HOW UNITARITY IN THE CKM MATRIX OF QUARK INTERACTIONS WAS PROVEN CORRECT*

Nickolas Solomey

Physics Division, Wichita State University, KS USA 67260

Received 30 January 2023, accepted 31 January 2023, published online 15 February 2023

In 1993, a new Hyperon Beta Decay study was introduced into the KTeV experiment and although it would have only collected less than 1000 events, it was to become a major important step in particle physics, because it showed that the CKM matrix obeyed unitarity. This new idea was introduced by myself while a new PostDoc just starting my career after getting a Ph.D. The 98% analyzing power of these decays allowed us to study beta decay form factors and showed that the CKM matrix element V_{us} historically used for 35 years was wrong and that this correction changed V_{us} by 6 sigma bringing a new understanding to quark flavor physics. Today the CKM matrix is a guide for a similar matrix in the neutrino matrix and continues to have an important impact on particle quark flavor searches for new physics.

DOI:10.5506/APhysPolBSupp.16.3-A15

1. Introduction

The CKM matrix [1, 2] describes the interaction strength between the different types of quarks, see Fig. 1. Each one of these values is the result of many experiments and the effort of theoretical scientists. Unitarity in the CKM matrix is a mathematical term but of important physical meaning such that in its simplest understanding says the sum of all the probabilities of interactions comes out to one such that the square-root of the sum of the elements in any row of column squared should be exactly one, such as

$$\sqrt{V_{ud}^2 + V_{us}^2 + V_{ub}^2} = 1\,.$$

Today, at this BEACH 2022 conference, we are hearing a lot of experimental results of scientists searching for violation of unitarity in the CKM matrix

* Presented at the XIV International Conference on *Beauty, Charm and Hyperon Hadrons*, Kraków, Poland, 5–10 June, 2022.

as a way to find new physics; however, back in the 1990s, when I was a young new scientist just having gotten my Ph.D., unitarity violation in the CKM matrix was observed for more than thirty years but unknown to us. This was because of a major mistake in the measurement of V_{us} from an old 1950s bubble chamber experiment.

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Fig. 1. The CKM matrix of quark–quark interactions.

Historically the value for V_{us} was from charged Kaon K_{l3} events in old bubble chambers having an average value of $V_{us} = 0.2165 \pm 0.0004$, where values for the other elements in the first row of the CKM matrix were $V_{ud} = 0.9749$ and $V_{ub} = 0.0035$. This gave the unitarity test as

$$\sqrt{V_{ud}^2 + V_{us}^2 + V_{ub}^2} = 0.9987 \pm 0.0004\,,$$

which was not consistent with 1.0 and at the time was considered to be a sign of new unexplained physics or an unexplained origin of CP violation.

2. The Ξ^0 hyperon beta decay used to measure a new V_{us} value

The KTeV experiment was designed and approved in 1992 before I joined it in January of 1993, in addition to the detailed study of CP violation with neutral kaons and rare K^0 decays, it had a Hyperon Beta Decay program using Λ^0 which were copiously produced along with the neutral kaons. But, I was within the first two months able to suggest and add the Ξ^0 beta decay study [3]. It had one great advantage over the Λ^0 beta decays because these Ξ^0 beta decays into $\Sigma^+ e^- \bar{\nu}_e$ where the subsequent decay of the Σ^+ into $p^+\pi^0$, which has the advantage of a 98% analysing power for the polarization vector determination, so a thousand of these events would be more powerful than a million Λ^0 decays. Although my PostDoc adviser permitted me to work on this it could not interfere with my other work so had to be on my own time, and I was not allowed to use the simulation computers when they were needed for the other more important parts of the experiment. While we were constructing the triggers for this system, I was able to get the Fermilab scintillator shop to build four trigger paddles out of left over pieces but the only photo-tubes we could find were old and not compatible with the faster readout of the newer ones being used; in the end I footed the bill for the four photo-tubes from my own savings for \$3 636.44.

Data taking for the KTeV experiment started in 1996 and a small percentage of the trigger bandwidth was given to the Ξ^0 trigger. By 1999, we had our first results, showing the reconstructed Ξ^0 decays of both the main mode and the important beta decay process, see Fig. 2, and published in May 1999 [4]. A study of the polarization that permitted the form-factor

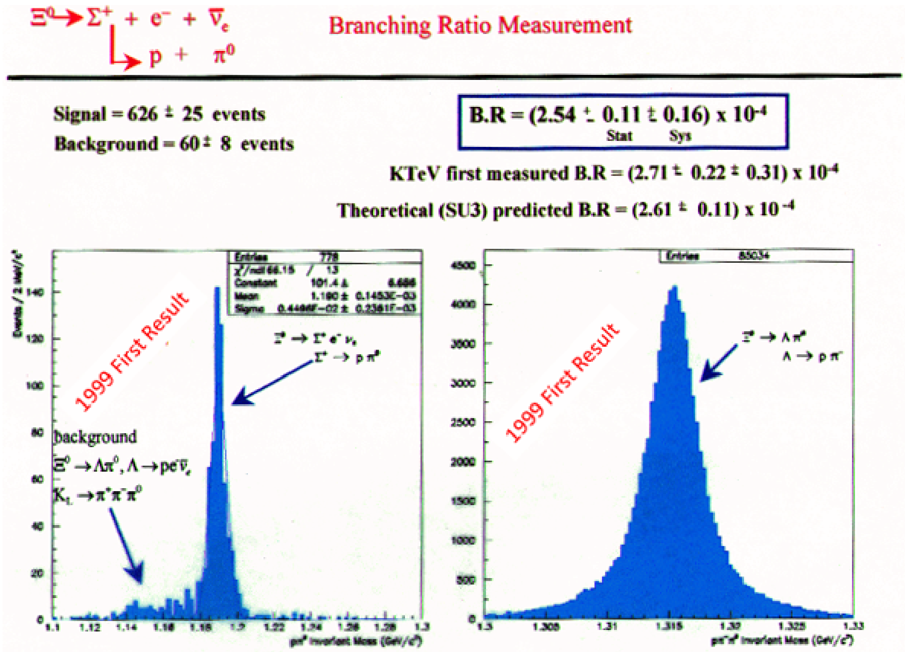

Fig. 2. Reconstructed Ξ^0 events.

analysis that was also performed from the data, which were first presented at the Kaon99 conference held in June of 1999 at the University of Chicago [5]. The hyperon group was able to analyze these events and measure the form factors, see Fig. 3, which got published by 2001 [6].

These results implied a new value of $V_{us} = 0.2240 \pm 0.0015$. This gave the unitarity test as

$$\sqrt{V_{ud}^2 + V_{us}^2 + V_{ub}^2} = 1.0002 \pm 0.0002\,,$$

which was now consistent with 1.0 statically and, for the first time, show the CKM matrix obeyed unitarity in the quark–quark interactions.

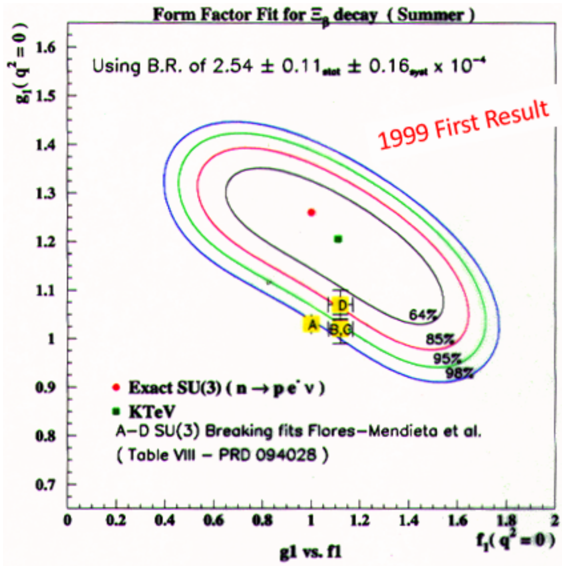

Fig. 3. Analysis of the Ξ^0 form factor and the deviation from the previous values.

3. Confirmation of the new V_{us} value

At the time of the Kaon99 conference presentation, some doubts were raised about the new value of V_{us}: Baryons like the Ξ^0 have a large strong-force distortion of the weak interaction strengths, so how could this measurement determine a fundamental weak parameter and the old V_{us} results from a bubble chamber had to be more correct due to the ability to do better tracking along the whole track's path-length. However, there were some endorsements that the hyperon Ξ^0 value could be correct. Prof. Sandid Pakvasa of the Univeristy of Hawaii who predicted a large CP violation in hyperons insisting it had to be just as correct as kaon decays. Prof. Julie Thompson of the University of Pittsburgh inspired by the hyperon results presented at Kaon99 to use the BNL E865 K^+ experimental data for further studies. The BNL E865 K^+ into $\pi^0 e^+ \nu$ measured a branching ratio 6% higher than expected giving a change in V_{us} that was consistent with unitarity [7]. The neutral kaon group within the KTeV experiment measured the decay in 2004 and also confirmed the new value of V_{us} [8]. By 2004, Cabibbo [9] used the published KTeV hyperon Ξ^0 decay parameters to get a value of $V_{us} = 0.2250 \pm 0.0027$.

4. Importance of unitarity in the CKM matrix

My goal in repeating this story of discovery was to provide inspiration and determination to the new younger generation of physicists — even if you are working in a large experiment, it is still possible to introduce new ideas and do something fantastically unexpected and important, your curiosity should be your inspiration and guide.

Today, we know the CKM matrix obeys unitarity but we continue to look for small variations from it since that can provide a new first hint for new physics. At the same time, unitarity in the CKM matrix is a guide for the neutrino matrix, adding a constraint that it must obey unitarity helps neutrino physicists to understand the neutrino oscillation and parameters better than without such an imposed constraint.

5. Conclusion

This Ξ^0 beta decay measurement was the last correction needed to the CKM matrix to show that it obeyed unitarity, but one must remember that every element in the CKM matrix represents many experiments. Any one element has many experiments that contributed to its final determination. Although I was lucky that I implemented the last correcting that saw unitarity come out of this new measurement, without the many experiments that proceeded me for all the CKM values measured and the thousands of people over the course of 50+ years that worked on it, we would not have been able to have seen the final understanding of quark-quark interactions. In addition to these experiments, many theoretical physicists worked on ideas for both why the CKM matrix should be unitarity as well as those that pondered what it meant if unitarity was violated in the CKM matrix, all provided a better understanding of particle physics fundamental interactions.

Although new experiments continue to look for violations in unitarity in the CKM matrix as a way to search for new physics, the unitarity in the CKM matrix is also relevant today beyond quark–quark interactions since the understanding of unitarity in the CKM matrix is applied today as a guiding constraint of the more difficult problem of the neutrino matrix and constraining it to resemble unitarity in the CKM matrix allows scientists to advance our understanding of neutrino processes better than it would be possible without applying that constraint.

First and foremost, I wish to thank the many science agencies from around the world that fund our many science investigations, supporting labs, institutes and universities' research, and the taxpayers in these many countries who contribute to fund these endeavors. Although to me it seems generous of them, but in the long run the return on their investment is seen in the many advances to our technology that is developed along the way and eventually helps every citizen of every country on earth lead a better life. Clearly, this small addition that I brought to the KTeV experiment was exciting and with hindsight very important, but it would not have been possible without the whole experiment that many people worked on and the accelerator that provided the high-energy particles. I also wish to thank Prof. Roland Winston who permitted me to add this new idea to the experiment since clearly, if he had said no then I would not have been able to have done what I did even though I had to buy with my own savings some equipment to perform this add-on measurement.

REFERENCES

[1] N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963).

[2] M. Kobayashi, T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

[3] N. Solomey *et al.*, «A Proposal for Hyperon Physics at KTeV», University of Chicago note EFI 93-25, April 1993.

[4] A. Affolder *et al.*, *Phys. Rev. Lett.* **82**, 3751 (1999).

[5] N. Solomey, (2001), «Recent Results in Weak Hyperon Decays», in: J. Rosner, B. Winstein (Eds.) «Kaon Physics», *University of Chicago Press*, June 1999, presented at the Kaon99 conference: https://hep.uchicago.edu/workshops/kaon99/talks/solomey/

[6] A. Alanvi-Harait *et al.*, *Phys. Rev. Lett.* **87**, 132001 (2001).

[7] A. Sher *et al.*, *Phys. Rev. Lett.* **91**, 261802 (2003).

[8] T. Alexopoulis *et al.*, *Phys. Rev. Lett.* **93**, 181802 (2004).

[9] N. Cabibbo *et al.*, *Phys. Rev. Lett.* **92**, 251803 (2004).