「フレーバー物理」特定領域の初年度にあたって

昔話でもしましょう

フレーバー物理
標準模型から取り残されたもの

ーフレーバーと素粒子物理の発展ー

東北大理　日笠 健一

フレーバーとは

素粒子物理の発展に数多くの寄与をし

標準模型の確立にも重要な役割を果たし

そしていまだに理解されていないもの

My 1st Encounter

湯 川 秀 樹
片 山 泰 久 著
福 留 秀 雄

素 粒 子

第 二 版

湯 川 秀 樹
片 山 泰 久 著
福 留 秀 雄

素 粒 子

第 二 版

岩 波 新 書

710

素粒子 第二版

（湯川・片山・福留）

1969**年**3**月**

素粒子の表 I

分類	名称	アイソスピン(奇妙さ)*	スピン	偶奇性	質量(Mev)	幅(Mev)
核子	N {p	1/2(0)	1/2	+	938.3	—
	n				939.6	—
	N′(1470)		1/2	+	1470	210
	N (1518)		3/2	−	1525	115
	N (1550)		1/2	−	1550	130
	N (1680)		5/2	−	1680	170
	N (1688)		5/2	+	1690	130
	N′(1710)		1/2	−	1710	300
	N (2190)		7/2	−	2200	250
	N (2650)		11/2	−	2650	360
	N (3030)		?	?	3030	400
デルタ粒子	Δ (1236)	3/2(0)	3/2	+	1236	120
	Δ (1640)		1/2	−	1640	180
	Δ (1920)		7/2	+	1950	220
	Δ (2420)		11/2	+	2420	310
	Δ (2850)		15/2	+	2850	400
	Δ (3230)		?	?	3230	440
ジイ粒子	Z (1865)	0(+1)	?	?	1865	180
ラムダ粒子	Λ	0(−1)	1/2	+	1115.5	—
	Λ (1405)		1/2	−	1405	50
	Λ (1520)		3/2	−	1519	16
	Λ' (1670)		1/2	−	1670	18
	Λ' (1690)		3/2	−	1690	45
	Λ (1750)		1/2	+	1750	
	Λ (1815)		5/2	+	1816	74
	Λ (1830)		5/2	−	1827	76
	Λ (1870)		7/2	+	1870	
	Λ (2100)		7/2	−	2100	140
	Λ (2350)		?	?	2350	210
シグマ粒子	Σ {Σ^+	1(−1)	1/2	+	1189.5	—
	Σ^0				1192.5	—
	Σ^-				1197.4	—
	Σ (1385)		3/2	+	1382	37
	Σ (1610)		1/2	+	1610	
	Σ (1660)		1/2	−	1660	50
	Σ (1690)		3/2	+	1690	120
	Σ (1770)		5/2	−	1767	95
	Σ (1910)		5/2	+	1910	60
	Σ (2030)		7/2	+	2030	120
	Σ (2250)		?	?	2250	200
	Σ (2455)		?	?	2455	140
	Σ (2595)		?	?	2595	140
グザイ粒子	Ξ {Ξ^0	1/2(−2)	1/2	+	1314.9	—
	Ξ^-				1321.3	—
	Ξ (1530)		3/2	+	1530	7

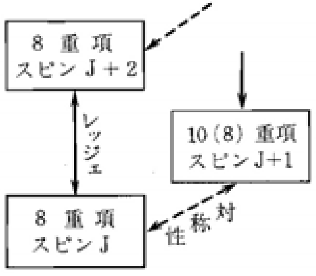
素粒子の表 II

分類	名称	アイソスピン(奇妙さ)	スピン	偶奇性	質量(Mev)	幅(Mev)
	Ξ (1815)		3/2	−	1815±3	16
	Ξ (1930)		?	?	1930	140
オメガ粒子	Ω^-	0(−3)	3/2	+	1672	—
パイ中間子	π {$\pi^\pm$	1(0)	0	−	139.6	—
	π^0				135.0	—
	ρ {$\rho^\pm$		1	−	755～775	110～140
	ρ^0				760～780	90～150
	δ		?	?	962	<5
	π_v		0	+	1016	25
	A_1		1	+	1070	80
	B		1	+	1220	129
	A_2		2	+	1270～1370	30
	F_1		?	?	1650	～70
	π_A		?	?	1654	109
	ρ_v		? (3)	? (−)	1660	169
	$R_1R_2R_3R_4$		?	?	1650～1850	
	S		?	?	1929±14	≦35
	T		?	?	2195±15	≦13
	U		?	?	2382±24	≦30
イータ中間子	η	0(0)	0	−	549	$2.3 \cdot 10^{-3}$
	ω		1	−	783	12
	$x^0(\eta')$		0	−	958	<4
	H		1	+	990	80
	ϕ		1	−	1019	3
	η_v		0	+	1069	80
	f		2	+	1263	141
	D		1	+	1285	32
	E		0	−	1424	71
	f′		2	+	1514	73
ケイ中間子	K {$K^+(\underline{K}^-)$	1/2(+1)	0	−	493.8	—
	$K^0(K^0)$				497.8	—
	K^*		1	−	893	49
	K_v				1100	～400
	$C(K_A)$		1	+	1230	60
	K_A		1	+	1320	60
	K_v'		2	+	1419	89
	$L(K_A)$		?	?	1781	72
軽粒子	ν {ν_e	—	1/2	+	～0	—
	ν_μ			+	<2.1	—
	e		1/2	+	0.5	—
	μ		1/2	+	105.7	—
光子	γ	0, 1(0)	1	—	0	—

＊ 反粒子の奇妙さは反対符号

粒子共鳴状態のふたつの組全体、スピン０の八種類の中間子とスピン１の八種類のふたつの組全体は、この議論ではそれぞれ全く同じ対称性質をもつというのである。もし、これが正しければ、素粒子群のさらに多数を統一することができる。

また一方では、前章で見てきたように、スピンのレッジェ軌道による素粒子の関連性がある。この二つの見方を結びつけていくことができるならば、見かけほど多種類の素粒子を相手としなくてもすむかも知れない（第27図）。



第27図　素粒子の関連性

幻の粒子コーク

坂田模型と八道説とを比べると、坂田模型は三つの基本粒子の土台から出発しているのに対し、八道説の八つの基本粒子は本当の意味の土台にはなっていない。それは、その模型で使われる論法がほとんど坂田模型と変っていないことから推量できる。実は八道説も前にのべた素粒子を統合していく条件で整理できるのである。

八道説を整理していくと、不思議な三つの基本粒子が登場してくる。それらは、すべて現実に見つかっていないものである。というのは、荷電が電気素量の⅔とか⅓という値をもって、今までの素粒子の通念に反したものになるからで（第10表）、この不思議な粒子を、ゲルマンはコーク、ツワイクはエースと名づけた。果してこれは粒子であるのかないのか。

第10表　コークの量子数

名称	重粒子数	荷　電	奇妙さ
u	＋1/3	＋2/3	0
d	＋1/3	−1/3	0
s	＋1/3	−1/3	−1

第11表　コークによる素粒子の構成

名　称		構　成
陽　子		uud
中 性 子		udd
ラムダ粒子		uds
シグマ粒子（共鳴も含む）	正	uus
	中	uds
	負	dds
グザイ粒子（共鳴も含む）	中	uss
	負	dss
デルタ粒子	正正	uuu
	正	uud
	中	udd
	負	ddd
オメガ粒子		sss

それはさておき、コークから素粒子を見なおすと、素粒子はコーク、あるいは反コークから構成された複合体と考えることができる。そして、八道説の対称性とは実は三つのコークのいれかえの対称性であったことがわかる。それもそのはずで、コークは荷電と重粒子数を別とすれば、その役割は全く坂田模型の基本粒子と異なっていない。その意味で、こういう種類の粒子を原重粒子とか坂田粒子という広い名でよぶ場合もある。

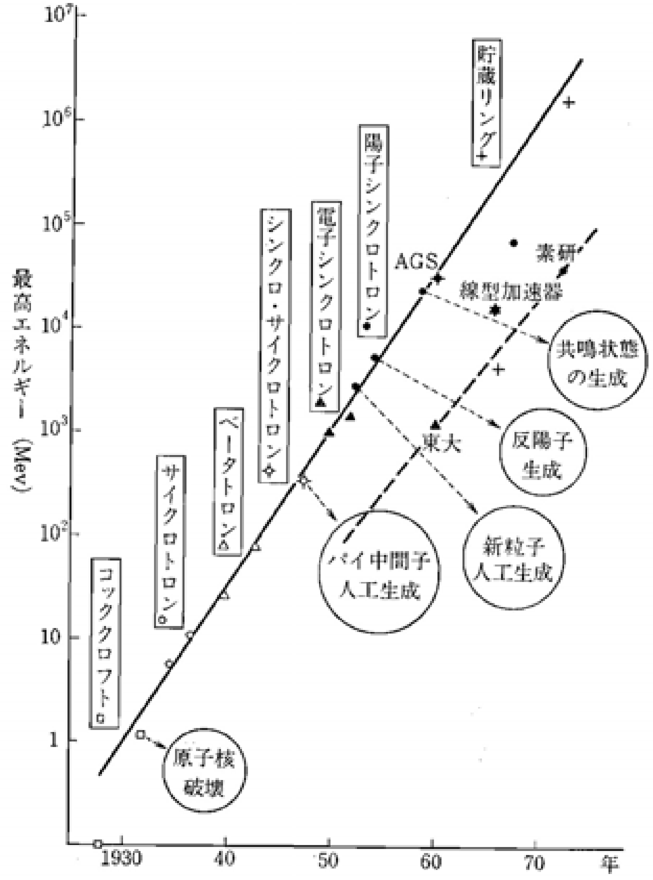
重粒子はコークの三個の複合体で（第11表）、中間子はコークと反コークそれぞれ一個の複合体と考えられる。このおかげで、⅓といった半端な数はなくなり、現実には整数の荷電や重粒子をもつ素粒子があらわれる。しかし、果してそううまくいくのだろうか。一個だけのコークとか、二個コークが組合わさった複合物とかは、整数荷電ではないが、なぜ現実に見つからないのだろう。

コークについて物理学者のなかにふたつの違った意見がある。ひとつは、コークは存在

ここでも素粒子の理論は完全な貧困さを示した。一面では、今までの素粒子とくらべて共鳴状態はその寿命が桁違いに短い。明らかにこれらふたつのものは区別できそうである。ところが、他方では、パイ中間子と核子の散乱では明白でなかったが、共鳴状態が生まれる過程では、それはその前後に存在する素粒子とはちがった個性をもったものとしてふるまうようである。つまり、明らかに素粒子に近いふるまいをする。共鳴状態が素粒子かそうでないのか答えられそうもない以上、われわれはもう一度素粒子について考えなおす立場に立たされたともいえよう。この問題はのちにふたたびふれることとして、共鳴状態を素粒子の第三世代とよんでおこう。

巨大科学へ

一九五〇年代から始まった素粒子の知識の驚くべき増加は、もっぱら巨大加速器によってもたらされた。加速器が素粒子の世界をひらく立役者と考えられ、世界中がこぞってより高いエネルギーの加速器の建設を競いはじめたのも当然である。いろいろの考案によって、われわれの達しうる最高エネルギーは年々順調に増している(第15図)。しかし、そのためにより広大な面積の土地と莫大な費用が必要になってくる。コスモトロンは二〇億円、ユーラトロンは五〇億円かかったといわれるが、現在計画されているものは数百億円から数千億円にのぼるという。わが国の素粒子研究所が計画している四〇〇億電子ボルトの加速器は、建設費三〇〇億円、年間維持費五〇億円を必要とする。このような巨額の投資はもはや国家的な事業としてでなければ不可能になってくるだろう。



第15図　加速器の推移とエネルギーの増加

第1表　素粒子の予見と実証

素粒子名	予見者	実証者
電子	ストーネイ (1890)	トムソン (1897)
陽子	長岡半太郎 (1904)	ラザフォード (1911)
光子	アインシュタイン (1905)	コンプトン (1923)
中性子	ラザフォード (1920)	チャドウィック (1932)
陽電子	ディラック (1930)	アンダーソン (1932)
反陽子	〔ディラック (1930)〕	カリフォルニア・グループ (1955)
中性微子	パウリ (1931)	レインズ，コワン (1953)
パイ中間子	湯川秀樹 (1935)	パウエル，ラッテス (1947)
ミュー中間子	坂田昌一 谷川安孝 (1942) 井上健	アンダーソン， ネッダーマイヤー (1937)＊ (パウエル，ラッテスの確認)(1947)
ミュー中性微子	同上	ブルックヘブン・グループ (1962)
ラムダ粒子	——	ロチェスター，バトラー (1947)
シグマ粒子	——	ロチェスター，バトラー (1947)
ケイ中間子	——	ブリストル・グループ (1949)
グザイ粒子	——	カリフォルニア・グループ (1954)

＊　宇宙線中での中間子の最初の発見(この時はミュー中間子ということは意識されていない)

Beginning of flavor physics

Muon and strange particles were
totally unexpected and unwanted.

“Who ordered the muon?” (I. Rabi)

My 2nd Encounter

学部3年後期「物理学ゼミナール」

「現代物理学における中性粒子」

担当：小柴昌俊

(1976年秋)

What we did

テーマ：

中性粒子： γ, n, π^0, Λ, K^0, ψ

各自1つの粒子を担当し，
自分で調べて発表する。

で，本にまとめる。

新物理学シリーズ 14

山内 恭彦 監修

培風館

高エネルギー物理学

東京大学助教授 Ph. D.

山本 祐靖 著

素粒子物理学の形成

素粒子の特性と相互作用

特性

相互作用

加速器

静電型加速器

線形加速器

円形加速器

ストレージ・リング

加速器からのビーム

検出・測定の機構と装置

断面積と吸収係数

荷電粒子の物質内でのエネルギー損失

レンジとエネルギーとの関係

多重散乱

γ線のエネルギー損失と制動輻射

Cherenkov輻射

カウンター類

放電箱類

泡箱類

素粒子の特性の測定法

π中間子の質量の測定

π中間子のスピンの測定

π中間子のパリティの測定

K中間子の質量の測定

K中間子のスピンとパリティの測定

強い相互作用——保存則

パリティとハイパーチャージ

アイソスピン

強い相互作用——共鳴状態

定価 ¥1500.

Final State Interactionの方法

Sチャネル共鳴状態

$\bar{p}+p$反応における選択則

弱い相互作用——中性K中間子

K_1^0とK_2^0

Regeneration

K^0の崩壊とCPの非保存

弱い相互作用——一般論

弱い相互作用の理論

$|\Delta I|=1/2$の法則

$\Delta S=\Delta Q$の法則

K^0崩壊でのCP非保存の理論的説明

弱い相互作用のその他の問題

電磁相互作用——Photoproduction

光子の性質

多重極展開とPhotoproduction

Vector Dominance

素粒子の分類——SU(3)の例

SU(2)とアイソスピン

SU(3)

Broken SU(3)と質量公式

Ω^-の発見

クォークと坂田モデル

SU(3)の問題点と応用

付録

相対論的運動学

位相空間

部分波解析

素粒子の特性表

Clebsch-Gordan係数と球面調和関数の表

物理定数

3342-2414-6955

D. 素粒子の特性表†

TABLES OF PARTICLE PROPERTIES

April 1973

N. Barash-Schmidt, A. Barbaro-Galtieri, C. Bricman, V. Chaloupka
R. L. Kelly, T. A. Lasinski, A. Rittenberg, M. Roos, A. H. Rosenfeld,
P. Söding, and T. G. Trippe

(Closing date for data: Feb. 1, 1973)

Stable Particle Table

For additional parameters, see Addendum to this table.

Quantities in italics have changed by more than one (old) standard deviation since April 1972.

Particle	$I^G(J^P)C_n$	Mass (MeV) Mass² (GeV)²	Mean life (sec) cτ (cm)	Partial decay mode Mode	Fraction^a	p or p_{max}^b (MeV/c)
γ	0,1(1⁻)⁻	0(<2×10^{-21})	stable	stable		
ν ν_e	J = ½	0(<60 eV)	stable	stable		
ν_μ		0(<1.2)				
e	J = ½	0.5110041 ±.0000016	stable (>2×10^{21}y)	stable		
μ	J = ½	105.6595 ±.0003 m²= 0.0112 $m_\mu - m_{\pi^+}$ = −33.909 ±.006	2.1994×10^{-6} ±.0006 S=1.1 cτ=6.593×10^4	$e\nu\bar{\nu}$	100 %	53
				$e\gamma\gamma$	(<1.6) 10^{-5}	53
				3e	(<6) 10^{-9}	53
				$e\gamma$	(<2.2) 10^{-8}	53
π±	1⁻(0⁻)	139.5688 ±.0064 m²= 0.0195	2.6024×10^{-8} ±.0024 cτ=780.2 $(\tau^+-\tau^-)/\bar{\tau}$= (0.05±0.07)% (test of CPT)	$\mu\nu$	100 %	30
				$e\nu$	(1.24±0.03) 10^{-4}	70
				$\mu\nu\gamma$	(1.24±0.25) 10^{-4}	30
				$\pi^0 e\nu$	(1.02±0.07) 10^{-8}	5
				$e\nu\gamma$	(3.0 ±0.5) 10^{-8}	70
				$e\nu e^+e^-$	(<3.4) 10^{-8}	70
π⁰	1⁻(0⁻)⁺	134.9645 ±.0074 m²= 0.0182 $m_{\pi^\pm} - m_{\pi^0}$ = 4.6043 ±.0037	0.84×10^{-16} ±.10 S=2.1 cτ=2.5×10^{-6}	$\gamma\gamma$	(98.83±0.05)%	67
				γe^+e^-	(1.17±0.05)%	67
				$\gamma\gamma\gamma$	(<5) 10^{-6}	67
				$e^+e^-e^+e^-$	(3.47) 10^{-5}	67

---

† 付録 D, E は California 大学 Lawrence Berkeley Laboratry 提供。

Stable Particle Table *(cont'd)*

Particle	$I^G(J^P)C_n$	Mass (MeV) Mass² (GeV)²	Mean life (sec) cτ (cm)	Partial decay mode Mode	Fraction^a	p or p_{max}^b (MeV/c)
K±	½(0⁻)	493.715 ±0.037 m²=0.244 $m_{K^\pm} - m_{K^0}$ = −3.99 ±0.13 S=1.1	1.2371×10^{-8} ±.0026 S=1.9 cτ=370.8 $(\tau^+-\tau^-)/\bar{\tau}$= (.11±.09)% (test of CPT) S=1.2	$\mu\nu$	(63.52±0.17)%	236
				$\pi\pi^0$	(21.06±0.18)% S=1.1	205
				$\pi\pi^+\pi^-$	(5.59±0.03)% S=1.1	125
				$\pi\pi^0\pi^0$	(1.73±0.05)% S=1.4	133
				$\mu\pi^0\nu$	(3.24±0.10)% S=1.9	215
				$e\pi^0\nu$	(4.85±0.06)% S=1.1	228
				$e\pi^0\pi^0\nu$	(1.8 $^{+2.7}_{-0.6}$) 10^{-5}	207
				$\pi^+\pi^- e^\pm\nu$	(3.7±0.2) 10^{-5}	203
				$\pi^\pm\pi^\pm e^\mp\nu$	(<5) 10^{-7}	203
				$\pi^+\pi^-\mu^\pm\nu$	(0.9 ±0.4) 10^{-5}	151
				$\pi^\pm\pi^\pm\mu^\mp\nu$	(<3) 10^{-6}	151
				$e\nu$	(1.38±0.20) 10^{-5}	247
				$e\nu\gamma$	(<7) 10^{-5}	247
				$\pi\pi^0\gamma$	(2.66±0.16) 10^{-4}	205
				$\pi\pi^+\pi^-\gamma$	(10 ±4) 10^{-5}	125
				$\pi^0 e\nu\gamma$	(3.7 ±1.6) 10^{-4}	227
				πe^+e^-	(<0.4) 10^{-6}	227
				$\pi^- e^+e^+$	(<1.5) 10^{-8}	227
				$\pi\mu^+\mu^-$	(<2.4) 10^{-6}	172
				$\pi\gamma\gamma$	(<3.5) 10^{-5}	227
				$\pi\gamma\gamma\gamma$	(<3) 10^{-4}	227
				$\pi\nu\bar{\nu}$	(<1.4) 10^{-6}	227
				$\pi\gamma$	(<4) 10^{-6}	227
				$\pi^- e^+\mu^+$	(<3) 10^{-8}	214
				$\pi^+ e^-\mu^+$	(<1.4) 10^{-8}	214
				$\mu\nu\nu\bar{\nu}$	(<7) 10^{-6}	236
K⁰	½(0⁻)	497.71 ±0.13 S=1.1	50% K_{Short}, 50% K_{Long}			
K^0_S	½(0⁻)	m²=0.248	0.882×10^{-10} ±.008 S=2.4 cτ=2.65	$\pi^+\pi^-$	(68.81±0.29)% S=1.1	206
				$\pi^0\pi^0$	(31.19±0.29)%	209
				$\mu^+\mu^-$	(<0.7) 10^{-5}	225
				e^+e^-	(<35) 10^{-5}	249
				$\pi^+\pi^-\gamma$	(2.3 ±0.8) 10^{-3}	206
				$\gamma\gamma$	(<0.7) 10^{-3}	249
K^0_L	½(0⁻)	$m_{K_L} - m_{K_S}$ = 0.5402×10^{10}ħ sec⁻¹ ± 0.0035	5.181×10^{-8} ±0.011 cτ=1553	$\pi^0\pi^0\pi^0$	(21.5 ±0.8)% S=1.4	139
				$\pi^+\pi^-\pi^0$	(12.6 ±0.3)%	133
				$\pi\mu\nu$	(26.9 ±0.6)% S=1.1	216
				$\pi e\nu$	(38.8 ±0.6)% S=1.1	229
				$\pi e\nu\gamma$	(1.3 ±0.8)%	229
				$\pi^+\pi^-$	(0.157±0.005)%	206
				$\pi^0\pi^0$	(0.094±0.019)% S=1.5	209
				$\pi^+\pi^-\gamma$	(<0.4) 10^{-3}	206
				$\pi^0\gamma\gamma$	(<2.4) 10^{-4}	231
				$\gamma\gamma$	(4.9 ±0.4) 10^{-4}	249
				$e\mu$	(<1.6) 10^{-9}	238
				$\mu^+\mu^-$	(<1.8) 10^{-9}	225
				e^+e^-	(<1.6) 10^{-9}	249
η	0⁺(0⁻)⁺	548.8 ±0.6 S=1.4 m²=0.301	Γ=(2.63±0.58)keV Neutral decays 71.1%	$\gamma\gamma$	(38.0 ±1.0)% S=1.2	274
				$\pi^0\gamma\gamma$	(3.1 ±1.1)% S=1.2	258
				$3\pi^0$	(30.0 ±1.1)% S=1.1	180
			Charged decays 28.9%	$\pi^+\pi^-\pi^0$	(23.9 ±0.6)% S=1.1	175
				$\pi^+\pi^-\gamma$	(5.0 ±0.1)%	236
				$\pi^0 e^+e^-$	(<0.04)%	258
				$\pi^+\pi^- e^+e^-$	(0.1 ±0.1)%	236
				$\pi^+\pi^-\pi^0\gamma$	(<0.2)%	175
				$\pi^+\pi^-\gamma\gamma$	(<0.2)%	236
				$\mu^+\mu^-$	(2.2 ±0.8) 10^{-5}	253
				$\mu^+\mu^-\pi^0$	(<5) 10^{-4}	211
p	½(½⁺)	938.2592 ±0.0052 m²=0.8803	stable (>2×10^{28}y)			
n	½(½⁺)	939.5527 ±0.0052 m²=0.8828 $m_p - m_n$ = −1.29344 ±0.00007	(0.918±0.014)10^3 cτ = 2.75×10^{13}	$pe^-\nu$	100 %	1

Role played by Kaons in history

- First strange particle to be observed

  (Leprince-Ringuet and Lheritier, 1944)
- Particle-Antiparticle mixing

  (Gell-Mann and Pais, 1955)
- $\tau - \theta$ Puzzle, leading to parity violation

  (many people, Lee and Yang, 1956)
- CP violation in $K_L \rightarrow 2\pi$

  (Christensen et al., 1964)

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE-ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER
AND
Dr. C. C. BUTLER
Physical Laboratories, University, Manchester

AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe that one of the forked tracks, shown in Fig. 1 (tracks *a* and *b*), represents the spontaneous transformation in the gas of the chamber of a new type of uncharged elementary particle into lighter charged particles, and that the other, shown in Fig. 2 (tracks *a* and *b*), represents similarly the transformation of a new type of charged particle into two light particles, one of which is charged and the other uncharged.

The experimental data for the two forks are given in Table 1; H is the value of the magnetic field, α the angle between the tracks, p and Δp the measured momentum and the estimated error. The signs of the particles are given in the last column of the table, a plus sign indicating that the particle is positive if moving down in the chamber. Careful re-projection of the stereoscopic photographs has shown that each pair of tracks is copunctal. Moreover, both tracks occur in the middle of the chamber in a region of uniform illumination, the presence of background fog surrounding the tracks indicating good condensation conditions.

TABLE 1. EXPERIMENTAL DATA

Photograph	H (gauss)	α (deg.)	Track	p (eV./c.)	Δp (eV./c.)	Sign
1	3500	66·6	*a* *b*	$3{\cdot}4 \times 10^8$ $3{\cdot}5 \times 10^8$	$1{\cdot}0 \times 10^8$ $1{\cdot}5 \times 10^8$	+ −
2	7200	161·1	*a* *b*	$6{\cdot}0 \times 10^8$ $7{\cdot}7 \times 10^8$	$3{\cdot}0 \times 10^8$ $1{\cdot}0 \times 10^8$	+ +

Though the two forks differ in many important respects, they have at least two essential features in common: first, each consists of a two-pronged fork with the apex in the gas; and secondly, in neither case is there any sign of a track due to a third ionizing particle. Further, very few events at all similar to these forks have been observed in the 3-cm. lead plate, whereas if the forks were due to any type of collision process one would have expected several hundred times as many as in the gas. This argument indicates, therefore, that the tracks cannot be due to a collision process but must be due to some type of spontaneous process for which the probability depends on the distance travelled and not on the amount of matter traversed.

This conclusion can be supported by detailed arguments. For example, if either forked track were due to the deflexion of a charged particle by collision with a nucleus, the transfer of momentum would be so large as to produce an easily visible recoil track. Then, again, the attempt to account for Fig. 2 by a collision process meets with the difficulty that the incident particle is deflected through 19° in a single collision in the gas and only 2·4° in traversing 3 cm. of lead—a most unlikely event. One specific collision process, that of electron pair production by a high-energy photon in the field of the nucleus, can be excluded on two grounds; the observed angle between the tracks would only be a fraction of a degree, for example, 0·1° for Fig. 1, and a large amount of electronic component should have accompanied the photon, as in each case a lead plate is close above the fork.

We conclude, therefore, that the two forked tracks do not represent collision processes, but do represent spontaneous transformations. They represent a type of process with which we are already familiar in the decay of the meson into an electron and an assumed neutrino, and the presumed decay of the heavy meson recently discovered by Lattes, Occhialini and Powell[1].

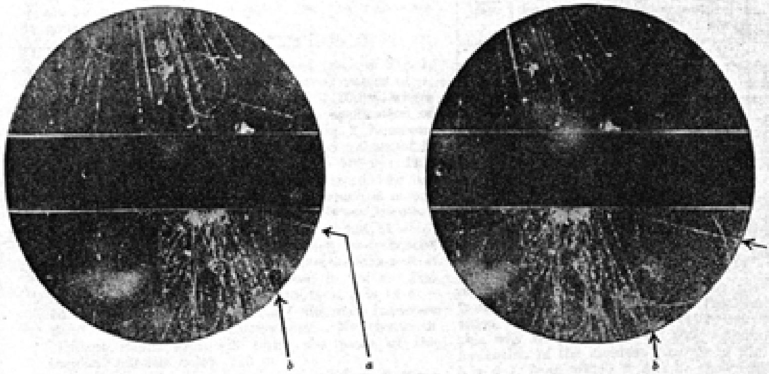


Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

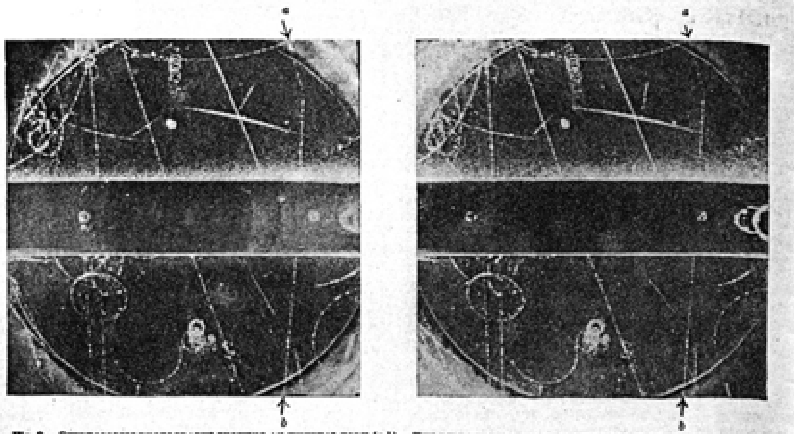


Fig. 2. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*). THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN A CLOCKWISE DIRECTION

The Masses of the Incident Particles

Let us assume that a particle of mass M and initial momentum P is transformed spontaneously into two particles of masses m_1 and m_2, momenta p_1 and p_2 at angles of θ and φ with the direction of the incident particle. Then the following relations must hold:

$$\sqrt{M^2c^4+P^2c^2} = \sqrt{m_1^2c^4+p_1^2c^2} + \sqrt{m_2^2c^4+p_2^2c^2} \qquad (1)$$

$$P = p_1 \cos\theta + p_2 \cos\varphi \qquad (2)$$

$$p_1 \sin\theta = p_2 \sin\varphi. \qquad (3)$$

These general relations may be used to obtain the mass of the incident particle as a function of the assumed masses of the secondary particles.

The value of M must be greater than that obtained by taking the rest masses of the secondary particles as small compared with their momenta; thus the minimum value $M_{\min}$ is given by the following equation:

$$M_{\min}c^2 = c\sqrt{(p_1 + p_2)^2 - P^2}. \qquad (4)$$

Applying this equation to the forked track of Fig. 1, after calculating P from the observed values of p_1 and p_2, it is found that $M_{\min}$ is $(770 \pm 200)m$, where m is the mass of the electron. The application of equation (4) to the forked track of Fig. 2, however, after calculating p_2 from the observed values of P and p_1, shows that $M_{\min} = (1{,}700 \pm 150)m$. This value of the mass would require an ionization for the incident particle of twice minimum, which is inconsistent with the observed ionization. We are therefore justified in assuming that the real value of P is greater than the observed value which, as indicated in Table 1, has a large error. If larger values of P are assumed, then $M_{\min}$ is reduced in value. The lowest value of $M_{\min}$ is $(980 \pm 150)m$ if P is $14{\cdot}5 \times 10^8$ eV./c. Beyond this value of P the mass increases slowly with increasing momentum. No choice of incident momentum will bring the mass of the incident particle below 980 m.

In the special case where the incident particle disintegrates transversely into two particles of equal mass m_s, giving a symmetrical fork, equation (1) reduces to the following expression,

$$\frac{M}{m} = \frac{2m_s}{m}\left(1 + \frac{p^2c^2}{m_s^2c^4}\cdot\sin^2\theta\right)^{1/2}. \qquad (5)$$

where p is the momentum of each of the secondary particles. Some typical results for different assumed secondary particles, calculated from equation (5), are given in Table 2. On the reasonable assumption that the secondary particles are light or heavy mesons, that is, with masses of $200m$ or $400m$, we find that the incident particle in each photograph has a mass of the order of $1{,}000m$.

TABLE 2. MASS OF INCIDENT PARTICLE AS A FUNCTION OF MASS OF SECONDARY PARTICLE

Photograph	Assumed secondary particle m_s/m	Momentum of observed secondary particle (eV./c.)	Incident particle M/m
1	0 200 400 1837	$3{\cdot}5 \times 10^8 \pm 1{\cdot}0 \times 10^8$ " " "	770 ± 200 870 ± 200 1110 ± 150 3750 ± 50
2	0 200 400 1837	$7{\cdot}7 \times 10^8 \pm 1{\cdot}0 \times 10^8$ " " "	980 ± 150 1080 ± 100 1280 ± 100 3820 ± 50

Upper values of the masses of the incident particles may also be obtained from the values of the ionization and the momenta. Thus for each of the observed particles in Fig. 1, the ionization is indistinguishable from that of a very fast particle. We conclude, therefore, that $\beta = v/c \gg 0{\cdot}7$. Since the momentum of the incident particle may be found from the observed momenta of the secondary particles, we can apply equation (1) to calculate M. In this way we find $M/m \ll 1{,}600$. Again, since the ionization of the incident particle in Fig. 2 is light, $\beta \gg 0{\cdot}7$, from which it can be shown that $M/m \ll 1200$. This last result, however, must be taken with

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LE JOURNAL DE PHYSIQUE
ET
LE RADIUM

EXISTENCE PROBABLE D'UNE PARTICULE DE MASSE (990 ± 12 pour 100) m_0 DANS LE RAYONNEMENT COSMIQUE

Par L. LEPRINCE-RINGUET et M. LHÉRITIER.

Sommaire. — La méthode de la collision élastique entre particule incidente et électron du gaz d'une chambre de Wilson a été appliquée à un certain nombre de chocs observés sur un total d'environ 10 000 trajectoires. Dans les cas favorables, la masse de la particule incidente peut ainsi être mesurée. Nous avons, en particulier, observé une collision permettant d'attribuer, si toutefois elle est élastique, à la particule incidente, la masse (990 ± 12 pour 100), m_0, soit environ quatre fois la masse du mésoton habituel et moitié de celle du proton.

L'observation, faite en 1940 par L. Leprince-Ringuet, E. Nageotte, S. Gorodetzky et R. Richard-Foy (1) d'un cliché de collision entre un mésoton du rayonnement cosmique et un électron du gaz d'une chambre de Wilson avait permis, en admettant le caractère élastique du choc, de calculer la masse du mésoton avec une assez bonne précision

Ringuet (4) ont permis de préciser les conditions expérimentales les plus favorables à une bonne détermination de la masse. A la suite de ces travaux, des recherches expérimentales ont été poursuivies au laboratoire de Largentière-la-Bessée (Hautes-Alpes) situé à 1000 m d'altitude, au moyen d'une grande chambre de Wilson (75 cm de hauteur, 15 de

Concept of strangeness

- Unjustified belief at that time
  - Fermions have half-integal isospin (like nucleons)
  - Bosons have integral isospin (like pions)

- Most important point of Gell-Mann, Nakano & Nishijima
  - V_1's (Λ, Σ) have isospin 0, 1
  - θ's (K) have isospin 1/2

Gell-Mann

The value of A_2 agrees with the value $A_2=-0.17\pm0.01$ corresponding to the maximum anisotropy found with the single, crystal sources. As to the electric quadrupole interaction energy the value obtained here should not be considered more than a rough estimate, due to the crude approximation for τ_c and also due to the fact that $\partial^2V/\partial z'^2$ is probably not the same for the different water-glycerine mixtures. Nuclear magnetic resonance absorption experiments, however, show a remarkable constancy of the details of the molecular motion for different water-glycerine mixtures up to $\eta=1$ poise at least as far as the magnetic interaction is concerned.

Further experiments, to study the validity of the assumptions made above and to arrive at a better estimate of the quadrupole interaction, are in progress and will be reported later.

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* Supported by the U. S. Atomic Energy Commission.

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Isotopic Spin and New Unstable Particles

M. Gell-Mann
Department of Physics and Institute for Nuclear Studies,
University of Chicago, Chicago, Illinois

(Received August 21, 1953)

PEASLEE[1] has considered the interesting possibility that the principle of charge independence, now believed to hold for nucleons and pions, may extend to the new unstable particles as well. In order to discuss this suggestion, let us suppose that both "ordinary particles" (nucleons and pions) and "new unstable particles" (V_1, V_4, τ, etc.) have interactions of three kinds:

(i) Interactions that rigorously conserve isotopic spin. (We assume these to be strong.)

(ii) Electromagnetic interactions. (Let us include mass-difference effects in this category.)

(iii) Other charge-dependent interactions, which we take to be very weak.

Peaslee inquires whether the quasi stability of the V_1^0 may be accounted for in this way if we assume it has isotopic spin 5/2. With respect to (i) the decay into pion and nucleon is absolutely forbidden. Interactions of type (iii) are supposed to be weak enough to account for the long observed lifetime of $\sim3\times10^{-10}$ second. However, he concludes that effects of type (ii) will cause transitions in a very much shorter time than this, since, for example, each electromagnetic interaction can change the isotopic spin of the system by one unit.

Recently Pais[2] has made the ingenious proposal that the new unstable particles differ from the ordinary ones in possessing one unit of "orbital isotopic angular momentum" and a negative "isotopic parity." If we then re-interpret (i) as referring to conservation of total isotopic angular momentum and isotopic parity, we see that as far as (i) is concerned, the decay of new unstable particles into ordinary ones is forbidden. Also, these particles will always be produced in even numbers, as Pais had suggested earlier.[3] Moreover, effects of type (ii) conserve isotopic parity, as Pais has introduced it, and so do not contribute to instability of the new particles.

In connection with the work of Peaslee and of Pais, the author would like to put forward an alternative hypothesis that he has considered for some time, and which, like that of Pais, overcomes the difficulty posed by electromagnetic interactions. Let us suppose that the new unstable particles are fermions with integral isotopic spin and bosons with half-integral isotopic spin. For example, the V_1 particles may form an isotopic triplet, consisting of V_1^+, V_1^0, and V_1^-. The τ^+ and V_4^0 may form an isotopic doublet, which we may call τ^+ and τ^0. To each of these particles there

would presumably correspond an antiparticle,[4] which we shall denote by means of square brackets.

In this scheme, (ii) is ineffective in causing decay because it can change isotopic spin only by integers, whereas in $V_1^0\rightarrow\pi^-+p$, for example, the isotopic spin is 1 on the left and $\frac{1}{2}$ or $\frac{3}{2}$ on the right. Only interactions of type (iii), which do not respect isotopic spin at all, can lead to decay. Moreover, the new unstable particles again are produced only in even numbers.

There is no difficulty associated with stating a generalized Pauli principle for each kind of new unstable particle. For example, let us postulate that the wave function of a collection of V_1's must be totally antisymmetric in space, spin, and isotopic spin. If the wave function of two V_1's is antisymmetric in space and spin, as it would be for particles of identical charge, then the total isotopic spin must be 0 or 2, which includes $V_1^+V_1^+$, $V_1^-V_1^-$, and $V_1^0V_1^0$. If the total isotopic spin is 1, the wave function is to be symmetric in space and spin, which is all right since the charges are then not identical. Similarly, the postulate that the wave function of a collection of τ's must be totally symmetric in space, spin, and isotopic spin leads to no contradictions.

It should be noted that according to this scheme the conservation of the z component of isotopic spin is more stringent than conservation of charge.[5] To see this, let us remark that the τ^+ and τ^0 have z components equal to $+\frac{1}{2}$ and $-\frac{1}{2}$, respectively, like the proton and neutron. Correspondingly the antiparticles $[\tau^+]$ and $[\tau^0]$ have z components equal to $-\frac{1}{2}$ and $+\frac{1}{2}$, respectively, like the antiproton and antineutron. Thus we see that the reactions $\pi^-+p\rightarrow V_1^0+\tau^0$ and $\pi^-+p\rightarrow V_1^-+\tau^+$ are allowed, while the reactions $\pi^-+p\rightarrow V_1^0+[\tau^0]$ and $\pi^-+p\rightarrow V_1^++[\tau^+]$ are forbidden, although all four are allowed by conservation of charge. In order to produce anti-τ's it would be necessary to resort to a reaction like $\pi^-+p\rightarrow n+\tau^++[\tau^+]$ or $\pi^-+p\rightarrow n+\tau^0+[\tau^0]$.

In a similar fashion, all reactions of the form nucleon+nucleon→V_1+V_1 and all reactions of the form τ+nucleon→$V_1+\pi$ are forbidden, while reactions such as nucleon+nucleon→$V_1+\tau$+nucleon or $[\tau]$+nucleon→$V_1+\pi$ are allowed.

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[2] A. Pais (unpublished). The author is indebted to Professor Pais for the communication of his results prior to publication.

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[4] We postulate the principle of invariance under the operation of charge conjugation, which carries every particle into its antiparticle. In the case of charged particles, such as the electron and the π^+, it is obvious that the antiparticles are the positron and the π^-, respectively. A neutral particle, however, may or may not be identical with its antiparticle. Among neutral fermions, it is necessary that the neutron and the antineutron be distinct, while the question of whether the neutrino and antineutrino are distinct is one that must be settled by experiment. Among neutral bosons, the γ ray and π^0 are apparently identical with their respective antiparticles, but there is no reason to believe that this is a general rule. We suppose here that the τ^0 is a neutral boson which is not identical with its antiparticle. A model for such a situation is provided by picturing the τ particle as a complex of a nucleon and an anti-V_1, while the $[\tau]$ is pictured as the corresponding complex of antinucleon and V_1.

[5] Of course the conservation of charge is absolute, while the conservation of the z component of isotopic spin can be violated by interactions of type (iii). Such violations should, however, play no important role in production phenomena.

Differential p-p Elastic-Scattering Cross Section at 144, 271, and 429 Mev*

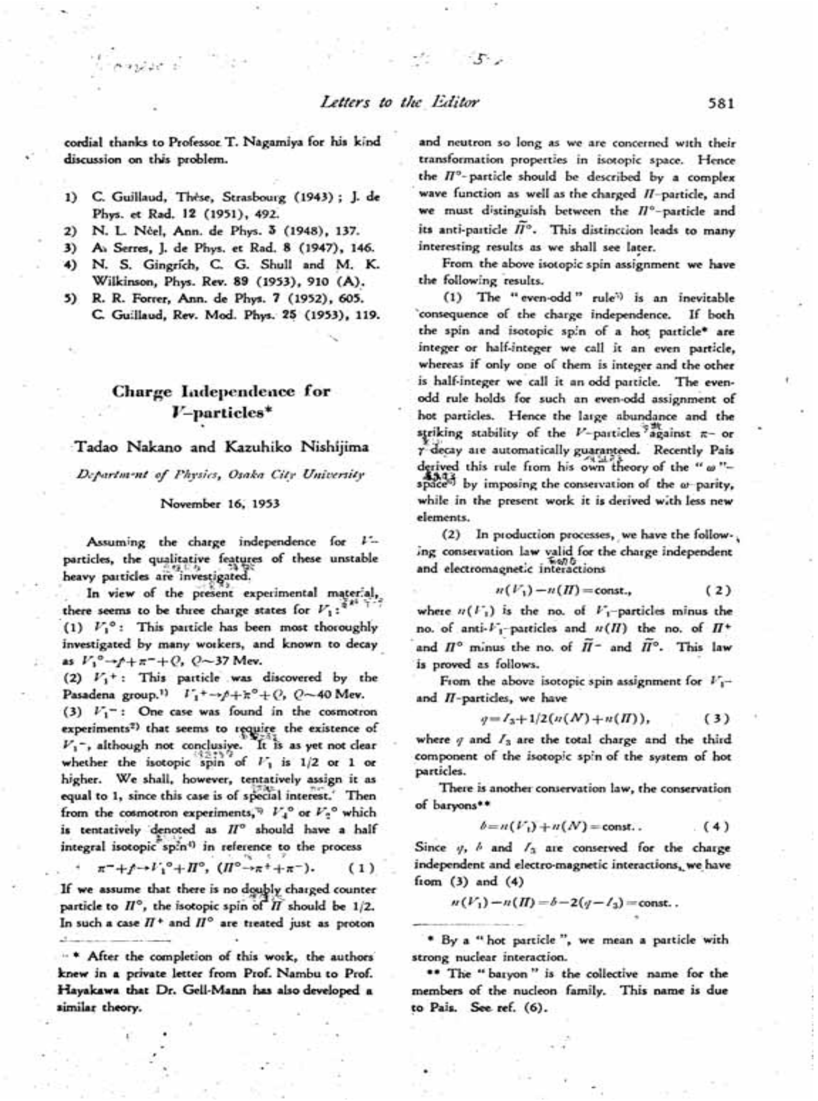
J. Marshall, L. Marshall, and V. A. Nedzel
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received August 24, 1953)

THE differential p-p elastic-scattering cross section at 90 degrees barycentric angle has been determined at 144, 271, and 429 Mev and has been found to be constant with energy within experimental error. In addition, the differential elastic-scattering cross section for 429-Mev protons on liquid hydrogen has been measured as a function of angle by a scintillation counter technique which counts both incident and scattered protons, individually.

A beam of protons was scattered from a beryllium target in the 170-inch synchrocyclotron, was analyzed in the fringing field

Nakano-Nishijima



cordial thanks to Professor T. Nagamiya for his kind discussion on this problem.

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Charge Independence for V-particles*

Tadao Nakano and Kazuhiko Nishijima
Department of Physics, Osaka City University

November 16, 1953

Assuming the charge independence for V-particles, the qualitative features of these unstable heavy particles are investigated.

In view of the present experimental material, there seems to be three charge states for V_1:

(1) V_1°: This particle has been most thoroughly investigated by many workers, and known to decay as $V_1^\circ\rightarrow p+\pi^-+Q$, $Q\sim37$ Mev.

(2) V_1^+: This particle was discovered by the Pasadena group.¹⁾ $V_1^+\rightarrow p+\pi^\circ+Q$, $Q\sim40$ Mev.

(3) V_1^-: One case was found in the cosmotron experiments²⁾ that seems to require the existence of V_1^-, although not conclusive. It is as yet not clear whether the isotopic spin of V_1 is 1/2 or 1 or higher. We shall, however, tentatively assign it as equal to 1, since this case is of special interest. Then from the cosmotron experiments,³⁾ V_4° or V_2° which is tentatively denoted as $\varPi^\circ$ should have a half integral isotopic spin⁴⁾ in reference to the process

$$\pi^-+p\rightarrow V_1^\circ+\varPi^\circ,\ (\varPi^\circ\rightarrow\pi^++\pi^-). \qquad (1)$$

If we assume that there is no doubly charged counter particle to $\varPi^\circ$, the isotopic spin of $\varPi$ should be 1/2. In such a case $\varPi^+$ and $\varPi^\circ$ are treated just as proton and neutron so long as we are concerned with their transformation properties in isotopic space. Hence the $\varPi^\circ$-particle should be described by a complex wave function as well as the charged $\varPi$-particle, and we must distinguish between the $\varPi^\circ$-particle and its anti-particle $\tilde{\varPi}^\circ$. This distinction leads to many interesting results as we shall see later.

From the above isotopic spin assignment we have the following results.

(1) The "even-odd" rule⁵⁾ is an inevitable consequence of the charge independence. If both the spin and isotopic spin of a hot particle* are integer or half-integer we call it an even particle, whereas if only one of them is integer and the other is half-integer we call it an odd particle. The even-odd rule holds for such an even-odd assignment of hot particles. Hence the large abundance and the striking stability of the V-particles against π- or γ decay are automatically guaranteed. Recently Pais derived this rule from his own theory of the "ω"-space⁶⁾ by imposing the conservation of the ω-parity, while in the present work it is derived with less new elements.

(2) In production processes, we have the following conservation law valid for the charge independent and electromagnetic interactions

$$n(V_1)-n(\varPi)=\text{const.}, \qquad (2)$$

where $n(V_1)$ is the no. of V_1-particles minus the no. of anti-V_1-particles and $n(\varPi)$ the no. of $\varPi^+$ and $\varPi^\circ$ minus the no. of $\tilde{\varPi}^-$ and $\tilde{\varPi}^\circ$. This law is proved as follows.

From the above isotopic spin assignment for V_1- and $\varPi$-particles, we have

$$q=I_3+1/2(n(N)+n(\varPi)), \qquad (3)$$

where q and I_3 are the total charge and the third component of the isotopic spin of the system of hot particles.

There is another conservation law, the conservation of baryons**

$$b=n(V_1)+n(N)=\text{const.}. \qquad (4)$$

Since q, b and I_3 are conserved for the charge independent and electro-magnetic interactions, we have from (3) and (4)

$$n(V_1)-n(\varPi)=b-2(q-I_3)=\text{const.}.$$

---

* After the completion of this work, the authors knew in a private letter from Prof. Nambu to Prof. Hayakawa that Dr. Gell-Mann has also developed a similar theory.

* By a "hot particle", we mean a particle with strong nuclear interaction.

** The "baryon" is the collective name for the members of the nucleon family. This name is due to Pais. See ref. (6).

In view of the present experimental material, there seems to be three charge states for V_1:

(1) V_1°: This particle has been most thoroughly investigated by many workers, and known to decay as $V_1^\circ \rightarrow p+\pi^- + Q$, $Q \sim 37$ Mev.

(2) V_1^+: This particle was discovered by the Pasadena group.[1] $V_1^+ \rightarrow p+\pi^\circ + Q$, $Q \sim 40$ Mev.

(3) V_1^-: One case was found in the cosmotron experiments[2] that seems to require the existence of V_1^-, although not conclusive. It is as yet not clear whether the isotopic spin of V_1 is 1/2 or 1 or higher. We shall, however, tentatively assign it as equal to 1, since this case is of special interest. Then from the cosmotron experiments,[3] V_4° or V_2° which is tentatively denoted as Π° should have a half integral isotopic spin[4] in reference to the process

$$\pi^- + p \rightarrow V_1^\circ + \Pi^\circ, \ (\Pi^\circ \rightarrow \pi^+ + \pi^-). \qquad (1)$$

If we assume that there is no doubly charged counter particle to Π°, the isotopic spin of Π should be 1/2. In such a case Π^+ and Π° are treated just as proton

where $n(V_1)$ is the no. of V_1-particles minus the no. of anti-V_1-particles and $n(\Pi)$ the no. of Π^+ and Π° minus the no. of $\tilde{\Pi}^-$ and $\tilde{\Pi}^\circ$. This law is proved as follows.

From the above isotopic spin assignment for V_1- and Π-particles, we have

$$q = I_3 + 1/2(n(N)+n(\Pi)), \qquad (3)$$

where q and I_3 are the total charge and the third component of the isotopic spin of the system of hot particles.

There is another conservation law, the conservation of baryons**

$$b = n(V_1) + n(N) = \text{const.}. \qquad (4)$$

Since q, b and I_3 are conserved for the charge independent and electro-magnetic interactions, we have from (3) and (4)

$$n(V_1) - n(\Pi) = b - 2(q - I_3) = \text{const.}.$$

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* After the completion of this work, the authors knew in a private letter from Prof. Nambu to Prof. Hayakawa that Dr. Gell-Mann has also developed a similar theory.

* By a "hot particle", we mean a particle with strong nuclear interaction.

** The "baryon" is the collective name for the members of the nucleon family. This name is due to Pais. See ref. (6).

Concept of strangeness

- With these assignments, strangeness conservation is automatic when we assume conservation of Q, B, I_3

$$Q = I_3 + ½ (B + S)$$

- Notable corollary: K^0 and $\bar{K}^0$ are different

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

I

IT is generally accepted that the microscopic laws of physics are invariant to the operation of charge conjugation (CC); we shall take the rigorous validity of this postulate for granted. Under CC, every particle

must not change sign can be inferred from the observed two-photon decay of the π^0. 推論される.

We are effectively dealing here with the "charge conjugation quantum number" C, which is the eigenvalue of the operator $\mathcal{C}$, and which is rigorously conserved in the absence of external fields. If only an odd (even) number

$K - \bar{K}$ mixing

- Neutral Kaons
  - Are produced as a $\bar{K}$ or K (by strong int.)
  - Decay as a K_S or K_L (by weak int.)
- Totally quantum mechanical phenomenon

- Smallness of the mixing ➡ GIM

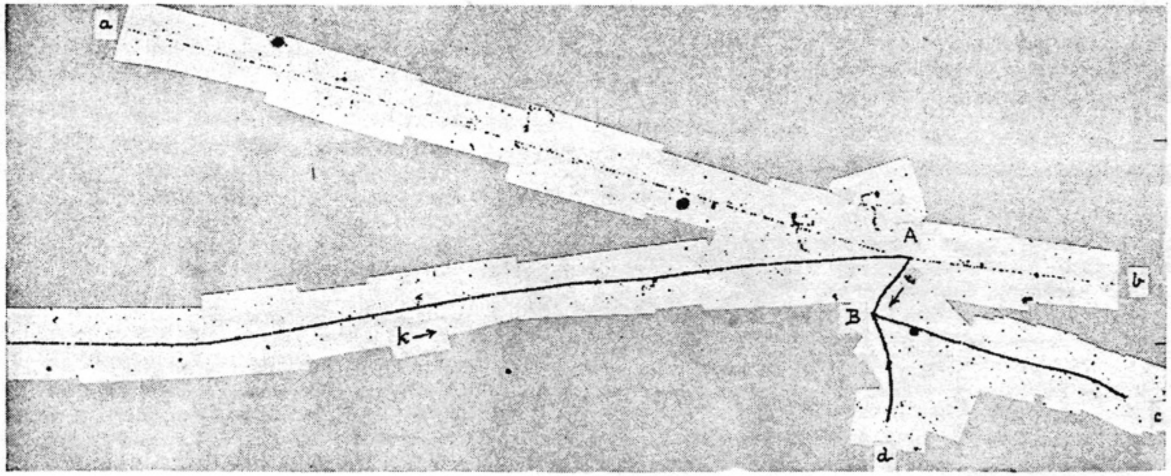
OBSERVATIONS WITH ELECTRON-SENSITIVE PLATES EXPOSED TO COSMIC RADIATION*

By Miss R. BROWN, U. CAMERINI, P. H. FOWLER, H. MUIRHEAD
and Prof. C. F. POWELL
H. H. Wills Physical Laboratory, University of Bristol

and D. M. RITSON
Clarendon Laboratory, Oxford

PART 2. FURTHER EVIDENCE FOR THE EXISTENCE OF UNSTABLE CHARGED PARTICLES, OF MASS ~ 1,000 m_e, AND OBSERVATIONS ON THEIR MODE OF DECAY

ONE of the first events found in the examination of electron-sensitive plates exposed at the Jungfraujoch is represented in the mosaic of photomicrographs shown in Fig. 8. There are two centres, *A* and *B*, from which the tracks of charged particles diverge, and these are joined by a common track, *t*. Because of the short duration of the exposure, and the small number of disintegrations occurring in the plate, the chance that the observation corresponds to a fortuitous juxtaposition of the tracks of unrelated events is very small—of the order 1 in 10^7. It is therefore reasonable to exclude it as a serious possibility. Further observations in support of this assumption are presented in a later paragraph.



Observer: Mrs. W. J. van der Merwe

Fig. 8

An inspection of the track *k* shows that the particle producing it approached the centre of disintegration *A*. The range of the particle in the emulsion exceeds

that it carried the elementary electronic charge; and that it had reached, or was near, the end of its range at the point *A*. We therefore assume that the particle *k* initiated the train of events represented by the tracks radiating from *A* and *B*. It follows that the particle producing track *t* originated in star *A*, and produced the disintegration *B*. In order to analyse the event, we first attempted to determine the mass of the particle *k*.

Mass Determinations by Grain-Counts

About a year ago, experiments were made in this Laboratory to determine the ratio, m_π/m_μ, of the masses of π- and μ-mesons, by the method of grain-counting[5], and by studying the small-angle scattering of the particles in their passage through the emulsion[4]. The values obtained by the two methods were $m_\pi/m_\mu = 1\cdot65 \pm 0\cdot11$, and $m_\pi/m_\mu = 1\cdot35 \pm 0\cdot10$*, respectively. Recent experiments at Berkeley[6] suggest that the true value is $1\cdot33 \pm 0\cdot02$, a result which throws serious doubt on the reliability of the method based on grain-counts. Because of the

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Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

The existence of parity selection rules which work well in atomic and nuclear physics is a clear indication that the degree of mixing, $\mathfrak{F}^2$, cannot be large. From such considerations one can impose the limit $\mathfrak{F}^2 \lesssim (r/\lambda)^2$, which for atomic spectroscopy is, in most cases, $\sim 10^{-6}$. In general a less accurate limit obtains for nuclear

Building the Standard Model

- Structure of the charged-current weak interactions (current-current form, flavor universality) suggested that a charged gauge boson (W) is responsible for CC
- Parity violation in W interactions leads to the introduction of neutral-current weak interactions (Glashow 1961), later confirmed in neutrino experiments (1973)

Building the Standard Model

- Absence of flavor-changing neutral current (FCNC) interactions posed theoretical problem, solved by the introduction of a fourth (charm) quark (Glashow, Iliopoulos, Maiani, 1970)
- Leptons and three colors of quarks are just right in canceling chiral anomaly, which could have destroyed the renormalizability (Bouchiat, Iliopoulos, Meyer, 1972)

Building the Standard Model

- CP violation can be successfully incorporated in the Standard Model by assuming six flavors of quarks (Kobayashi and Maskawa, 1972)

Wealth of new particles in 1970's

- Weak neutral current (1973)
- November revolution (J/ψ) (1974)
- Third generation (τ lepton) (1975)
- Charmed particles (1976)
- Upsilons (1977)

bottom lifetime

$$\frac{1}{\tau_b} \simeq \frac{1}{\tau_\mu} \times \left(\frac{m_b}{m_\mu} \right)^5 \times 9 \times \mathrm{CKM}$$

Naïve expectation before 1983:

$$\mathrm{CKM} \approx \sin^2 \theta_C \quad \Rightarrow \quad \tau_b \sim 4 \times 10^{-14}\,\mathrm{sec}$$

Too short to be easily observable

Pioneering experiment

JADE Collab., Phys. Lett. 114B, 71 (1982)

muon impact parameter distrib.
in *b* enriched sample

$\tau_b < 1.4 \times 10^{-12}$ sec (95%CL)

UPPER LIMIT ON BEAUTY LIFETIME AND LOWER LIMIT ON WEAK MIXING ANGLES

JADE Collaboration

W. BARTEL, D. CORDS, P. DITTMANN, R. EICHLER [1], R. FELST, D. HAIDT, H. KREHBIEL, K. MEIER, B. NAROSKA, L.H. O'NEILL [2], P. STEFFEN, H. WENNINGER [3]
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

E. ELSEN, A. PETERSEN, P. WARMING, G. WEBER
II. Institut für Experimentalphysik der Universität Hamburg, Germany

S. BETHKE, H. DRUMM [4], J. HEINTZE, G. HEINZELMANN, K.H. HELLENBRAND, R.D. HEUER, J. von KROGH, P. LENNERT, S. KAWABATA, S. KOMAMIYA, H. MATSUMURA, T. NOZAKI, J. OLSSON, H. RIESEBERG, A. WAGNER
Physikalisches Institut der Universität Heidelberg, Germany

A. BELL, F. FOSTER, G. HUGHES, H. WRIEDT
University of Lancaster, England

J. ALLISON, A.H. BALL, G. BAMFORD, R. BARLOW, C. BOWDERY, I.P. DUERDOTH, J.F. HASSARD [5], B.T. KING [6], F.K. LOEBINGER, A.A. MACBETH, H. McCANN, H.E. MILLS, P.G. MURPHY, K. STEPHENS
University of Manchester, England

D. CLARKE, M.C. GODDARD, R. MARSHALL, G.F. PEARCE
Rutherford Appleton Laboratory, Chilton, England

and

J. KANZAKI, T. KOBAYASHI, M. KOSHIBA, M. MINOWA, M. NOZAKI, S. ODAKA, S. ORITO, A. SATO, H. TAKEDA, Y. TOTSUKA, Y. WATANABE, S. YAMADA and C. YANAGISAWA [7]
Lab. of Int. Coll. on Elementary Particle Physics and Department of Physics, University of Tokyo, Japan

Received 18 March 1982

Surprise from PEP

MAC Collab., Phys. Rev. Lett. 51, 1022 (1983)

Mark II Collab., Phys. Rev. Lett. 51, 1316 (1983)

$\tau_b = (1.8 \pm 0.6 \pm 0.4)\ \mathrm{x}\ 10^{-12}$ sec (MAC)

$\tau_b = (1.2 \pm {}^{0.45}{}_{0.36} \pm 0.3)\ \mathrm{x}\ 10^{-12}$ sec (MKII)

$|V_{cb}|$ unexpectedly small ➡

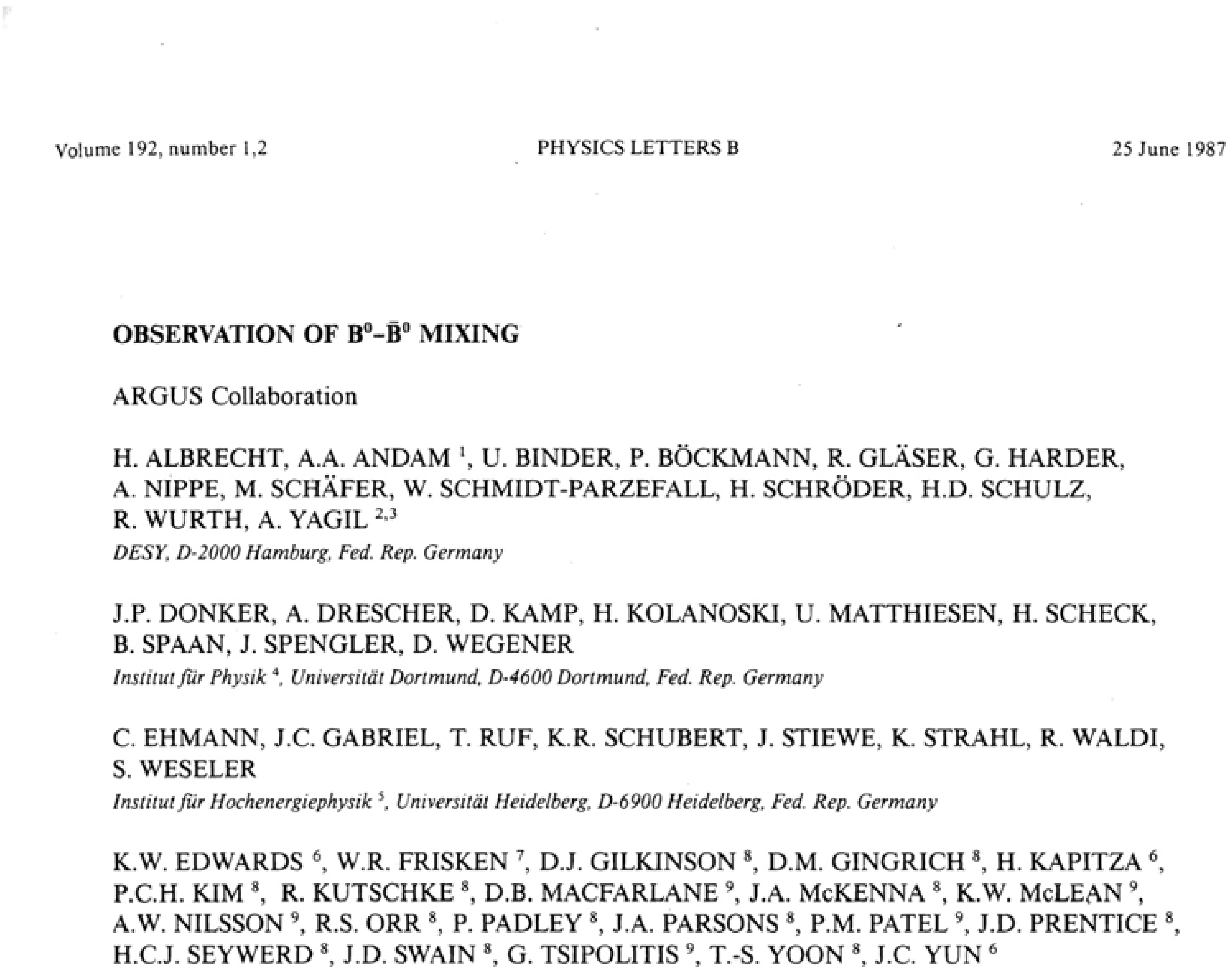
blossom of B physics possible

Importance of vertex detectors recognized

B – $\bar{B}$ mixing

- 1984: 35 GeV top “discovered” by UA1
- 1986: TRISTAN started operation, in the hope of producing the top quark
- With the mass in this range, B – $\bar{B}$ mixing expected to be tiny
- 1987: ARGUS at DESY announced large mixing in the neutral B system Then
- Top quark should be unexpectedly heavy

ARGUS shock



Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

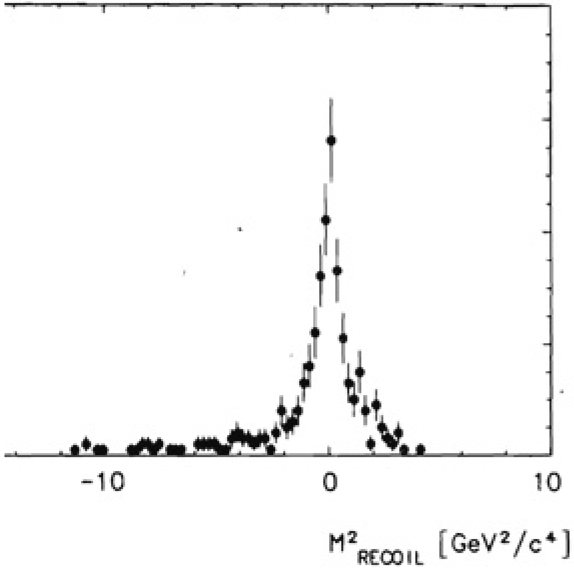
ARGUS Collaboration

H. ALBRECHT, A.A. ANDAM [1], U. BINDER, P. BÖCKMANN, R. GLÄSER, G. HARDER, A. NIPPE, M. SCHÄFER, W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ, R. WURTH, A. YAGIL [2,3]
DESY, D-2000 Hamburg, Fed. Rep. Germany

J.P. DONKER, A. DRESCHER, D. KAMP, H. KOLANOSKI, U. MATTHIESEN, H. SCHECK, B. SPAAN, J. SPENGLER, D. WEGENER
Institut für Physik [4], Universität Dortmund, D-4600 Dortmund, Fed. Rep. Germany

C. EHMANN, J.C. GABRIEL, T. RUF, K.R. SCHUBERT, J. STIEWE, K. STRAHL, R. WALDI, S. WESELER
Institut für Hochenergiephysik [5], Universität Heidelberg, D-6900 Heidelberg, Fed. Rep. Germany

K.W. EDWARDS [6], W.R. FRISKEN [7], D.J. GILKINSON [8], D.M. GINGRICH [8], H. KAPITZA [6], P.C.H. KIM [8], R. KUTSCHKE [8], D.B. MACFARLANE [9], J.A. McKENNA [8], K.W. McLEAN [9], A.W. NILSSON [9], R.S. ORR [8], P. PADLEY [8], J.A. PARSONS [8], P.M. PATEL [9], J.D. PRENTICE [8], H.C.J. SEYWERD [8], J.D. SWAIN [8], G. TSIPOLITIS [9], T.-S. YOON [8], J.C. YUN [6]



oil mass $M^2_{\mathrm{Recoil}} = [E_{\mathrm{beam}} - (E_{\mathrm{D}^{*-}}$ $)^2$ with $\mathrm{D}^{*-} \to \bar{\mathrm{D}}^0\pi^-$, $\bar{\mathrm{D}}^0 \to \mathrm{K}^+\pi^-$, $\mathrm{K}^+\pi^-\pi^+\pi^-$ and one lepton (π^+, e^+) with eV/c.

ther reconstructed in the hadronic].

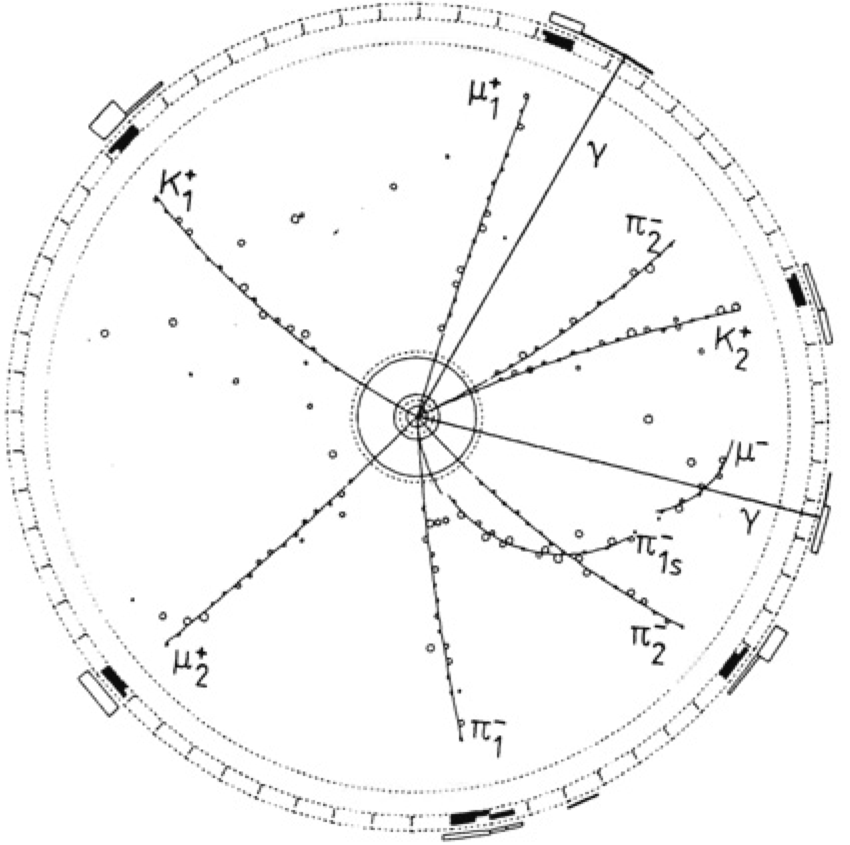


Fig. 2. Completely reconstructed event consisting of the decay Υ (4S)$\to \mathrm{B}^0\mathrm{B}^0$.

observation of B^0–$\bar{\mathrm{B}}^0$ mixing. The two B^0 mesons (B^0_1 and B^0_2) decay in the following way:

The last quark flavor

- In agreement with the indirect information from B mixing and electroweak precision measurements, the top quark was finally discovered by CDF in 1994 at the mass of 175 GeV, more than twice as large as the W mass

Neutrino masses and mixings

- Solar neutrino problem (Davies)
- Atmospheric neutrino anomaly (Kamiokande & others)

- Neutrino flavor oscillations predicted by Maki, Nakagawa, Sakata (1962) may explain these measurements

Neutrino masses and mixings

- Atmospheric neutrino anomaly suggested before 1980
- Nucleon-decay experiments gave conflicting results for muons (1980’s)
- Kamiokande gave rather good indication of anomaly (1988, 1992)
- Everybody accepted after beautiful SuperK results in 1998

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EXPERIMENTAL STUDY OF THE ATMOSPHERIC NEUTRINO FLUX

K.S. HIRATA, T. KAJITA, M. KOSHIBA, M. NAKAHATA, S. OHARA, Y. OYAMA, N. SATO,
A. SUZUKI, M. TAKITA, Y. TOTSUKA
ICEPP, Department of Physics, Department of Astronomy, Faculty of Science, University of Tokyo, Tokyo 113, Japan

T. KIFUNE, T. SUDA
Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan

K. NAKAMURA, K. TAKAHASHI, T. TANIMORI
National Laboratory for High Energy Physics (KEK), Ibaraki 305, Japan

K. MIYANO, M. YAMADA
Department of Physics, University of Niigata, Niigata 950-21, Japan

E.W. BEIER, L.R. FELDSCHER, E.D. FRANK, W. FRATI, S.B. KIM, A.K. MANN,
F.M. NEWCOMER, R. VAN BERG, W. ZHANG
Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA

and

B.G. CORTEZ
AT&T Bell Laboratories, Holmdel, NJ 07922, USA

Received 25 January 1988

We have observed 277 fully contained events in the KAMIOKANDE detector. The number of electron-like single-prong events is in good agreement with the predictions of a Monte Carlo calculation based on atmospheric neutrino interactions in the detector. On the other hand, the number of muon-like single-prong events is $59 \pm 7\%$ (statistical error) of the predicted number of the Monte Carlo calculation. We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes.

Primary cosmic rays striking the atmosphere pro-

We have made a detailed study of the atmospheric

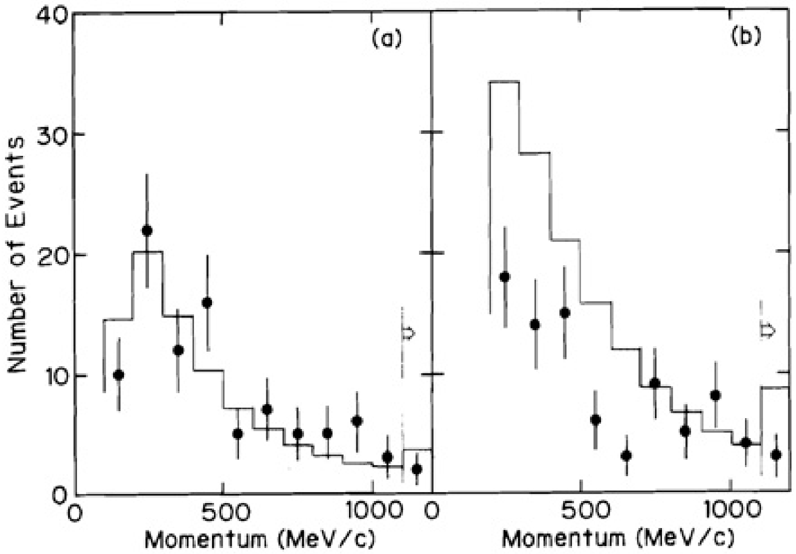

Fig. 1. Momentum distributions for: (a) electron-like events and (b) muon-like events. The last momentum bin sums all events with their momenta larger than 1100 MeV/*c*. The histograms show the distributions expected from atmospheric neutrino interactions.

1, the observed number of single-ring events accompanied by decay electrons is 60, while the number predicted by the Monte Carlo simulation is 110.3. On the other hand, the fraction of events accompanied by decay electrons in the observed electron-like and muon-like events is consistent with the Monte Carlo prediction as seen from table 1. It should be noted events, where Θ is the zenith angle. the histograms show the distributions expected from the atmospheric neutrino interactions. One finds that the distributions for electron-like events are in good agreement with the expectation. On the other hand, the distributions for muon-like events deviate from the expectation.

We have investigated a number of possible sources of errors or uncertainties in our data analysis and event assignments. Among them are: (i) the electron-like events are not of neutrino but of gamma-ray or neutron origin from sources outside the detector, while at the same time the detection efficiency and/or the atmospheric neutrino fluxes are much lower than estimated; however, the vertex positions for both the electron-like and muon-like events are distributed uniformly in the detector, and show no accumulation near the edges of the fiducial volume; (ii) possible systematic effects which might produce the deficiency in muon-like events such as trigger bias, event reduction, event scanning, event fitting, absolute energy calibration, and the Monte Carlo program itself. We have as yet found no effect that reproduces the deficiency of muon-like events relative to the total of electron-like events.

olute ν_μ and ν_e flux values, comparison of the ob-
ed and calculated momentum spectra in fig. 1
gests the two possible channels $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\tau$,
med, for simplicity, to be independent and sep-
e. We emphasize the there also is the possibility
$_\mu$ oscillating to a sterile, i.e., right handed, neu-
o of unknown mass and flavor, which would be
sistent with the observed small $R(\mu/e)$. The con-
ences of this oscillation channel need to be ex-
ed elsewhere.

o test neutrino oscillations the e- and μ-events are
ectively mapped on (zenith angle(cos Θ) and
nentum (p)) planes, where the (cos Θ, p) is
hed into (10×11) cells. Then a χ^2 is defined to
v contours of allowed regions on the (Δm^2,
2θ) plane:

$$\text{Min.}(\alpha,\beta)\left(L(\alpha,\beta)+\frac{\alpha^2}{\sigma_\alpha^2}+\frac{\beta^2}{\sigma_\beta^2}\right),$$

$, \beta)$

$$-2\sum_i\sum_j\left[\ln\left(\frac{(X_{ij}(e))^{N_{ij}(e)}\exp[-X_{ij}(e)]}{N_{ij}(e)!}\right)\right.$$

$$\left.\ln\left(\frac{(X_{ij}(\mu))^{N_{ij}(\mu)}\exp[-X_{ij}(\mu)]}{N_{ij}(\mu)!}\right)\right],$$

same allowed regions.

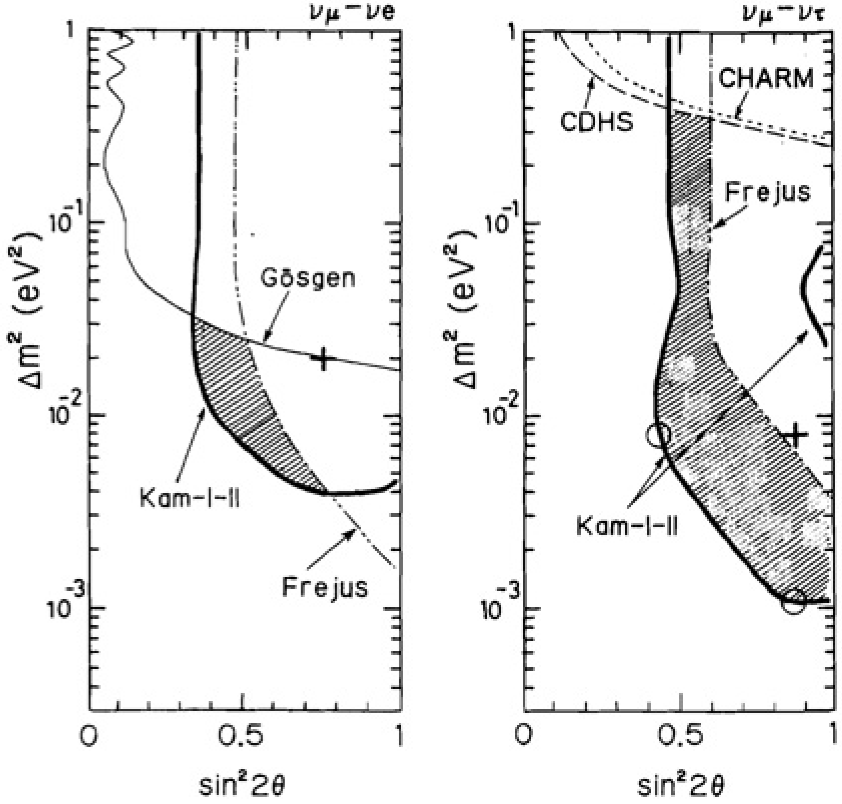

Fig. 4. The allowed neutrino oscillation parameters at 90% CL from the Kam-I–II data, for the case of $\nu_\mu \leftrightarrow \nu_e$ (left), and $\nu_\mu \leftrightarrow \nu_\tau$ (right). The best fit parameter sets are shown by crosses. The two open circles in the figure for $\nu_\mu \leftrightarrow \nu_\tau$ indicate the points which are used in figs. 2 and 3. All the other experimental results [13,22–24] show excluded regions.

Neutrino masses and mixings

- It took so long partly because theorists did not believe large mixing, but now we know
- Neutrino mixings are nearly maximal, totally different from quark mixings

Yukawa sector in SM

- Most # of parameters in SM
  - gauge: 3
  - Higgs: 2
  - Yukawa: 13 (+ ν sector)
- No guiding principles
  - Sharp contrast with gauge int.
  - No understanding of its origin

Flavor sector with SUSY

- New sources of flavor mixing
  - Squark, slepton masses (left and right)
  - Sfermion-higgs int. (A terms)
- New sources of CP violation
  - Gaugino mass, A, B terms
- Possible lepton flavor violation
  - from GUT effect/sneutrino mixing

Outlook

- Experiments should take lead in investigation of flavor physics
- Theorists should be more inventive and try to get enlightenment
- A lot to be done in coming 5 years and more!