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Elected FRS 1960

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Richard (Dick) Henry Dalitz was a theoretical physicist whose principal contributions were intimately connected to some of the major breakthroughs of the twentieth century in particle and nuclear physics. His formulation of the ‘τ–θ’ puzzle led to the discovery that parity is not a symmetry of nature—the first of the assumed space-time symmetries to fail. He pioneered the theoretical study of hypernuclei, of strange baryon resonances, and of baryon spectroscopy in the quark model (at a time when many considered it ‘naive’), to all of which he made lasting contributions. The ‘Dalitz plot’ and ‘Dalitz pairs’ are part of the vocabulary of particle physics. Throughout his career he remained in close touch with many experimentalists, and he had an encyclopaedic knowledge of the data. Many of his papers were stimulated by experimental results and were concerned with their analysis and interpretation, work that often required the forging of new phenomenological tools; many also indicated what new experiments needed to be done. As a consequence, he was a theorist exceptionally valued by experimentalists. He created and ran a strong particle theory group at Oxford, which attracted many talented students and researchers, and which has continued to thrive.

Family background and early years

Dick was born in Dimboola, a small town in western Victoria, Australia. His grandfather Heinrich had a smallholding near the town, but his main income was as a stonemason. He and his wife, Anna, had a large family of ten boys and three girls; the boys had little schooling and had to go out to work as soon as possible. Dick’s father, Friedrich Wilhelm, was the eldest boy; he took work as a blacksmith in Dimboola. There he married Dick’s mother, Hazel Drummond, who was a schoolteacher in the town, and was of Scottish descent.
Heinrich had been born in 1861, soon after his parents arrived in Australia. As the family had emigrated from Germany, it was generally assumed that they were originally Germans, but the name was an unusual one, and Dick was sceptical. However, it was not until after he settled in Oxford in 1963 that he found proof that they were descended from pre-German inhabitants of what later became Brandenburg, who were known as Wends, or Sorbs. With characteristic thoroughness, and with the help and encouragement of Gerald Stone, then of Nottingham University, Dick eventually identified the exact village and found his forbears listed in the parish records. He was able to trace, and then to meet in Australia, many other Sorbian families who had settled in Dimboola and elsewhere in the Wimmera district.

With Hazel’s support, Dick’s father passed examinations and became a government clerk in Melbourne, where Dick was educated. Dick won the first of many scholarships to attend Scotch College for the last four years of his secondary schooling. There major influences on him were Mr A. D. Ross, Senior Mathematics Master, and Mr Kaye, the Senior Physics Master. Dick graduated from Scotch College in 1941, with many prizes and scholarships, including the Ormond Exhibition in Mathematics at Ormond College, Melbourne University. He became a physics and mathematics student at the university, living at home. He profited from the teaching of Sir Thomas Cherry (FRS 1954), in mathematical analysis and the theory of functions; his interest in theoretical physics was first aroused by Dr H. C. Corben, then lecturer in mathematics and physics at Melbourne. During the summers of 1944–45 and 1945–46 Dick conducted research on the flow of compressible fluids under the guidance of Professor Cherry, as described in (1)*.

**EARLY CONTRIBUTIONS AND DALITZ PAIRS**

In 1946 Dick left Melbourne for Trinity College, Cambridge, supported by a travelling scholarship from the University of Melbourne, and accompanied by his wife, Valda (née Suiter); they had been married at Scotch College Chapel on 9 August 1946. During 1946–48 Dick worked towards his Cambridge DPhil under the supervision of Nicholas Kemmer (FRS 1956), on problems of nuclear physics and electrodynamics. By the end of the two years the money had run out and the couple had a young child, so in 1948 Dick took up a one-year post as a research assistant in the H. H. Wills Physical Laboratory at the University of Bristol, where he enjoyed close contact with the cosmic ray group of Cecil Powell (FRS 1949). Then in 1949 Dick joined the Department of Mathematical Physics at the University of Birmingham under Rudolf (later Sir Rudolf) Peierls FRS, where he would spend the next four, very formative, years.

He submitted his Cambridge thesis entitled ‘Zero-zero transitions in nuclei’ on 13 December 1950. It concerned primarily the transition from the first excited $0^+$ state of $^{16}$O at 6.05 MeV to the $0^+$ ground state. Conservation of angular momentum prevents the transition from proceeding by the emission of a single photon, but it is allowed for a longitudinally polarized virtual photon that converts to an electron–positron pair. Motivated by experiments of Samuel Devons (FRS 1955) and others (Devons & Lindsey 1949; Devons et al. 1949), the thesis described the calculation of radiative corrections to angular correlations in such an internal pair-creation process. The techniques for higher-order calculations in quantum electrodynamics had only recently been developed in the independent work of Sin-Itiro Tomonaga, Julian Schwinger and Richard Feynman (ForMemRS 1965). Their different

* Numbers in this form refer to the bibliography at the end of the text.
formalisms had been remarkably synthesized by Freeman Dyson (FRS 1952) in 1949, who spent the years 1949–51 as a Teaching Fellow in Peierls’s department. At the end of the paper (2) describing the main results of his Cambridge thesis, Dick wrote that he ‘would like to acknowledge here his debt to the lectures [on quantum field theory and electrodynamics] of Mr. F. J. Dyson and to thank Professor R. E. Peierls for his continual interest in this work’. Both Dyson and Peierls, especially the latter, would exert a strong influence on Dick.

This work on internal pair creation bore fruit in the first of Dick’s seminal contributions to particle physics—the realization that $e^+e^−$ pairs (‘Dalitz pairs’) can be produced in the decays of neutral $\pi$-mesons (3). At the 1987 Bristol Meeting to celebrate 40 years of particle physics (50) Dick recalled how, on a weekend visit to Bristol in early 1951 to visit ‘old friends on the fourth floor’ (i.e. Powell’s group), they showed him some of the emulsion events they were working on, after which

they said ‘Here are two peculiar pairs’. In each of these cases, the outgoing pair of tracks were clearly identified as electronic. What was peculiar about them was that the origin of each pair could not be seen as separate from the centre of the cosmic ray star from which it emerged. What could give rise to these two pairs? On my way back to Birmingham, I suddenly realized that the $\pi^0$ itself could give rise to them by a direct decay to $\gamma e^+e^−$, through the process of internal pair conversion of one of its product photons,

$$
\pi^0 \rightarrow \gamma + \gamma' \rightarrow \gamma + e^+e^-.
$$

His thesis work was now relevant, because his calculations had shown (2) that the internal pair creation rate in that $0 \rightarrow 0$ transition in $^{16}\text{O}$ depended very little on the nuclear charge, and was certainly non-zero for $Z = 0$. ‘So’, he recalled (50), ‘I calculated the rate for the internal conversion of one of the $\gamma$-rays in $\pi^0 \rightarrow \gamma\gamma$ decay for a free $\pi^0$.

Dick obtained (3) a branching ratio of 1.185% for this $\pi^0$ decay mode, later increased to 1.195% by radiative corrections (Joseph 1960); today’s value is $(1.198 \pm 0.032)\%$. At that time the Bristol group was reluctant to claim discovery of the mode from their two events; it was established a year or so later (Daniel et al. 1952).

Dalitz pairs became a useful tool in particle physics. For example, the decay $\Sigma^0 \rightarrow \Lambda^0 + e^+e^-$, in which the photon in the decay $\Sigma^0 \rightarrow \Lambda^0 + \gamma$ converts to a pair, was used to establish that the $\Sigma^0$ and $\Lambda^0$ have the same parity. In another example, Dick’s work on the single conversion in $\pi^0$ decays was extended by N. N. Kroll and W. Wada to the double-Dalitz process $\pi^0 \rightarrow e^+e^-e^+e^-$ (Kroll & Wada 1955). Their analysis was used by Plano et al. (1959) to establish that the parity of the $\pi^0$ was odd, the same as that of the charged pions.

**The $\tau$–$\theta$ puzzle and the Dalitz plot**

Dick’s analysis of $\tau^+$-meson* decays led to a revolution in particle physics, and secured his place in the first rank of particle theorists.

His interest in strange particles had begun during the year 1948–49 at Bristol. He became well informed about the discoveries being made by Powell’s group, and he continued to follow their work after moving to Birmingham. Data on the ‘new’ (i.e. strange) particles accumulated slowly, and in 1953 Powell organized a Royal Society Discussion Meeting, held on 29 January 1953, to review the available evidence. By then 11 events of the type

* Subsequently identified as the charged strange meson $K^+$.  

* Subsequently identified as the charged strange meson K⁺.
were known, and as Dick later recalled (46), ‘the time was ripe to give some serious consideration to their characteristics’. The result of this consideration was first reported at the International Cosmic Ray Conference held on 6–12 July at Bagnères-de-Bigorre in the Basque country on the northern slopes of the Pyrenees.

This conference, organized by Patrick (later Lord) Blackett FRS (PRS 1965–70) and Louis Leprince-Ringuet, was a watershed in particle physics. Dick himself felt (46) that it ‘was a major event in the lives of all the physicists who took part in it’. The historical account of it by James Cronin (ForMemRS 2007) is entitled ‘The 1953 Cosmic Ray Conference at Bagnères-de-Bigorre: the birth of sub-atomic physics’ (Cronin 2011), and he places it in the same category as the 1927 Solvay Conference and the 1947 Shelter Island Conference. It marks the moment when, in particle physics research, cosmic ray studies gave way to experiments at accelerators.*

Two contributions to the conference were particularly noteworthy. The first was given by Robert Thompson of Indiana University. He presented measurements of the decay of the ‘heavy meson’ $\theta^0 \rightarrow \pi^+\pi^-$ observed in a precision cloud chamber (Thompson et al. 1953). The mass of the $\theta^0$ was $971 \pm 10$ electron masses ($m_e$). Because the pions were known to be spinless, the parity of the $\theta^0$ was necessarily $(-)^J$, where $J$ is the spin of the $\theta^0$, which is carried away as angular momentum by the two pions.

The second was Dick’s contribution, which was concerned with the analysis of the $\tau^+$ decay process in terms of its spin-parity, and on which he had started to work in Birmingham after the Royal Society Discussion Meeting. The $\tau^+$ was by then well established, with a mass of $970 \pm 5$ $m_e$. His talk was a brief summary of the main results obtained in the paper that he had sent to the journal (received 1 July 1953) before leaving for the conference (4). As he later recalled (46):

It was my opinion that the amplitude for the [$\tau^+$] decay mode should be largely calculable in form (although not in magnitude) in terms of angular momentum barrier considerations, apart from a few parameters necessary when the total angular momentum and parity could be apportioned to the internal orbital motions within the three-particle system in more than one comparable way. If so, it would then be possible to deduce the values of these internal angular momenta from the distribution of events and from them to reach some conclusions about the total spin-parity [of the $\tau$-meson], at least to exclude some possibilities. First, a representation was needed to display the distribution of events pictorially.

That representation was, of course, the first Dalitz plot. To appreciate its construction, some kinematics have to be introduced.

The decay may first be considered in the centre-of-mass system of the two like pions (labelled 1 and 2 in figure 1), where the unlike pion (labelled 3) has momentum $\mathbf{p}$ and the like pions have momenta $\pm \mathbf{q}$. The magnitudes $p$ and $q$ of $\mathbf{p}$ and $\mathbf{q}$ are related by the conditions of energy and momentum conservation; $\ell$ is the angular momentum of the like pions and $L$ is that of the unlike pion.

It is also convenient to treat the decay in the rest frame of the $\tau^+$-meson. The three outgoing pions then have zero total momentum and total kinetic energy $E = m_\tau - 3m_\pi$. Apart from the spatial orientation, the specification of the decay configuration requires two

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* The proceedings of the conference were not formally published, and existed only in mimeographed form available to the participants. However, the contributions may now be found online; Dick’s is at http://inspirehep.net/record/1344834/files/Rayonnement-236-238.pdf.
parameters, for example the kinetic energies of two of the pions, say $\epsilon_1$ and $\epsilon_2$. At that time (July 1953) the data were not able to distinguish the charges of the outgoing mesons, and so Dick adopted a parametrization that was symmetrical between the three pions: namely, he retained all three kinetic energies $\epsilon_i$, subject to the constraint $\epsilon_1 + \epsilon_2 + \epsilon_3 = E$. Then, referring to figure 2, an event corresponding to the kinetic energies $\epsilon_i$ may be specified by a point $P$ in the interior of an equilateral triangle $YUV$ of height $E$, such that the perpendiculars (PL, PM, PN) from $P$ onto the three sides of the triangle are of length $\epsilon_i$ (the sum of these three perpendiculars being equal to the height of the triangle). Interchange of any two energies $\epsilon_i$ corresponds to reflection of $P$ in a corresponding altitude of the triangle so that, because no charge information was available, the event is represented in each of the six sub-triangles of $YUV$. The distribution in any sub-triangle is obtainable from that in $AOV$ by successive reflections in the altitudes, and so only that ordering of the energies for which $P$ lies in $AOV$ need be considered.

However, the full interior of the triangle is not kinematically available. To find the allowed region, Dick at this point moved to a non-relativistic description, for which the error is at most a few percent. Then one finds (4) that the boundary of the physical region may be written as

\[ E_{\text{boundary}}(\epsilon_1, \epsilon_2, \epsilon_3) = \epsilon_1 + \epsilon_2 + \epsilon_3 = E. \]
\[ x^2 + y^2 = \frac{1}{3}E^2, \text{ where } x = (\epsilon_1 - \epsilon_2)/\sqrt{3}, \ y = \epsilon_3 - \frac{1}{3}E. \] This is the circle inscribed in the triangle of figure 2, having radius \( \frac{1}{3}E \). All the events must fall inside this circle. Plotting the events on this diagram results in the ‘Dalitz plot’.

The crucial property of such a plot is that the distribution of events on the plot is proportional to the square of the matrix element for the decay. This follows from the fundamental fact that the density of states, up to numerical factors, is

\[ \delta(\epsilon_1 + \epsilon_2 + \epsilon_3 - E) \, d\epsilon_1 d\epsilon_2 d\epsilon_3 = \frac{1}{2\sqrt{3}} \, dx \, dy, \]

so that variation in the density of events on the plot is a direct consequence of non-trivial structure in the decay matrix element†. It was a brilliant construction, allowing the events themselves to reveal the physics of the decay. It perfectly united Dick’s fondness for geometry and the primacy he always accorded to the data.

The key question was whether the \( 0^0 \)-particle and the \( \tau \)-particle could be closely related, in view of the near equality of their masses. In particular, could the \( \tau^+ \) have parity \((-)^L\), as was necessarily the case for the \( 0^0 \)? The matrix element for the \( \tau \) decay could be expanded in a series of products \( Y_{LM} (\theta_p, \phi_p) Y_{LM} (\theta_q, \phi_q) \) (see figure 1). Bose statistics for the like pions requires \( \ell \) to be even, so that the \( \tau \) parity is \((-)^{L+1}\). Dick now argued that, given the small energy release, angular momentum barrier considerations would limit \( L \) and \( \ell \) to low values. If the parity of \( \tau \) were even, then \( L = 1 \) would be the most likely value. This would produce a factor \( p^2 \) in the squared matrix element, which is proportional to \( \epsilon_3 \), and vanishes at the point \( C \) on figure 2, or at \( A \) in the folded plot of figure 3. More generally, when the \( \pi^- \) is stationary (at \( C \)) \( J \) is carried by the two \( \pi^-\)-mesons, and must be even by Bose statistics. Hence the density of events must vanish near \( C \) (or \( A \)) unless \( J^\rho \) is \( 0^-, 2^-, 4^-, \ldots \). A uniform distribution of events would signal \( J = 0 \) and odd parity.

The data he showed at Bagnères-de-Bigorre (figure 3) were too sparse to draw a firm conclusion, but Dick allowed himself the statement that ‘The data available at present … offers no significant evidence for any lack of isotropy in the decay process’ (4).

* Dick actually rescaled the variables to produce a circle of unit radius.
† Dick himself referred to his plot as ‘the usual phase-space diagram’.
The analysis of (4) had, however, provided the predicted energy distributions for the unlike pion for spin-parity combinations $0^-, 1^\pm, 2^+$ and $3^-$, which were generally more sharply distinguishable than the corresponding predictions for the charge-averaged case. For example, the amplitudes for natural parities ($-\gamma^J$) must all contain an axial vector factor $p \times q$, whose square vanishes on the boundary of the plot. By January 1954, 13 $\tau^-$ events with mostly identified charges could be placed on the full plot, as shown in figure 4, taken from Dick’s 1954 paper in *Physical Review* (5) (the plot is symmetrical about the axis DC as a result of the symmetry of the two $\pi^+$-mesons). By this time, Dick was at Cornell, where he moved in September 1953 on a two-year leave of absence from Birmingham, having been invited by Hans Bethe (ForMemRS 1957).

There was certainly no dearth of events near the point C (slow $\pi^-$), but Dick’s conclusion was still cautious: ‘the number of $\tau$-decay events giving a slow unlike $\pi$-meson rather suggests that the least $L$ is $L = 0$, which would imply that the $\tau$ meson belongs to the class of even $[J]$ and odd $[P]$, a class for which [if $P$ is conserved] the $2\pi$ decay is forbidden’. Two weeks after Dick’s paper was received (on 9 February 1954), Fabri (1954) submitted a paper that gave a formal derivation of the decay amplitudes for the spin-parity combinations $0^-, 1^\pm, 2^+$ and $3^-$, and extended the kinematics to the relativistic case.

Thus by early 1954 there was already emerging a ‘$\tau$–$\theta$ puzzle’: the near equality of the masses suggested that they were simply different decay modes of a common particle (in different charge states), but that could not be the case, it seemed, because the parities were different. The puzzle came into sharper focus at the Pisa Conference the following year, when Edouardo Amaldi presented a report on $\tau$ decays based on 106 events, reaching the quite firm conclusion that the spin-parity of the $3\pi$ state from $\tau$ decay was most probably $0^-$. One resolution of the puzzle, raised at the time by Dick himself and others, was to suppose that the $0^+$ and $\tau^+$ were indeed different charge states of the same particle (i.e. a charge doublet ($K^0, K^+$)), but that parity was not conserved in their decays. This would imply a failure
of invariance with respect to space reflections. However, as he recalled at the 1982 Paris Colloquium (46):

How was it possible that reflection invariance should not hold, people asked—was not left–right invariance inherent in our most fundamental conceptions about space-time? The only answer available was that the occurrence of both $K \rightarrow 2\pi$ and $K \rightarrow 3\pi$ decays actually did demonstrate this, but this answer did not have compelling force because it could not point to any explicit empirical demonstration of parity failure. ... It required much less faith to suppose that ... there existed two distinct K-meson charge doublets, labelled $\tau$ and $\theta$, close in mass but with different spin-parities. ... The mental obstacle [to accepting the parity violation explanation] arose from the fact that the $\tau$–$\theta$ puzzle did not provide an explicit demonstration of parity nonconservation.

By this twice-repeated lack of ‘explicit demonstration’ of the failure of reflection invariance Dick meant some observable effect, the existence of which would unequivocally show that this symmetry did indeed fail. In fact, he himself came very close to predicting just such an effect. As he recalled in (59), the $K \rightarrow 2\pi$ and $K \rightarrow 3\pi$ amplitudes can interfere if they both contribute virtually to a process leading to a common final state—and such interfering amplitudes will have opposite parities. One such example is the pair of amplitudes for the processes $\Lambda \rightarrow n + K^0 \rightarrow n + \pi^- + \pi^+ \rightarrow \pi^- + p$ and $\Lambda \rightarrow p + K^- \rightarrow p + \pi^- + \pi^+ + \pi^- \rightarrow \pi^- + p$. Dick thought of making a calculation of these processes in 1955 (59): it would have shown that a parity violation effect would be expected in the decay of polarized $\Lambda$-particles. But there were major theoretical uncertainties, and the effect was (mistakenly) thought likely to be small. So he did not complete the calculation.

It was, as Dick acknowledged (46, 59), the genius of Tsung Dao Lee and Chen Ning Yang (Lee & Yang 1956) to relate the question of possible parity violation in K-meson decays with the whole class of weak interactions, so that the first empirical demonstrations of parity non-conservation were not carried out with strange particles but in nuclear $\beta$ decay and in $\pi$–$\mu$–$e$ decay. Nevertheless, it was Dick’s analysis of $\tau$ decay that had led to this momentous discovery.

The discovery of parity (P) violation was soon followed by that of charge-conjugation (C) violation, and later of CP violation. Dick always maintained a strong interest in these discrete symmetries. Frank von Hippel and Dick discussed the implications of electromagnetic $\Lambda$–$\Sigma^0$ mixing for charge symmetry in $\Lambda$ physics (22); and in 1986 Neil Tanner and Dick (49) drew attention to the possibilities afforded by the antiproton beam of LEAR for new measurements concerning $T$, CP- and CPT-violation parameters in the $K^0$–$\bar{K}^0$ system.

In his first paper on the plot (4) Dick had shown how it could not only reveal the spin-parity of the decaying state but also provide information about strong pairwise interactions in the final state. Both properties made the plot a powerful tool in the exploration of the hadronic resonance spectrum in the 1960s and 1970s. The energies $\epsilon_i$ remained suitable relativistic variables, the only new feature being that the shape of the plot was no longer circular, even in the equal-mass case. An important early application was to the $\omega$-meson, which decays to three pions; the density of events on the plot clearly vanished at the boundary, hence establishing $J^P = 1^-$ for the $\omega$ (Maglić et al. 1961; Stevenson et al. 1962). Resonance states involving pairs of final-state particles could be immediately identified as concentrations of events (bands) near lines of constant $\epsilon_i$. This was particularly relevant in cases where the mass of the resonance was such that it could not be directly formed in a ‘beam plus target’ channel. An early example was the strangeness $-1$ baryon $Y^*(1385)$ (now called $\Sigma(1385)$), whose mass, 1385 MeV, is below that of the $K^-p$ system. This was discovered in a
hydrogen bubble chamber at the Berkeley Bevatron by a Dalitz plot analysis of the reaction $K^- p \rightarrow \Lambda^0 + \pi^+ + \pi^-$ (Alston et al. 1960). The strangeness $-2$ baryon $\Xi^*(1530)$ (which also can only be seen in final states) followed soon after, via the reaction $K^- p \rightarrow \Xi^- + K^+ + \pi^0$ (Pjerrou et al. 1962; Schlein et al. 1963).

As the data improved, Dalitz plots found an important new application. By exploiting the interference between different resonance bands, it proved possible to extract information about the phases of production amplitudes. Originally pioneered in the context of (inelastic) nucleon resonances (Herndon et al. 1975a, b), the technique has more recently been successfully applied to measure CP-violating phases (del Amo Sanchez et al. 2010a; Poluektov et al. 2010) and $D^0$–$\bar{D}^0$ mixing parameters (Zhang et al. 2007; del Amo Sanchez et al. 2010b). Dalitz plots produced from the B-factories now contain upwards of $10^5$ events—some distance from the original 13! Dick’s beautiful ‘pictorial representation’ is certain to remain an indispensable tool in particle physics.

**Y–N, Y–Y INTERACTIONS AND HYPERNUCLEAR PHYSICS**

Dick returned to Birmingham as Reader in Mathematical Physics in 1955, and then moved to the University of Chicago in 1956, where he was based for the next seven years. Enrico Fermi had died in 1954, and as Dick recalled in an interview he gave in 2003 (O’Byrne 2004), several leading theoretical physicists had left Chicago, providing a ‘tremendous opportunity—to build up groups again and get things going’. It was in Chicago that his interest in hypernuclear events developed particularly well … because a young emulsion experimenter, Riccardo Levi-Setti, whose work I had known from his hypernuclear studies in Milan, came to the [Enrico Fermi] Institute for Nuclear Studies at this time. We benefited from each other, I think, and we got quite a lot done.

Dick worked on the physics of strange particles throughout his career. Of some 220 main publications listed in the bibliography (see the electronic supplementary material), almost one-half broadly involve strange particles; nearly one-third relate more specifically to hypernuclei, a field he pioneered and in which he was a recognized leader for 50 years.

The observation of the first hyperfragment event, in a balloon-flown photographic emulsion, was announced in Warsaw by Marian Danysz and Jerzy Pniewski (Danysz & Pniewski 1953). Subsequently, the light s-shell hypernuclei $\Lambda^+_3 H$, $\Lambda^+_4 H$, $\Lambda^+_4 He$ and $\Lambda^+_5 He$ were analysed by Dick and collaborators. In Dick’s first published work on $\Lambda$ hypernuclei, he focused on the near equality of the ($\Lambda^+_4 H$, $\Lambda^+_4 He$) binding energy and its origin in the charge symmetry of the $\Lambda$–N interaction; he also noted the very small binding energy of the $I = 0$ $\Lambda^+_3 H$, the only bound $A = 3$ hypernucleus (6). By 1958–59 Dalitz and B. W. Downs reported that the existence of a bound $\Lambda$–N system was strongly excluded and that analysis of the $I = 1$ triplet $\Lambda^+_3 He$, $\Lambda^+_3 H$, $\Lambda^+_3 n$ indicated that these systems were not expected to form bound states, a conclusion unaffected by the existence of moderately strong three-body forces arising from pion exchange processes (8, 9, 11).

Soon after the discovery of parity violation, Dick initiated the theory of mesonic weak decay of hypernuclei. He realized that the two-body decays $\Lambda^+_3 H \rightarrow 4 He + \pi^-$ and $\Lambda^+_3 H \rightarrow 3 He + \pi^-$, then being studied in photographic emulsions, could be used to extract the parent hypernuclear ground-state spins and parities, and hence provide information about the spin dependence of the $\Lambda$–N force (10). An improved calculation by Dalitz and Liu (12) provided a plot of the branching ratio $(\Lambda^+_3 H \rightarrow 4 He + \pi^-)/(all \pi^- decays of \Lambda^+_3 H)$ for the possible
ground-state spins \( J = 0 \) and \( J = 1 \), as a function of the relative amounts of \( s \)-wave (parity-violating) and \( p \)-wave (parity-conserving) amplitude in the elementary decay \( \Lambda \rightarrow p\pi^- \). The data at that time were not able to establish the value of \( J \), but within a few years this type of analysis yielded the \( J^P \) assignments for \( ^3\Lambda\text{H}, ^4\Lambda\text{H}, ^4\Lambda\text{He}, ^8\text{Li}, ^{11}\text{B} \) and \( ^{12}\text{B} \) (Block et al. 1964; Bertrand et al. 1970; Ziemińska 1975). In particular, the ground-state spins 0\(^+\) for \( ^4\Lambda\text{H} \) and 1–2\(^+\) for \( ^3\Lambda\text{H} \) showed that the \( s \)-wave \( \Lambda-N \) interaction was more attractive in the singlet state than in the triplet state.

The complete spin dependence of the \( \Lambda-N \) interaction can be obtained from the energy spacings of the \( J = J_c \pm 1 \) spin doublets in \( \Lambda \)-hypernuclei, where the hyperon in the \( s \) shell couples to a ground-state nuclear core with non-zero spin \( J_c \). Together with Avraham Gal and John Soper, Dick introduced shell-model techniques to predict the anticipated \( \gamma \)-ray transitions (29, 30, 39, 40). The effective \( \Lambda-N \) interaction contains spin–spin, spin–orbit and tensor terms, in addition to a spin-independent term. This work was further developed with Gal, John Millener and Carl Dover (48) and served as the basis for the interpretation of \( \gamma \)-ray spectroscopy experiments, which began in 1998 at the High Energy Accelerator Research Organization (KEK) in Japan and at Brookhaven National Laboratory in New York, and continued with systematic programmes at both laboratories (Hashimoto & Tamura 2006). The spin dependence of the effective \( \Lambda-N \) interaction is now rather well understood.

In addition to the mesonic modes, hypernuclear ground states also decay by non-mesonic weak decay (NMWD) modes of the type \( \Lambda n \rightarrow nn \) or \( \Lambda p \rightarrow np \). This is a four-fermion, \( \Delta S = 1 \), baryon–baryon weak interaction, and is the only practical way to obtain information on the weak process \( \Lambda N \rightarrow nN \). In particular, NMWD processes offer new systems for exploring the still incompletely understood \( \Delta I = 1/2 \) rule. Once again, it was Dick who led the way in the analysis of these decays. With G. Rajasekharan he proposed a simple but very effective phenomenological model (17), in which the non-mesonic rates \( \Gamma_{\text{NM}}(\Lambda Z) \) were expressed as linear combinations of rates \( \Gamma_{\text{N}}(\Lambda Z) \) for the elementary \( \Lambda N \rightarrow nN \) interactions, where \( N = n, p \) and \( J = 0, 1 \). The four \( s \)-shell hypernuclei \( ^3\Lambda\text{H}, ^4\Lambda\text{H}, ^4\Lambda\text{He} \) and \( ^5\Lambda\text{He} \) were considered. Thus, for example,

\[
\Gamma_{\text{NM}}(^3\Lambda\text{H}) = \frac{1}{3}(3R_{n0} + R_{n1} + 3R_{p0} + R_{p1})\rho_3,
\]

where \( \rho_3 \) is the average \( A = 3 \) nucleon density at the position of the \( \Lambda \) baryon. This model was then used by Dick and Martin Block (19) to determine the rates \( \Gamma_{\text{N}}(\Lambda Z) \) from data recently obtained by Block et al. (1964). One interesting relation, which can be tested experimentally in principle, follows from assuming the validity of the \( \Delta I = 1/2 \) rule: \( R_{n0}/R_{p0} = 2 \). The early data were such that no definite conclusion could be drawn about the \( \Delta I = 1/2 \) rule. Indeed, even according to a much more recent analysis (Alberico & Garbarino 2000), using the phenomenological Dalitz–Rajasekharan–Block model, a pure \( \Delta I = 1 \) rule could be excluded only at the 40% confidence level.

A final example of Dick’s early and continuing pivotal role in this field concerns \( \Lambda \Lambda \) double hypernuclei. The first such double hypernucleus, an example of \( ^{10}_{\Lambda\Lambda}\text{Be} \), was announced by the Warsaw group in 1962 (Danysz et al. 1963a, b), and Dick was among the first to extract information about the \( \Lambda-\Lambda \) interaction from it (20). A second event, an example of \( ^6_{\Lambda\Lambda}\text{He} \), was reported by D. J. Prowse in 1966 (Prowse 1966). Then, in 1977, Bob Jaffe predicted (Jaffe 1977) the existence of the H-particle, a deeply bound (by perhaps 80 MeV) six-quark system with the quark content of two \( \Lambda \) hyperons. The existence of such an H-particle would bring into question the existence of double hypernuclei stable against all except weak interactions,
because a strong decay of the type $^6_{\Lambda\Lambda}\text{He} \rightarrow ^4\text{He} + \text{H}$ would be possible, given the much weaker binding of the two $\Lambda$s in the hypernucleus. At Dick’s prompting, the evidence for the two double hypernuclei was re-examined (53). An independent analysis of unpublished photomicrographs taken of the event by Peter Fowler (FRS 1964) in Bristol some 25 years earlier confirmed the interpretation of the $^{10}_{\Lambda\Lambda}\text{Be}$ event, but the $^6_{\Lambda\Lambda}\text{He}$ event seemed less secure; furthermore, the binding energies in the two cases were in some considerable disagreement. In 2001 the issue was resolved by the discovery of a tightly constrained $^6_{\Lambda\Lambda}\text{He}$ event with a net binding energy of about 1 MeV (Takahashi et al. 2001); this implied that the $\Lambda–\Lambda$ interaction is weakly attractive.

Personal accounts of Dick’s career-long involvement with hypernuclear physics have been given by Don Davis (Davis 2008) and Avraham Gal (Gal 2008).

### K–N INTERACTIONS AND THE K-MATRIX

Notwithstanding his attachment to hypernuclear physics, Dick was primarily a particle physicist, and a constant aim of his research was the traditional one of establishing the properties of the various states, and the nature of the forces between them. In the mid 1950s, theoretical attention was mostly focused on the interactions of pions and nucleons. Never one to follow fashion, Dick turned to the study of the strong interactions of strange particles, in the course of which he developed new and lasting phenomenological tools.

An early and very influential series of papers was concerned with low-energy $\bar{K}$N interactions. In 1959 Dick and San Fu Tuan (13) analysed the available data, using as parameters two complex $\bar{K}$N scattering lengths in the isospin 0 and 1 channels, as was then conventional. They found one solution set (‘$b$’) in which the real part of the $I=0$ scattering length could indicate binding. They pointed out, for the first time, that in this case the $I=0 \bar{K}–p$ scattering amplitude would have a pole just below threshold, in the (unphysical) lower half-plane of the complex energy variable, reached by analytic continuation from the upper half-plane across the cut lying between the $\pi\Sigma$ and $\bar{K}$N thresholds. This focus on analytic continuation across cuts to look for poles was something quite unfamiliar in hadron phenomenology at the time. The authors noted that the imaginary part of the amplitude would exhibit a pronounced peak below the $\bar{K}$N threshold. They concluded that ‘under certain circumstances, the appearance of this maximum would correspond to the existence of a resonance … in pion–hyperon scattering [i.e. in $\pi\Sigma$] for a closely related energy value’. A note added in proof stated that the situation had ‘now been analysed in greater detail’ in a further publication.

In this second paper (14) (confined for simplicity to the $I=0$ channel) the authors took what would prove to be a very significant step: they introduced a new parametrization based on a two-channel $\bar{K}$-matrix, describing the coupled $\bar{K}$N and $\pi\Sigma$ channels (all in the $s$-wave and $I=0$). This parametrization was fully relativistic; further, Hermiticity of the Hamiltonian, together with time-reversal invariance, implied that $K$ had to be a real symmetric matrix, and any such matrix would guarantee a unitary $T$-matrix. The authors argued that at low energies it would suffice to take the elements of $K$ to be constant, in analogy with the scattering length approximation. Thus three parameters were required, two of which could be related to the (complex) $I=0$ scattering length of the previous fit. The authors noted that the data pointed towards the solution $b_-$ and the resulting pole structure found in (13), which they
now interpreted as corresponding to ‘the existence of a bound state in the $\bar{K}N$ channel’. The situation made it quite possible that there ‘should exist a resonant state for pion–hyperon scattering at an energy of about 30 MeV below the $K^-p$ (c.m.) threshold energy’. This state became known as the $Y^*_{(1405)}$.

There soon followed a fuller description of the approach (15). Although its title still referred specifically to $\bar{K}N$ reactions, it is in fact a classic in the field of general hadron phenomenology. It set out the general $K$-matrix formalism in a relativistic (rather than potential theory) context, as appropriate to the analysis of particle physics experiments. The authors emphasized, in addition to the guarantee of unitarity, the utility of the formalism in dealing with strong inter-channel coupling effects—in particular (in this case) the reaction of the $K^-p$ channel on the $\pi\Sigma$ channel. The formalism provided an economical parametrization, generalizing non-relativistic effective range theory. Detailed consideration was given to both the $I=0$ and $I=1$ $K^-N$ channels: assuming charge independence, six real parameters were required, two more than in the previous fits. Attention was paid to the structure of the cuts in the complex energy plane associated with the branch points at the $\pi\Lambda$, $\pi\Sigma$, $K^-p$, $K^0n$ thresholds. Although the implications of the $b_-$ solution were reiterated, when the paper was submitted it no longer appeared to be favoured by the data.

By the time of the 1961 Aix-en-Provence conference, the situation had changed again, as discussed by Dick in his contribution (18). In Dick’s words, ‘some tentative experimental evidence was presented by Alston et al. (Alston et al. 1961)’, in the reaction $K^-+p \rightarrow \Sigma^+ + \pi^- + \pi^+ + \gamma$ for $K^-$ momentum 1.15 GeV/c. A plot of the invariant mass distribution of the $(\Sigma\pi)\bar{0}$ system showed a concentration of events near a mass of about 1405 MeV, but the sample contained only 32 events. Soon afterwards, Alexander et al. (1962) analysed 189 events of the type $\pi^-p \rightarrow \Sigma^0\pi^-K^0$ at 2.1 GeV/c; examination of the Dalitz plot and its projections showed a prominent enhancement in $M_{\Sigma\pi}$ at 1410 MeV. Later analyses (Thomas et al. 1973; Hemingway 1985) provided even stronger evidence for the state, which is now known as the $\Lambda(1405)$.

It is, perhaps, a measure of Dick’s intuition in selecting this system for study 56 years ago that, although the existence of the $\Lambda(1405)$ is now accepted, its interpretation is still not settled. From the beginning he appreciated the need for a dynamical theory that went beyond the strictly phenomenological $K$-matrix approach. At the time, such a theory of strong interactions was provided by partial wave dispersion relations—specifically the $N/D$ method (Chew & Mandelstam 1960). Here the $N$ function contains the contributions from forces (particle exchanges), and $D$ accounts for unitarity effects. In a more pedagogical follow-up (16) to his paper with Tuan (15), Dick showed how the $K$-matrix could be simply related to $N$ and $D$ (namely $K = N/ReD$ in the single-channel case). Then, with Wong and Rajasekaran (26), he showed that a $\Lambda(1405)$ state could be dynamically generated by an exchange of vector mesons between the meson and baryon fields, lending support to the idea that it was a composite system, somewhat analogous to the deuteron (a bound n–p system).

By then, of course, Dick had become intensely interested in the quark model for hadrons, as we shall discuss shortly. Here the picture of the $\Lambda(1405)$ is apparently very different. Having $J^P = \frac{1}{2}^-$, it would be an $L = 1$ SU(3)-singlet state of u, d and s quarks, coupled to the $s$-wave meson baryon systems. In the hadronic channels, it would be an ‘elementary’, not composite, particle, not generated by hadronic dynamics. But the quark model had difficulty in accounting for the large difference in mass between this state and its spin–orbit partner, the $J^P = \frac{1}{2}^+ \Lambda(1520)$ (Isgur & Karl 1978). On the other hand, a purely hadronic interpretation of the
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\( \Lambda(1405) \) would—according to the quark model—require the existence of a new partner of the \( \Lambda(1520) \) in a region already well explored.

This was a new ‘puzzle’, this time in hadronic physics. Which interpretation was correct? Was the state elementary or composite? Or did the truth lie somewhere between? As it happened, a formal way to insert an elementary particle into the \( N/D \) framework had been discovered by Dick, Leonardo Castillejo and Freeman Dyson in the famous ‘CDD’ paper (7). There is an ambiguity in the \( N/D \) procedure, which allows one or more poles to be added to the \( D \) function without spoiling the solution. Such a pole will give rise to a zero of the amplitude, but depending on the residue it may also lead to a nearby zero of \( \text{Re}D \), which will appear as a resonance in the amplitude. Such a resonance will persist, however weak the forces represented in \( N \), and will hence be interpreted as ‘elementary’.

Dick revisited this puzzle many times (42, 43, 45, 55, 60). From today’s perspective, the answer is most likely to be found from lattice quantum chromodynamics (QCD). Indeed, a recent calculation indicates that the \( \Lambda(1405) \) is a \( \bar{K}N \) molecule (Hall et al. 2015).

Oxford and Quarks

When he was in Birmingham, Dick was strongly influenced by Rudolf (Rudi) Peierls, who (in Dick’s words in the biographical notes he provided for the Royal Society when he became a Fellow in 1960) ‘showed a stimulating enthusiasm for the questions of interest to me and discussions with him showed me a viewpoint towards physics which I found refreshing and novel’. After Peierls accepted the Wykeham Chair in Oxford, which he took up in 1963, he persuaded Dick to join him, as a Royal Society Research Professor and Fellow of All Souls College.

Dick moved to Oxford in 1963 on a trial basis, with the option of returning to Chicago. He brought with him an enormous American convertible, in which he negotiated the narrow English roads. But he eventually exchanged it for a Mini, and he was based in Oxford for the rest of his life, remaining very active after he retired in 1990.

At All Souls he pushed for the creation of a Visiting Fellows scheme, against rival proposals that had already been partly accepted. Since 1966 the scheme has brought some 700 Visiting Fellows to Oxford for between one and three terms, to the great benefit of academic life in the university. Dick and Dennis Sciama (FRS 1982) were active in persuading a series of very distinguished scientists (including, for example, Subrahmanyan Chandrasekhar FRS, John Ellis (FRS 1985) and Claude Shannon (ForMemRS 1991)) to come to Oxford on this scheme. Dick also took an active part in college elections, as a member of the college’s governing body and its Academic Purposes Committee. His quiet presence was appreciated by the other Fellows who were mainly drawn from the arts and humanities, and when he chose to speak in Governing Body meetings his words carried all the more weight for being brief, to the point and authoritative.

When he arrived in Oxford, Dick also took on the role of advisor on theoretical matters at the nearby Rutherford High-Energy Laboratory, as it was then called. Experiments at the laboratory’s Nimrod accelerator and elsewhere were revealing the existence of new resonances in pion–nucleon scattering. Dick’s intense interest in these experiments was greatly valued by the experimentalists, and he was driven to seek an understanding of the emerging hadronic spectra in terms of the quark model. This would be a major focus of his research in Oxford, and of work by others in his group.
The idea of quarks as constituents of hadrons arose from the work of Y. Ne’eman and M. Gell-Mann (ForMemRS 1978), who proposed classifying the known baryons and mesons in the octet $8$ representation of the group SU(3) (Ne’eman 1961; Gell-Mann 1961). This scheme made several successful predictions, and was generally accepted after the discovery in 1964 of the spin $\frac{3}{2}$ $Ω^-$ baryon, with the mass predicted by Gell-Mann, who argued for its existence as the missing member of a decuplet $10$ representation of SU(3).

No physical particles were then assigned to the fundamental (triplet) representation of SU(3). In August 1961 Gell-Mann lectured on the eightfold way, as he called his classification, in the first Tata Institute for Fundamental Research Summer School in Theoretical Particle Physics. Rajasekaran (2006) has reported that during one of his talks, Dick—who was also speaking in the school—repeatedly asked him why he was ignoring the SU(3) triplets, but Gell-Mann evaded the question, which was not picked up by any of the participants.

Stimulated by Serber, Gell-Mann (1964) later found it ‘tempting to try to use unitary triplets as fundamental objects’. These proposed spin $\frac{1}{2}$ objects, which he dubbed quarks, would have non-integral electric charges, and he found it ‘fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities as they would be in the limit of infinite mass)’. He concluded that a search for stable quarks ‘would help to reassure us of the non-existence of real quarks’. Very shortly thereafter, Zweig (1964) independently proposed the existence of quarks (which he called aces) and (in contrast to Gell-Mann) used a model with quarks as constituents (the quark model) to explain many features of the data*.

Those who, like Dick, took the quark model seriously, assumed that, as no quarks had been observed, the lightest quark (which, as pointed out by Gell-Mann, would be stable) had a mass of at least 5 GeV. Hence, although the $π$-meson and K-meson have very different masses (140 and 500 MeV respectively), the binding energies of the quark–antiquark pairs—of which they are composed—would differ by 10% or less. It was therefore reasonable to believe that they have similar wave functions and properties, as implied by SU(3) symmetry. As pointed out by Morpurgo (1965), it was also reasonable to believe—as assumed by quark modellers—that, although very tightly bound, quarks would move non-relativistically inside light mesons and baryons.

Dick first took up the quark model in his 1965 Les Houches summer school lectures (23). After tracing its origin back to the Fermi–Yang model (in which the $π$-meson was regarded as a nucleon–antinucleon bound state) he observed:

these bound state models have never been considered fully respectable … it is not really possible to meet all the objections that can be made to such models from a field-theoretic point of view.

Yet the models are instructive and suggestive, and have at present rather more contact with the experimental data than do the more formal considerations based on group theory.

His lectures provided the first comprehensive, critical overview of the quark model, and became a bible for the relatively few who then took it seriously.

Dick focused particularly on the baryons, which are composed of three spin $\frac{1}{2}$ quarks according to the model. He faced head-on the fact that if quarks obey Fermi statistics (as required by the spin-statistics theorem), then the lowest lying baryons (in the $8$ and $10$ representations of SU(3)) would necessarily have spatially antisymmetric wave functions. He described this as

* In fact, Petermann (1965) was the first to explore the possibility of assigning particles to the triplet representation of SU(3), in a short paper written in French (received on 30 December 1963 but not published until 1965) that passed unnoticed for 50 years.
strange’ and ‘surprising’, as the wave function would have three nodes and would therefore be expected to have high kinetic energy, but ‘perfectly possible … despite many remarks to the contrary in the literature’. He then discussed briefly what inter-quark potentials could produce such a wave function, conceding that we ‘know of no particularly natural mechanism’ that would lead to the necessary features. Next he outlined the possibility, proposed by Greenberg (1964), that quarks obey para-statistics of order 3 and the three-quark wave is anti-symmetric in the extra three-valued variable, which would allow the space wave function to be symmetric—but he did not pursue it ‘in view of the deep additional assumptions which are involved’.

The major new feature of Dick’s Les Houches lectures was his description of the expected spectrum of baryon states in which one of the quarks carries one ($L = 1$) or two ($L = 2$) units of angular momentum. As in the case of the ground state, spin-dependent forces were expected to split these states, whereas spin–orbit coupling would further split the 70 negative parity $L = 1$ states into the supermultiplets shown in figure 5. These levels would in turn be split into 30 isospin multiplets as a consequence of the strange quark’s being heavier than the non-strange quarks. Dick showed that the ten negative-parity baryons then known could all be assigned to one of these states. He also showed that the four positive-parity resonances that were then known fitted the $L = 2$ quark scheme (figure 6). Remarkably, resonances corresponding to all the states in the $L = 1$ and $L = 2$ level schemes first* spelled out by Dick are known today.

The specific assignments that Dick proposed at Les Houches, and subsequently as more resonances were discovered, involved making choices; for example, he assigned the lower-mass pion–nucleon resonance in the $J^P = \frac{3}{2}^-$ channel to the 2P state and the higher to the 4P

* Greenberg (1964) had previously tabulated a large number of states allowed in a three para-quark shell model (some of them, as he pointed out, spurious), including states with the quantum numbers in figures 5 and 6, but ‘postpone[d] assigning the known baryons to multiplets’.
state (anticipating the effect of the colour hyperfine interaction abstracted from quantum chromodynamics a decade later). All his assignments have stood the test of time, except those for the $Y = I = 0$ states, which are subject to large SU(3) mixing (Dick anticipated ‘appreciable distortion’ of the mass values expected for isolated SU(3) multiplets).

Shortly after the Les Houches School, Dick gave an invited talk (24) on resonant states and strong interactions at the 1965 Oxford International Conference on Elementary Particles, which he based on the quark model. Apart from a section on di-baryonic states, his talk mirrored his earlier lectures, albeit with a more detailed discussion of the data. In his conclusions Dick noted that ‘it is remarkable that all of the baryonic resonances known to have negative parity can be accommodated [in the] $L = 1$ configuration’, although he cautioned that ‘it is entirely possible that whatever parallelism is found between the data and the simple quark model might simply reflect the existence of general relationships which would also hold in a more sophisticated and complicated theory of elementary particle stuff’.

This possibility had become much less likely by the time Dick spoke, a year later, as rapporteur on Symmetries and the Strong Interactions (25) at the XIII International Conference on High-Energy Physics in Berkeley, California, when he began his talk by describing three theorems that essentially ruled out any relativistic generalization of the SU(6) symmetry group. The rest of his talk was based on the quark model. He began by reviewing limits on the existence of real quarks set by several searches. After his talk, Dick was asked whether the successes of the model require the existence of real quarks. He replied, ‘my opinion is that, if there do not exist real quarks, this model has no interest’.

Dick again insisted that Fermi statistics require an antisymmetric space wave function for the lowest-lying baryons, while conceding that, although logically possible, this would require dynamics that are ‘not easy to understand’. He also reported the additional problem that (as first found in a model calculation by Mitra & Majumdar (1966)) ‘there is a serious possibility’ that antisymmetry for the baryon space wave function ‘may require a zero in the baryon structure form-factor at quite low momentum transfer’, in contradiction with the data (in fact a zero is almost certainly required although it can be shifted to arbitrarily high momentum transfer by constructing a sufficiently complicated wave function (32)).
Dick’s Berkeley Conference talk, and his work in the following years, was well received by experimentalists, but theorists’ reactions were generally not so warm, although the quark model continued to explain a growing volume of data. First, many found it hard to believe that very strongly bound—and hence presumably strongly interacting—quarks could behave as almost free, independently moving, particles as ‘naively’ assumed. Dick’s response to such objections was that it was better to ‘take [these simple] models seriously as a semi-phenomenological approach, calculating their predictions in detail and pushing forward their comparison with experiment as far as possible, rather than dwell on their shortcomings from the standpoint of theoretical physics today’ (27). In support of this position, which was justified by subsequent developments, he cited initial objections to the nuclear shell model that were later understood to be invalid.

Second, an antisymmetric ground-state space wave function, on which Dick initially insisted, was generally considered highly implausible or impossible. Some thought this ruled out the quark model. Others believed that the difficulty was removed in ways already proposed (e.g. by assuming anti-symmetry in a new three-valued variable), or hoped that it would be resolved by a new idea. In fact already in 1967 Dick (28) assumed ‘without comment’ that three-quark wave functions for baryons should be totally symmetric in the labels of the three quarks, before noting the conflict with the spin statistics theorem, and describing para-statistics and the three triplet model of Han & Nambu (1965) as possible ways out of the dilemma. He pointed out, however, that in both cases it could not be assumed (as tacitly done in the literature) that all low-lying states would have the same permutation symmetry as the ground state, so additional states could exist.

Between 1965 and his first peer-reviewed paper on quarks in 1973, Dick reported mounting evidence for the quark model in 14 more summer school lectures and conference talks. This period witnessed a growing interest in quarks in the ‘Dalitz group’ in Oxford. At first he did not ask his students to work on quarks but some did so anyway. In 1967 one of us (C.Ll.S.) developed a relativistic quark model for mesons after asking Dick why the so-called Weisskopf–Van-Royen paradox had not led him to abandon quarks, and receiving the answer that he would do so if someone could derive the paradox in a relativistic framework; C.Ll.S.’s later pioneering applications of the quark–parton model to deep inelastic neutrino scattering played a role in convincing sceptics of the ‘reality’ of quarks and gluons.

In 1969 three visitors to Oxford (L. Copley, G. Karl and E. Obryk) successfully applied the quark model to photo-excitation of the $L = 0$, spin $\frac{1}{2}$ ($\Lambda$), and $L = 1$ and $L = 2$ states of the nucleon (Copley et al. 1969a, b). Many years later Karl, with Isgur (a frequent visitor to Oxford), provided a very successful description of the spectrum of $p$-wave baryons by using the inter-quark spin–spin and spin–tensor potential given by the QCD Fermi–Breit Hamiltonian (Isgur & Karl 1978). In his thesis on the separation of the centre of mass and internal motions in composite systems, F. Close (a Dalitz student from 1968 to 1970) applied his results to quarks, without any prompting from Dick. In 1972, while at Stanford Linear Accelerator Center (SLAC), Close and Gilman extended the work of Copley et al. to electro-production and successfully explained variations with momentum transfer that could hardly be attributed to some abstract symmetry (Close & Gilman 1972). In 1981, in one of his last papers (43) on light quarks (to which, without any prompting, he added Close’s name), Dick combined results in Close’s thesis with ideas derived from QCD to cast light on attempts to understand the quark–quark spin–orbit coupling in $p$-wave baryons.
In the early 1970s working on the quark model became increasingly ‘politically acceptable’ for various reasons: its continuing to describe all new data; Feynman’s authorship with Kislinger and Ravndal (Feynman et al. 1971) of a paper on quarks, partly inspired by the work of Copley et al.; having revealed in 1968 that nucleons contain charged point-like constituents, deep inelastic electron scattering data from SLAC showed in 1969 that they have spin $\frac{1}{2}$, and increasingly suggested that they are quarks, as complementary neutrino data from CERN made clear in 1973; recognition that—as described below—the colour quantum number resolved the statistics problem, while QCD and the discovery that it is asymptotically free provided a framework in which it can be convincingly argued (if not rigorously proved) that only colour singlets should exist as free particles, whereas quarks should be forever confined.

Dick’s first paper on quarks in a refereed journal (31), written with his student R. Horgan (whose name he put first), set out a formalism for constructing three quark states in a shell model, extending and generalizing earlier work by Greenberg and others. This is the first of Dick’s papers that employed explicit wave functions, which were assumed to be symmetric under interchange of the quark labels. A lecture later that year on this work (32), and on Horgan’s use of it to fit all the then known data (Horgan 1974), began by addressing the statistics problem. After describing para-statistics and the Han–Nambu model, Dick discussed the three-valued colour variable proposed by Gell-Mann (1972), in which the wave function can also be anti-symmetrized. He then expressed concern that, without additional dynamical assumptions, all three of these possibilities imply the existence of additional unobserved states, a problem finessed by Gell-Mann who proposed that—for a yet to be identified reason—only colour singlet states are allowed (in which case, with a corresponding assumption, order 3 para-statistics and colour make identical spectroscopic predictions).

Dick then reported that Lipkin (1973) had recently proposed that the inter-quark potential is generated by the exchange of an octet of coloured gluons; Fritzsch & Gell-Mann (1973) had noted this possibility earlier, attributing it to J. Wess. Lipkin observed that such a potential could promote all coloured states to high masses. A year later, Dick (35) pronounced himself fully satisfied with this solution, while still referring to Lipkin—although by then a relativistic field theory (QCD) that embodied his idea had been proposed (Fritzsch et al. 1973) and meanwhile non-Abelian gauge theories such as QCD had been shown to be asymptotically free (Gross & Wilczek 1973; Politzer 1973).

In a 1977 paper (36) with M. Jones (a visitor, who was listed as first author), Dalitz and Horgan used their earlier results to analyse the latest data. This paper and Horgan (1974) are today still the standard references for the classification of baryons expected in experiment and their masses. Dalitz and Horgan, with a postdoctoral visitor Reinders (37), went on to apply the model to $L = 3$ states.

Through the 1970s and into the 1980s Dick continued to present reviews of the successes of the quark model accompanied by meticulous comparisons of its predictions with the data, taking account of the latest experimental and theoretical developments. He discussed the spectroscopy of charmed particles (34), before they had been discovered, and of the $J/\psi$ family (38), and in (44) and (47) the implications of QCD for hadronic spectroscopy (Isgur–Karl, etc.), the MIT bag model, and the possible existence of sub-quarks. In the 1980s Dick became interested in Monte Carlo simulations of QCD formulated on a discrete space-time lattice. With Ford (his student, who was the first author) and Hoek (51), he performed state-of-the-art calculations of the potential between two static colour charges in a pure lattice gauge theory (without dynamical quarks) on the largest lattice yet constructed (34$^2$).
A very productive collaboration between Dalitz and Goldstein led to a series of influential papers related to heavy quarks, published in the period 1988–99. The first (52), with R. Marshall (FRS 1995), was on correlations between the decays of heavy particle (charm, bottom or top) antiparticle pairs in back-to-back jets resulting from electron–positron annihilation into a heavy quark–antiquark pair. The standard model predicts correlations between the helicities of the initial quark–antiquark pair, which depend on how close the energy is to the Z pole. At high energy compared with the quark mass, the helicities are conserved when the quarks fragment, according to QCD. This leads in the case of charm (for example) to correlations between the spins of the charmed vector mesons (D*/anti-D*) that contain the initial charm/anti-charm quarks, which are manifested in the angular distributions of their decay products. The results of (52) were used by the ARGUS Group at the DORIS II DESY e+e− storage ring (Albrecht et al. 1996) and produced the expected result.

The second paper (54), also with Marshall, proposed a way to determine the helicity of charm quarks (produced in any hard process, not necessarily in pairs) via the subsequent jet hadronization into a D plus two π-mesons. Disappointingly, the predicted effect, which depended on the interference between D* and non-resonant D plus pion, was small, as confirmed at SLAC (Abe et al. 1995), but the paper led to further theoretical developments related to a transverse spin-dependent fragmentation function (Collins 1993), which in turn stimulated experiments that continue to this day.

In a subsequent paper (56), Dalitz and Goldstein studied the top/anti-top case in more detail and showed that the parity-violating effects in the decay chain t → bW+, W → lν are large and will test closely the detailed spin structure of electroweak interactions involving the top quark. This is now a standard reference for experiments that study top through the so-called lepton decay channel. In (57) they showed that in collider production of a top–anti-top pair, both of which decay to leptons, the momenta of the decay products are correlated. A given configuration of momenta depends on the top mass and determines a probability distribution for possible top masses.

In (56) and (57) Dalitz and Goldstein developed a means of analysing the decays of top–anti-top pairs produced in hadronic interactions. This involved what they described as an ‘illuminating’ geometrical construction, reproduced here as figure 7. They applied it to a single candidate for top–anti-top pair production found by the Collider Detector at Fermilab (CDF) as an illustration of the procedure they proposed (this candidate implied a top quark mass of around 125 GeV; today the mass is known to be around 173 GeV). Although they were careful to describe this as ‘pure speculation’, it was not well received by CDF (and the controversy was picked up by the scientific press), but the other Fermilab collider experiment (D0) used their work, which was recently also used by the CMS collaboration in analysing data from the Large Hadron Collider (LHC).

In their next paper on top quarks (58), written with Sliwa, Dalitz and Goldstein presented a technique for separating top-quark production from standard model background events that is applicable to the channel in which one top quark decays semi-leptonically while its antiquark decays hadronically into three jets, or vice versa. They showed that the method, which was subsequently used by both the CDF and D0 collaborations, discriminates dramatically between Monte Carlo-generated events with and without simulated top quarks of mass around 120 GeV.

In 1994 the top quark was discovered by CDF and D0. In his final paper (61) on quarks, Dick—again with Goldstein—reported Monte Carlo calculations that tested the likelihood
methods they had proposed for determining the top mass for masses of order 170 GeV. Various versions of the ‘matrix element/dynamic likelihood method’, which is based on that paper, have been used by D0 and CDF at the Tevatron and by ATLAS and CMS at the LHC.

**SCIENTIFIC STYLE AND PERSONAL CHARACTERISTICS**

Dick described his pragmatic, data-driven approach to physics in an interview in October 2003 (O’Byrne 2004), which we have quoted, when the photograph in figure 8 was taken. He once said to one of us, ‘My job’s not to make theories—it’s to understand the data.’ In the same vein, when Gabriel Karl told him about a paper that considered the possible effects of a hypothetical interaction, he replied, ‘But there is no such thing.’ ‘Yes,’ said Gabriel, ‘but you can imagine that there is’; to which Dick replied, ‘In that case you must stop yourself.’

Dick immersed himself in the experimental data, of which he had an encyclopaedic knowledge until their volume became too great. Once, when wondering whether he had quoted an experimental result correctly (he had), he said to one of us, ‘I used to know all the data; at one time I knew every event’. He saw his role as being to seek ways to represent data so that they directly reveal nature’s secrets, as the Dalitz plot had done.

After Dick’s analysis of K decays hinted that parity is violated, he might conceivably have been the first to analyse this possibility had it not been for his reluctance to speculate. Yet, ironically, his pioneering work on the quark model was regarded as outrageously speculative
by many. For Dick, however, the theoretical objections were outweighed by the fact that the model provides a simple way to describe a huge quantity of data. When almost overnight in the 1970s the ‘naive’ quark model became accepted, Dick’s seminal work was soon largely forgotten. This, and the scepticism it attracted at first, must have been hard to take, but he never publicly expressed bitterness about it.

Dick’s work was characterized by great professionalism. He tackled every problem with exemplary thoroughness, and his review articles and lecture notes were wonderfully useful sources of comprehensive information, concisely presented. He worked long hours. After a burglary in the Oxford Theoretical Physics Department one Christmas, it was thought that the large electromechanical calculator that he kept next to his desk (and used with great skill well into the 1970s) was among the stolen items. But it turned out that Dick had taken it home for work over the Christmas break.

Dick’s style soon became clear to his students who, within a month or two of their arrival, were set to carry out calculations of immediate relevance to experiments. They were both impressed and rather intimidated by his intellect, knowledge and reputation, and by the way in which he would reflect on a question in silence for what often seemed like minutes before supplying a highly concise answer. They also greatly appreciated the pains he took in writing long letters providing advice on career options after they had left Oxford.
Dick served on several advisory bodies including the UK’s Nuclear Physics Board (1972–85), the Council of the Royal Society (1979–81) and the CERN Scientific Policy Committee (1974–78). He took detailed notes but spoke little, although the contributions that he did make were valued, and his colleagues greatly appreciated the opportunity to talk to him outside the formal sessions. As a research professor he had no formal administrative duties, but he ran the Oxford particle theory group with quiet efficiency, to the relief of others on whom the lot might have fallen. It is fitting that the flourishing group that he founded is today housed in premises known as the Dalitz Institute.

Dick was very happily married, and is survived by his wife, Valda, a son, three daughters and eleven grandchildren. He was a private person whose shy and modest exterior hid a deeply caring and kind man. He has left fond memories with his many colleagues, students and friends, as well as a great scientific legacy.

**Honours and Awards**

- 1966 Maxwell Medal and Prize, Institute of Physics and Physical Society
- 1969 Bakerian Lecture, Royal Society
- 1972 Jaffé Prize, Royal Society
- 1975 Hughes Medal, Royal Society
- 1978 Corresponding Member, Australian Academy of Sciences
- 1980 Foreign Member, Polish Academy of Science
- 1980 J. Robert Oppenheimer Memorial Prize, University of Miami
- 1982 Royal Medal, Royal Society
- 1990 Foreign Member, National Indian Academy
- 1991 Harrie Massey Prize, Institute of Physics and Australian Institute of Physics
- 2005 Foreign Associate, US National Academy of Sciences
- 2005 Gian Carlo Wick Commemorative Gold Medal

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