$, this gave $T(1)_\pi$, hence $\mathbf{p}(1)_\pi$, $\mathbf{p}(1)_\pi + \mathbf{p}_p \rightarrow \mathbf{p}(1)_{HF} \rightarrow T(1)_{HF} \rightarrow T(2)_\pi \rightarrow \mathbf{p}(2)_\pi$, $\mathbf{p}(2)_\pi + \mathbf{p}_p \rightarrow T(2)_{HF}$, and so on. The procedure rapidly converges; after two iterations the pion kinetic energy is stable to 5 keV. The compatibility with reaction (1) was then tested by comparing the measured and computed ranges and directions of the hypernucleus. The compiled data revealed a sharp spike, of the order 1 MeV wide, in the pion spectrum. Such a spike suggests that many of the events proceeded *via* a two-body reaction



This was written up and sent to Nuclear Physics but the referee demurred — 'Not every spike implies a resonance.' It was resubmitted with the inclusion of phase space and impulse model curves. The spike remained prominent, but still the referee was not happy, and so it went to a second referee. The second referee was more forthcoming, 'first observation of a highly excited state of a hypernucleus', and so it was published [19]. I saw Dick shortly afterwards and thanked him for overruling the first referee. He was taken aback and said that Nuclear Physics had no business to divulge the referee's name. I had to assure him that they had not. Remember, this was well before the coming of the Word, the Microsoft Word that is. Referees wrote reports which were typed by a secretary. However, as anyone who has received a typewritten document from Dick will know, he was never satisfied and always modified the text in his own neat but unmistakable handwriting, and so it was here.

We published a further paper on the subject with some more statistics but then left the field to go hunting for charm and beauty particles. The subject was taken up by the counter (K, π) and (π, K) spectroscopy groups at CERN, BNL and later KEK. I was brought back to the subject by Dick, who else, approaching me at the 1982 Heidelberg Conference. He had a problem. Was the Λ in $^{12}_\Lambda$ C* bound or unbound? Theoreticians worry about such things. The Brookhaven group had two values for B_A in $^{12}_\Lambda$ C*, one measured with the pion going off in the forward direction as everyone else had done, the other with the pion making a large, 15° angle to the kaon direction.

$$\begin{aligned} \theta_{K\pi} = 0^\circ &\Rightarrow B_A = +0.033 \pm 0.180 \text{ MeV}, \\ \theta_{K\pi} = 15^\circ &\Rightarrow B_A = -0.027 \pm 0.160 \text{ MeV}. \end{aligned}$$

He remarked that he had also checked our two papers and in both the B_A values were positive, but they did not agree with one another! This was a problem. Dave Tovee and I went back to our old results and discovered

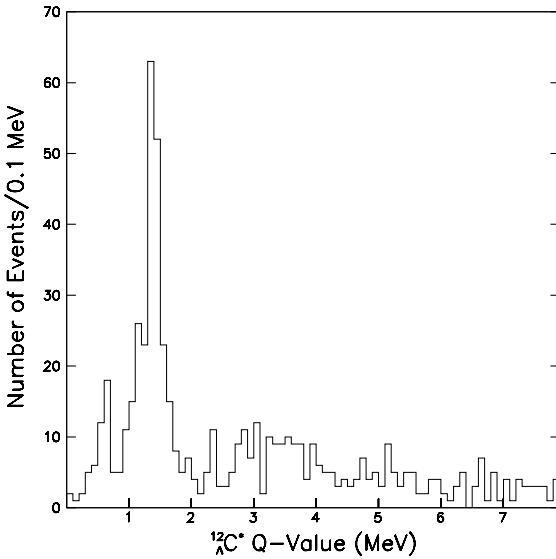


Fig. 1. Distribution of the Q -values in the $^{12}\Lambda C^* \rightarrow p + ^{11}\Lambda B$ decay, treating all events as occurring on ^{12}C .

the cause of the discrepancy; the input mass values necessary to our analysis, especially that of the kaon, had changed in the Particle Data Group's listings in the early seventies by considerably more than the stated errors. We reanalysed all of our old data, including a large sample of events obtained using the resonance peak to identify $^{11}\Lambda B$ events in order to study their non-mesonic decays [20] and the results of this analysis were presented at the 1985 Brookhaven Conference [21]. The Q value distribution in the decay $^{12}\Lambda C^* \rightarrow p + ^{11}\Lambda B$ is given in Fig. 1 [22].

A good fit to the spectrum below 2 MeV, the events there comprise an essentially pure sample of $^{12}\Lambda C^*$, requires at least three Breit-Wigner distributions. One stands alone, but two more are needed, both centred around $Q \approx 1.4$ MeV, a very narrow one and a wider one. What do we expect? The states are formed by the addition of a $P_{\frac{3}{2}}^3$ neutron hole and either a $P_{\frac{1}{2}}^1$ or a $P_{\frac{3}{2}}^3$ Λ hyperon.

$$\bar{n}(P_{\frac{3}{2}}^3) + \Lambda(P_{\frac{1}{2}}^1) \Rightarrow 1^+, 2^+,$$

$$\bar{n}(P_{\frac{3}{2}}^3) + \Lambda(P_{\frac{3}{2}}^3) \Rightarrow 0^+, 1^+, 2^+, 3^+.$$

The low energy $\bar{K}N$ interaction is s -wave, which contains no spin flip, and so we expect only the 0^+ and the two 2^+ states to be produced. Since the $^{11}\Lambda B$ ground state has spin $\frac{5}{2}^+$, while the proton from the two 2^+ states may be emitted in the s -wave, that from the 0^+ state has to be d -wave. It is thus natural to assign the observed narrow state to be the 0^+ , since the angular momentum barrier for such a small energy release, ~ 1 MeV, will strongly inhibit its decay. With this assignment we construct the level scheme given in Table 2.

To conclude, three states are expected, and three are found. The real widths of the 2^+ states have been determined, whereas it is only possible to give an upper limit to the width of the 0^+ state; there are limits even to the resolution of the emulsion technique! The B_A difference

Table 2. Level scheme for the observed $^{12}\Lambda C^*$ states.

	No of events	Γ (keV)	B_A (MeV)
0^+	64	< 100	$+0.14 \pm 0.05$
2^+	193	~ 600	$+0.20 \pm 0.05$
2^+	48	~ 150	$+0.95 \pm 0.05$

between the two 2^+ states places a limit on the ΛN spin-orbit interaction and the relative production rates following K^- capture at rest on ^{12}C are given. Finally, in answer to Dick's original question, the B_A values have been determined and in ALL states the Λ hyperon is bound.

The remaining problem with this analysis; why did the 0^+ state not decay quickly by s -wave proton emission to the expected $\frac{1}{2}^+$ excited state of $^{11}\Lambda B$ was solved recently when it was found that this state was energetically out of reach [23].

4 Conclusions

In conclusion, it should be emphasised that neither of these two investigations would have been undertaken without Dick's encyclopaedic knowledge of past results and his nagging persistence to obtain solutions to puzzling situations. The relevant information would otherwise have mouldered away on my bookshelves, forgotten.

I greatly miss his friendship and his phone calls, usually at home late on a weekend evening, asking for details of things recorded in his notebooks of which I had presumably told him some twenty or thirty years before. The whole hypernuclear community will sorely miss him too.

I would like to thank the organisers for giving me the opportunity to speak of Dick, for a very enjoyable conference and for contributing generously towards my expenses.

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