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The scientific heritage of Richard Henry Dalitz, FRS (1925-2006)

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Professor Richard H. Dalitz passed away on January 13, 2006. He was almost 81 years old and his outstanding contributions are intimately connected to some of the major breakthroughs of the 20th century in particle and nuclear physics. These outstanding contributions go beyond the Dalitz Plot, Dalitz Pair and CDD poles that bear his name. He pioneered the theoretical study of strange baryon resonances, of baryon spectroscopy in the quark model, and of hypernuclei, to all of which he made lasting contributions. His formulation of the "$\theta - \tau$ puzzle" led to the discovery that parity is not a symmetry of the weak interactions. A brief scientific evaluation of Dalitz's major contributions to particle and nuclear physics is hereby presented, followed by the first comprehensive list of his scientific publications, as assembled from several sources. The list is divided into two categories: the first, main part comprises Dalitz's research papers and reviews, including topics in the history of particle physics, biographies and reminiscences; the second part lists book reviews, public lectures and obituaries authored by Dalitz, and books edited by him. This provides the first necessary step towards a more systematic research of the Dalitz heritage in modern physics.

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I. DALITZ'S IMPACT ON 20TH CENTURY PHYSICS

by Frank E. Close and Avraham Gal

Dick Dalitz was born in Dimboola, Victoria Australia, on February 28th 1925, and gained B.A. and B.Sc. degrees in Mathematics and Physics in 1944 and 1945, respectively, from the University of Melbourne. He moved to Britain in 1946 to do his Ph.D. at Cambridge, and then worked at the University of Bristol before joining in 1949 Rudolf Peierls in Birmingham where he subsequently became a Lecturer. He spent two years in the U.S. from 1953, holding research positions at Cornell and Stanford, visiting also Princeton and Brookhaven National Laboratory, and returned as a Reader in Mathematical Physics to the University of Birmingham for a year before becoming Professor of Physics in the Enrico Fermi Institute for Nuclear Studies and the Department of Physics at the University of Chicago. He moved to Oxford in 1963 as a Royal Society Research Fellow, the post he held until his retirement in 1990. Dick Dalitz made many outstanding contributions to particle physics, beyond the Dalitz Plot, Dalitz Pair and CDD (Castillejo, Dalitz, Dyson) poles that bear his name. He pioneered the theoretical study of strange baryon resonances, of baryon spectroscopy in the quark model, and of hypernuclei, to all of which he made lasting contributions. His formulation of the "$\theta-\tau$ puzzle" led to the discovery that parity is not a symmetry of the weak interactions.

His Cambridge Ph.D. thesis, supervised by Nicholas Kemmer and completed in 1950, was on "Zero-zero transitions in nuclei". It evolved from the theoretical advice that Sam Devons sought on his novel nuclear experiments at Cambridge. Primarily it was a study of the well-known deexcitation by electron-positron pair emission of the 0^+ first excited level at 6.05 MeV to the 0^+ ground state of ^{16}O. Emission of a real photon is forbidden due to angular momentum conservation, but it is allowed for a longitudinally polarised virtual photon that converts into an electron-positron pair. His work on the higher order radiative corrections in such pair emission transitions in nuclei rapidly bore fruit in particle physics in 1951 with his seminal contribution of "Dalitz pairs" [1]. This is a form of internal conversion in $\pi^0 \to 2\gamma$ decay where one of the photons converts into an e^+e^- pair, with a branching ratio 1.2×10^{-2}, or for both photons to convert into Dalitz pairs with a branching ratio of 3.1×10^{-5}. These Dalitz pairs were observed in photographic emulsion experiments, as pairs coming from the origin of a π or K interaction or decay and, to mention just two examples, were used to measure the parity of the π^0 [2] and to establish, by the decay of the Σ^0, that the Σ^0 and Λ have the same parity [3].

It was his work with the τ meson that revolutionised particle physics. During his Ph.D. thesis he had spent a year working alongside Cecil Powell's cosmic ray group at Bristol and it was during this period that he took particular interest in the strange particles that were beginning to appear in cosmic rays and at particle accelerators. These included the first hyperfragment in 1953, which inspired a lifelong interest in hypernuclei, and the observation of two kinds of mesons named θ and τ, with essentially the same masses and lifetimes. The positive-charge species, both now understood to be the same K^+ meson, were clearly distinguished by their decays $\theta^+ \to \pi^+\pi^0$ into two pions and $\tau^+ \to \pi^+\pi^+\pi^-$ into three pions. Conservation of parity in $\theta \to 2\pi$ would imply that it had $J^P = 0^+, 1^-, 2^+ ...$, and the question was whether the τ which decays to three pions could have any of these quantum numbers. In 1953, Dalitz looked at the decays of the τ into three pions and in doing so introduced what he would modestly call a phase space plot, but which is known throughout physics as the Dalitz plot [4, 5]. The distribution of events in this kinematical two-dimensional plot led to the conclusion that the τ had even spin and odd parity, such as 0^-. Thus was born the $\theta-\tau$ puzzle: how could two mesons have the same masses and lifetimes and yet have different quantum numbers? The puzzle persisted for two years: Dalitz even musing to colleagues that perhaps the law of parity had to be abandoned, although all the evidence at the time appeared to say otherwise. It was T.D. Lee and C.N. Yang, who in 1956 realised that the assumption of conserved parity in weak interactions, such as β decay of nuclei, had not been tested, and it was the weak force that was at work in the $\theta - \tau$ decays. They were proved to be right, for which they won in 1957 a well-deserved Nobel Prize. Thus, the θ and the τ were the same K meson.

In his 1957 review *K Mesons and Hyperons* [6], Dalitz showed that their parity could be neatly derived from a strong-interaction production process; this established in due course that the K-meson parity is opposite to that of the Λ, precisely the same relation as between the parities of the π meson and the nucleon.

Dalitz's interests and contributions were not limited to electromagnetic and weak interactions. He made significant contributions to the strong interactions of the strange particles and their resonant states, soon reviewed in Reviews of Modern Physics [7] and in Annual Review of Nuclear Science [8]. In fact, as early as 1959 Dalitz and Tuan, by analysing the data on the strong interactions of K^- mesons with protons, predicted the existence of an $I = 0,\ J^P = (1/2)^-$ 'strange' resonance about 20 MeV below the K^-p threshold [9]. This $\Lambda(1405)$ resonance was discovered two years later, during Dalitz's sabbatical year in Berkeley, by the Alvarez team in the Berkeley hydrogen bubble chamber, studying the reaction $K^-p \to \Sigma + 3\pi$ for several charge states [10]. The discovery of $\Lambda(1405)$ had been preceded by that of the $I = 1,\ J^P = (3/2)^+$ strange resonance $\Sigma(1385)$ [11] in $K^-p \to \Lambda\pi^+\pi^-$ interactions, displaying the three final state particles on a Dalitz plot. The p-wave $\pi\Lambda$ resonance $\Sigma(1385)$ provided a straightforward generalisation of the non-strange p-wave πN $\Delta(1238)$ resonance discovered by Fermi and coworkers in 1952 into the strange sector, and within a few years led to a complete SU(3) decuplet; by contrast, the $\Lambda(1405)$ required a different dynamical origin. The proximity of this s-wave $\pi\Sigma$ resonance to the $\bar{K}N$ threshold suggested that it can be generated by the $\bar{K}N - \pi\Sigma$ inter-hadron forces, and this was shown in 1967 by Dalitz, Wong and Rajasekaran to be possible within a dynamical model of SU(3)-octet vector-meson exchange [12]. The underlying vector mesons $\rho, \omega, K^\star, \phi$, which were discovered in the years 1960-61, relying heavily on Dalitz plots for some of these, were unknown when Dalitz and Tuan predicted the $\Lambda(1405)$. In the years to follow, Dalitz repeatedly considered the completeness of this dynamical picture, whether or not the $\Lambda(1405)$ S-matrix pole due to the inter-hadron forces need not be augmented by a CDD pole arising from inter-quark forces upon allowing for an intermediate uds configuration. It is here that the earlier CDD discussion [13] found a fertile physical ground.

The discoveries of these, and other baryon and meson resonances as well, paved the way for Gell Mann and Ne'eman in 1961 to introduce SU(3) (flavour) symmetry into particle physics and the idea that a more fundamental level of reality existed in what Gell Mann called quarks in 1964. It was initially unclear whether these fractionally-charged quarks were just a mathematical convenience or were themselves real particles. It was around this time that Dalitz returned to Britain in 1963 joining Rudolf Peierls at Oxford as Royal Society research professor.

Dalitz took the idea of physical quarks very seriously and proposed that they were the basic blocks of baryons and mesons. In his remarkable Les Houches summer school notes (1965), Tokyo summer lectures (1966) and Berkeley conference talk (1966), he showed how the idea explained properties of the proton and neutron, such as their response to a magnetic field and then took his more radical step of exciting the quarks into different energy states for mesons and baryons, following the established rules of non-relativistic quantum mechanics. To explain the pattern of the baryon SU(3) octet and decuplet representations, embedded in the **56** dimensional SU(6) (spin-flavour) *symmetric* representation, required assuming what became known as a symmetric quark model, in defiance of the established antisymmetry for fermions. While this was developed by several others, it was Dalitz who analysed the three body state with internal orbital angular momentum excitations, using his earlier experience with the $\tau \to 3\pi$ decay, leading to a **70** dimensional SU(6) representation with negative parity as the first excited states, as seen empirically, and with higher excitations in **56**, **70** and **20** dimensional representations of SU(6) with negative or positive parity. Over the following decades many other resonances were discovered, for both baryons and mesons, in many cases by application of Dalitz plots, such that the non-relativistic quark model, with QCD motivated SU(3) (colour) effects incorporated later, became established as a description of what had hitherto been a menagerie of particles.

While the quark model description of the low lying baryons has proved generally successful, its classification for the $\Lambda(1405)$ as a uds SU(3)-singlet $P_{\frac{1}{2}}$ poses a serious problem. It was shown by Close and Dalitz [14] that a consistent application of the Fermi-Breit interaction in QCD produces a spin-orbit splitting that places this $P_{\frac{1}{2}}$ state higher than its LS doublet partner $P_{\frac{3}{2}}$, hence above the D-wave $\bar{K}N$ resonance $\Lambda(1520)$ which is fitted well by this assignment. Even if one accepts that the structure of $\Lambda(1405)$ is dominated by inter-hadron forces, as in the original scenario put forward by Dalitz and Tuan, there remains a lingering doubt about a missing candidate for the quark model assignment.

Dalitz pioneered the theoretical study of hypernuclei, atomic nuclei in which a Λ hyperon is bound and which are as long lived as the Λ's free-space lifetime of order 10^{-10} sec. Λ hypernuclei, produced by K^- mesons stopping in emulsion and identified by their decay products, were discovered by Danysz and Pniewski in 1953, and have been produced systematically in accelerators for the last 30 years using K^- and π^+ beams to convert a bound neutron into a bound Λ. [Danysz and Pniewski also headed the discovery in 1963 of the first of several known to date double-Λ hypernuclei, from which Dalitz immediately provided the first estimate on the $\Lambda - \Lambda$ interaction; he would come back in 1989 to this issue in connection with the then argued stability of a dihyperon H made out of $uuddss$ quarks in a different configuration than just two Λs (each one made out of uds)]. Hypernuclei provide unique information on the strangeness degree of freedom for studies of dense hadronic or quark matter in stars.

Dalitz's first published work on hypernuclei dates back to 1955, dealing with charge independence in light hypernuclei. In a series of works covering three decades, he used the main $\Lambda \to p\pi^-$ weak-decay mode of the light species ($A \lesssim 13$) studied in emulsion and bubble chambers to determine their ground-state spins and, thereby to gain information on the spin dependence of the ΛN force. But his early outstanding contribution to weak interactions in hypernuclei, together with Martin Block [15], was to formulate the phenomenology of non-mesonic $\Lambda N \to NN$ weak-interaction decay modes that dominate the decays of heavier hypernuclei, a process that cannot be studied on free baryons and which offers new systems, Λ hypernuclei, for exploring the little understood $\Delta I = 1/2$ rule in non-leptonic weak interactions.

Another important contribution, in the 1970s, following the introduction of shell-model techniques by Gal, Soper and Dalitz, was to chart together with Avraham Gal [16] the production and electromagnetic decay schemes anticipated for excited states in light hypernuclei in order to derive the complete spin dependence of the ΛN interaction effective in these hypernuclei. This work, developed further together with John Millener and Carl Dover [17], served as a useful guide to the hypernuclear γ-ray measurements completed in the last few years, at KEK and BNL [18], which yielded full determination of the spin dependence in the low-lying spectrum.

Dalitz and Gal also studied the extension of Wigner's spin-isospin SU(4) symmetry in light nuclei to SU(6) approximate symmetry in light hypernuclei [19], following a suggestion by Kerman and Lipkin to generalise isospin SU(2) into Sakata SU(3) symmetry for the p, n, Λ constituents of hypernuclei. This resulted in a unique feature named by them 'supersymmetry' (before this attribute was taken up in particle physics), holding for particularly symmetric Λ-hypernuclear excited states in which the Λ occupies a quantum state forbidden for nucleons owing to the Pauli principle. Such states have been observed in ${}^{9}_{\Lambda}$Be at KEK [18] and bear important information on the effective ΛN interaction in the p shell.

In later years Dalitz, mostly with Don Davis and Toshio Motoba, focused attention to unbound Λ-hypernuclear levels that had been precisely studied in nuclear emulsions by following their proton emission tracks. With Andrzej Deloff he collaborated on K^- interactions in deuterium and helium. He was the recognised leader of this field of research for 50 years, and it is instructive to read through his own recollection of events in his last published paper [20] which is based on a talk given in HYP2003 at Jlab.

He was also intimately involved with the identification of the top quark where he thought about the problems of how one might identify it from the decay processes that seemed most natural for it. With Gary Goldstein he worked out a geometrical method by which experimental data could be used to deduce the top mass. They applied the method to an early possible event from Fermilab and concluded that if this event indeed signalled top production, the top quark mass most probably exceeded 130 GeV [21]. This was regarded as an unexpectedly large value at the time. This one event might not even have been due to a top quark and the confirmation could only be decided on the basis of a large number of observed events, all of them being consistent with a unique mass. This was the case later when two experimental groups came to conclude that the top quark mass was about 180 GeV.

Dalitz worked close to data and was greatly admired by experimentalists. He brought scholars to Oxford, which became a centre for the quark model, and trained generations of students, including Chris Llewellyn Smith a future Director-General of CERN. Following retirement he remained an inspirational figure to students new and old, continuing to work on theoretical physics with undiminished enthusiasm. With his death, international physics has lost a major figure and Britain one of its greatest unsung scientists. As the next phase in the quest for the ultimate nature of reality begins at CERN's Large Hadron Collider, it is likely that evidence for Higgs Bosons, supersymmetric particles, or whatever other surprises may await, may be revealed by Dalitz plots.

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