

Table of Contents

Abstract	ii
Table of Contents	iii
List of Figures	vi
Dedication	vii
Acknowledgements	viii
1 Introduction	1
1.1 Dual Measurements	2
1.2 Differences Between Measurements of Space and Measurements of Time .	7
1.3 Inaccuracies and Uncertainties	10
1.4 What Lies Ahead	11
2 When does an Event Occur	15
2.1 Probabilities at a Time and in Time	16
2.2 Did it Occur vs. When Did it Occur	17
2.3 Time of a Measurement or Arrival	21
2.4 Continual Event Monitoring	25
3 Physical Clocks and Time-of-Arrival	30
3.1 A Limitation on Time-of-Arrival Measurements	31
3.2 Free Clocks	33

3.3	Measurement of Time-of-Arrival	35
3.3.1	Measurement with a clock	36
3.3.2	Two-level detector with a clock	40
3.3.3	Local amplification of kinetic energy	44
3.3.4	Gradual triggering of the clock	46
3.3.5	General considerations	49
4	Time-of-Arrival Operators	52
4.1	Indirect Time-of-Arrival Measurements	53
4.2	Conditions on A Time-of-Arrival Operator	54
4.3	Time-of-Arrival Operators vs. Continuous Measurements	56
4.4	The Modified Time-of-Arrival Operator	60
4.5	Normalized Time-of-Arrival States	63
4.6	Contribution to the Norm due to Modification of \mathbf{T}	67
4.7	Limited Physical Meaning of Time-of-Arrival Operators	69
5	Traversal Time	71
5.1	A Limitation on Traversal Time Measurements	72
5.2	Measuring Momentum Through Traversal-Distance	73
5.3	Measuring Traversal Time	74
5.4	General Argument for a Minimum Inaccuracy	77
5.5	From Traversal Time to Barrier Tunneling Time	83
6	Order of Events	85
6.1	Past and Future	86
6.2	Which first?	88
6.3	Coincidence	92

6.4	Coincident States	97
6.5	In Which Direction Does the Light Cone Point	99
7	Conclusion	101
	Bibliography	106
	Appendices	110
A	Zero-Current Wavefunctions	110
B	Gaussian Wave Packet and Clocks	111
C	Time-of-Arrival Eigenstates	114

List of Figures

4.1	Unmodified part of time-of-arrival eigenstate. $ \tau^+(x, \tau) ^2$ vs. x , with $\Delta = m$ (solid line), and $\Delta = \frac{m}{10}$ (dashed line). As Δ gets smaller, the probability function gets more and more peaked around the origin.	66
4.2	Modified part of time-of-arrival eigenstate. $\frac{1}{\epsilon} \tau^+(x, \tau) ^2$ vs. ϵx , of $\sqrt{\frac{m}{\Delta}}x$. with $\Delta\epsilon^2 = \frac{m}{10}$ (solid line) and $\Delta\epsilon^2 = \frac{m}{100}$ (dashed line). As Δ or ϵ gets smaller, the probability function drops near the origin, and grows longer tails which are exponentially far away.	67
6.3	A potential which can be used to measure which of two particles came first (given by $V(x, y) = \alpha\delta(\mathbf{x})\theta(-\mathbf{y})$). The wave function for two incoming particles in one dimension looks like a single wave packet in two dimensions travelling towards the origin.	89
6.4	Potential for measuring whether two particles are coincident.	93
6.5	Phase shifts for coincidence detector ($\delta_1(ka)/\delta_0(ka)$ vs. ka)	97