Pentaquarks

Forschungsseminar Quantenfeldtheorie

Christian Schmidt

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Übersicht

Journalclub

zum Thema Pentaquarks

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3. Experimentelle Belege
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Einführung

NEW YORK TIMES **INTERNATIONAL** TUESDAY, JULY 1, 2003

A Subatomic Discovery Emerges From Experiments in Japan

By KENNETH CHANG

Slamming high-energy particles of light into carbon atoms, physicists have unexpectedly produced a new type of subatomic particle.

Protons and neutrons, the building blocks of atoms, are made of smaller particles known as quarks, which come in six varieties. A proton, for example, consists of three quarks — two so-called up quarks and one down quark. Physicists know of slews of particles containing two or three quarks.

Now they believe they know of a particle containing five quarks that perhaps could have been common in the very early universe. (No one has yet conclusively found particles with four or six or more quarks.)

The experiments, performed at the Spring-8 laboratory in Osaka, Japan, three years ago, were intended to examine two-quark particles known as mesons. At a conference in Australia, a Russian theoretical physicist, Dr. Dimitri Diakonov, approached the director of the experiments, Dr. Takashi Nakano, of the Research Center for Nuclear Physics at Osaka University, and told Dr. Nakano that he should look through the data for signs of five-quark particles.

"Dimitri Diakonov was very confident of that," Dr. Nakano said. Dr. Nakano and his collaborators looked, and they found a peak in their graphs corresponding to the mass of the five-quark particle that Dr. Diakonov had predicted. "He was right," Dr. Nakano said. "Actually, I was very surprised."

Dr. Kenneth H. Hicks, a professor of physics at Ohio University and another member of the Spring-8 collaboration, said that even with the data matching the prediction, he did not believe it.

"There's been a general bias in the community against this particle existing," Dr. Hicks said.

When months of checking the apparatus produced no alternative explanation, the scientists concluded that they had indeed found a five-quark particle. The particle would consist of two up quarks, two down quarks and one known as an anti-strange quark.

The findings will be reported Friday in the journal Physical Review Letters.

Dr. Hicks and other researchers then reviewed data from similar experiments at the Thomas Jefferson National Accelerator Facility in Newport News, Va., and again found the same signs of a five-quark particle. Physicists in Russia have also found similar evidence.

A glimpse at a possible feature of the early universe.

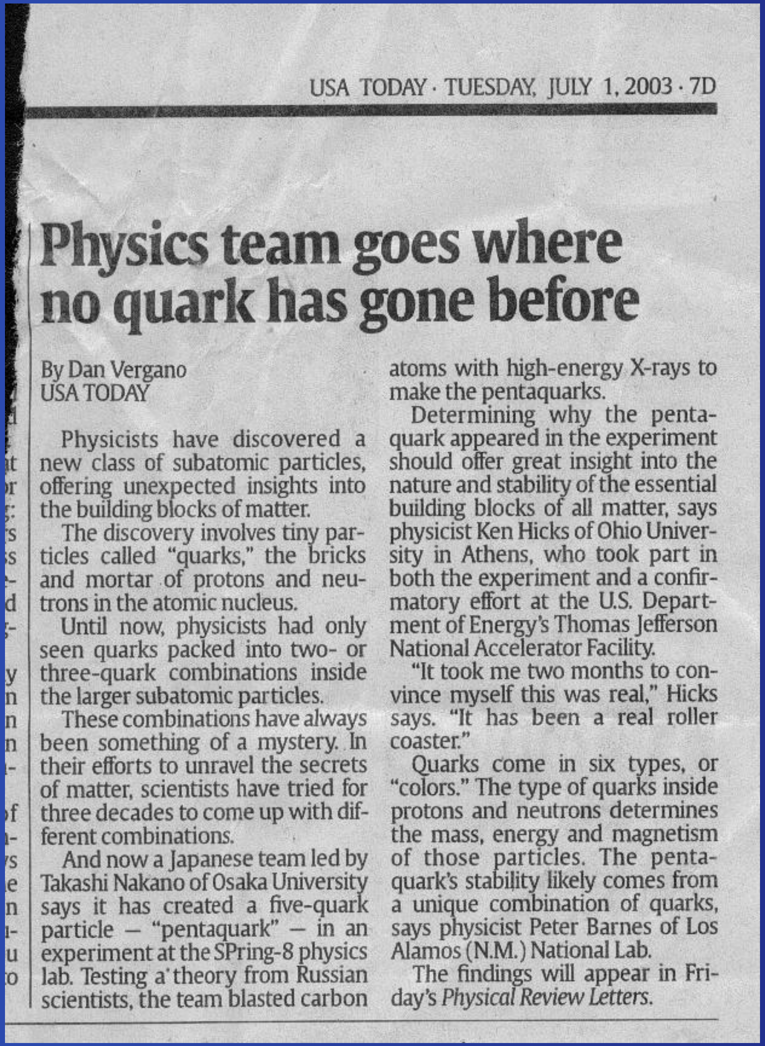
The basic theory of how quarks behave, known as quantum chromodynamics, or Q.C.D., does not prohibit five-quark particles, but no one had seen any in three decades of searching, so physicists wondered if their theory was incomplete.

"It immediately removes a worry that there might be something missing from Q.C.D. that forbids things," said Dr. Andrew Sandorfi of the Brookhaven National Laboratory on Long Island, who was not involved in any of the experiments. "It's not overwhelming proof yet, but it's highly suggestive."

Future experiments are needed to determine other properties of the particle and to rule out the possibility that the data resulted from some other effect.

Dr. Hicks said the new particles could potentially affect theories of the very early universe or even exist in the cores of some stars. "Does that have any dramatic effect?" he said. "I don't know. No one's paid any attention, because in 30 years, no one's seen them."

Einführung



USA TODAY · TUESDAY, JULY 1, 2003 · 7D

Physics team goes where no quark has gone before

By Dan Vergano
USA TODAY

Physicists have discovered a new class of subatomic particles, offering unexpected insights into the building blocks of matter.

The discovery involves tiny particles called "quarks," the bricks and mortar of protons and neutrons in the atomic nucleus.

Until now, physicists had only seen quarks packed into two- or three-quark combinations inside the larger subatomic particles.

These combinations have always been something of a mystery. In their efforts to unravel the secrets of matter, scientists have tried for three decades to come up with different combinations.

And now a Japanese team led by Takashi Nakano of Osaka University says it has created a five-quark particle — "pentaquark" — in an experiment at the SPring-8 physics lab. Testing a theory from Russian scientists, the team blasted carbon atoms with high-energy X-rays to make the pentaquarks.

Determining why the pentaquark appeared in the experiment should offer great insight into the nature and stability of the essential building blocks of all matter, says physicist Ken Hicks of Ohio University in Athens, who took part in both the experiment and a confirmatory effort at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility.

"It took me two months to convince myself this was real," Hicks says. "It has been a real roller coaster."

Quarks come in six types, or "colors." The type of quarks inside protons and neutrons determines the mass, energy and magnetism of those particles. The pentaquark's stability likely comes from a unique combination of quarks, says physicist Peter Barnes of Los Alamos (N.M.) National Lab.

The findings will appear in Friday's *Physical Review Letters*.

Einführung

Im September dann auch ausführliche Artikel in *Physics Today* und im *Physikjournal*.

Q: Was genau wurde entdeckt?

A: Ein neues Baryon (θ^+) mit folgenden Eigenschaften:

- Ladung: +1
- Masse: 1540 MeV
- Zerfall: $\theta^+ \longrightarrow n + K^+$

Einführung

Warum ist das ungewöhnlich?

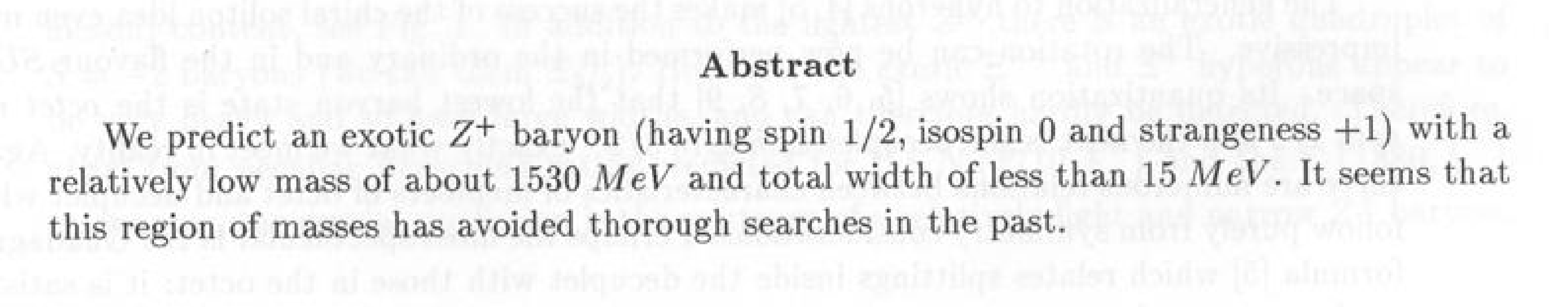
Beim starken Zerfall bleiben erhalten:

- Baryonenzahl $B = 1$
- Strangeness $S = +1$
- Ladung $Q = +1$

$\Rightarrow$ Im Quarkmodell nur möglich mit Pentaquark-Konfiguration ($uudd\bar{s}$)

Theoretisches Modell

Diakonov, Petrov und Polyakov im März 1997 (arXiv:hep-ph/9703373)



Abstract

We predict an exotic Z^+ baryon (having spin 1/2, isospin 0 and strangeness +1) with a relatively low mass of about 1530 MeV and total width of less than 15 MeV. It seems that this region of masses has avoided thorough searches in the past.

Diese Vorhersage gründet sich auf das Chirale Soliton-Modell.

Theoretisches Modell

Solitonen (Wiederholung)

Betrachte die *Sine-Gordon*-Lagrangedichte

$$\begin{aligned}\mathcal{L}_{SG} &= \frac{1}{2}(\partial_\mu \phi)^2 - \frac{\alpha}{\beta^2}[1 - \cos(\beta\phi)] \\ &= \frac{1}{2}(\partial_\mu \phi)^2 - \frac{\alpha}{2}\phi^2 + \frac{\alpha\beta^2}{4!}\phi^4 + \mathcal{O}(\beta^4\phi^6)\end{aligned}$$

Dieses Modell besitzt eine statische Soliton-Lösung

$$\phi_0(x) = \frac{4}{\beta}\tan^{-1}[\exp(\sqrt{a}x)]$$

mit der Energie $E_0 = 8\sqrt{a}/\beta^2$ und der Ausdehnung $\alpha^{-1/2}$.

Theoretisches Modell

Chirale Störungstheorie (Wiederholung)

- Im Grenzwert $m_q \to 0$ ist $\mathcal{L}(QCD)$ symmetrisch bezüglich $SU(N_f) \times SU(N_f)$
- spontane Symmetriebrechung auf $SU(N_f)$ führt zu $N_f^2 - 1$ pseudoskalaren Goldstone-Bosonen (für $N_f = 2$: Pionfelder π^0, π^+, π^-)
- Beschreibung dieser Felder durch die $SU(N_f)$-Matrix $U(x) = \exp\left(\frac{i}{F_0}\pi_a(x)\lambda_a\right)$

Theoretisches Modell

Das chirale SU(2) Soliton

Ausgangspunkt ist die Lagrangedichte

$$\mathcal{L}_{Sk} = \frac{F_\pi^2}{4}\,\mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger) + \frac{1}{32e^2}\,\mathrm{Tr}[\partial_\mu U\, U^\dagger, \partial_\nu U\, U^\dagger]^2.$$

Skyrme-Ansatz: $U_0(\vec{x}) = \exp[iF(r)\vec{\tau}\hat{x}]$

Minimierung des Energiefunktionals ergibt

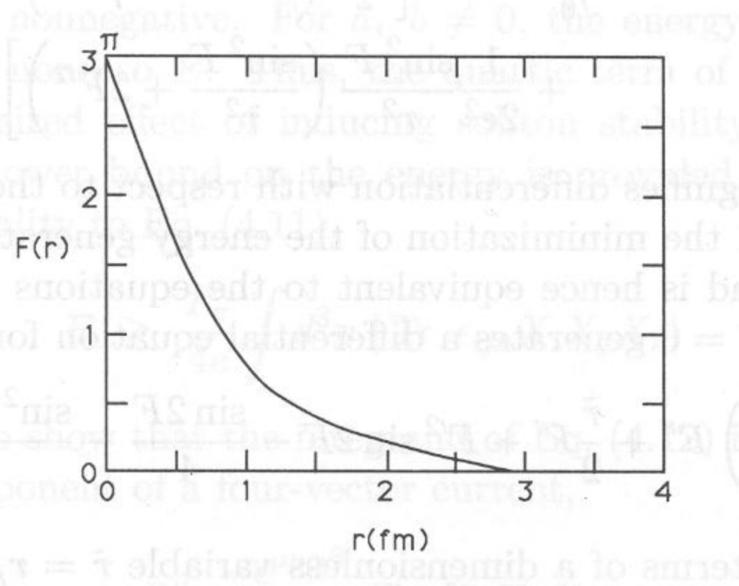
DGL 2.Ord. für $F(r)$ mit Randbedingungen $F(\infty) = 0$ und

$$B = \frac{1}{2\pi}[2F(0) - 2F(\infty) - \sin 2F(0) + \sin 2F(\infty)] = 1.$$

Theoretisches Modell

Das chirale SU(2) Soliton

Für die klassische Lösung erhält man die Radialfunktion



und die Masse $M \approx 73 F_\pi / e = 1138$ MeV.

Theoretisches Modell

Quantisierung

Globale chirale Rotation des klassischen Feldes:

$$\tilde{U}(\vec{x},t) = R(t)U(\vec{x})R^\dagger(t)$$

Idee: Die beobachteten Baryonen werden als verschiedene Rotations-Quantenzustände des klassischen Skyrmions betrachtet

$\Rightarrow$ Relationen für Massen und Zerfallsbreiten innerhalb und zwischen verschiedenen Multiplets

Theoretisches Modell

Hamiltonian für $SU(3)$-Erweiterung:

$$H = \frac{1}{2I_1} \sum_{A=1}^{3} J_A^2 + \frac{1}{2I_2} \sum_{A=4}^{7} J_A^2 .$$

Mit Quant.-Bed. aus *Wess-Zumino*-Term für J_8 erhält man

- Oktet mit Spin $1/2$ $\Leftarrow p, n$
- Dekuplet mit Spin $3/2$
- Anti-Dekuplet mit Spin $1/2$ $\Leftarrow \theta^+$
- 27-plets mit Spin $1/2$ und $3/2$, etc.

Theoretisches Modell

Berücksichtigung von $m_s \neq 0$

$\Rightarrow$ *Gell-Mann-Okubo*-Relationen (innerhalb Multiplets)

$$2(m_N + m_\Xi) = 3m_\Lambda + m_\Sigma$$

$$m_\Delta - m_{\Sigma^*} = m_{\Sigma^*} - m_{\Xi^*} = m_{\Xi^*} - m_{\Omega^-}$$

und *Guadagnini*-Formel (zwischen Multiplets)

$$8(m_{\Sigma^*} + m_N) + 3m_\Sigma = 11m_\Lambda + 8m_{\Sigma^*}.$$

Exp: Erfüllt innerhalb 1% Genauigkeit!

Theoretisches Modell

Zerfallsbreiten:

Gute Übereinstimmung mit Exp. für Oktet und Dekuplet

Vorhersagen für Anti-Dekuplet:

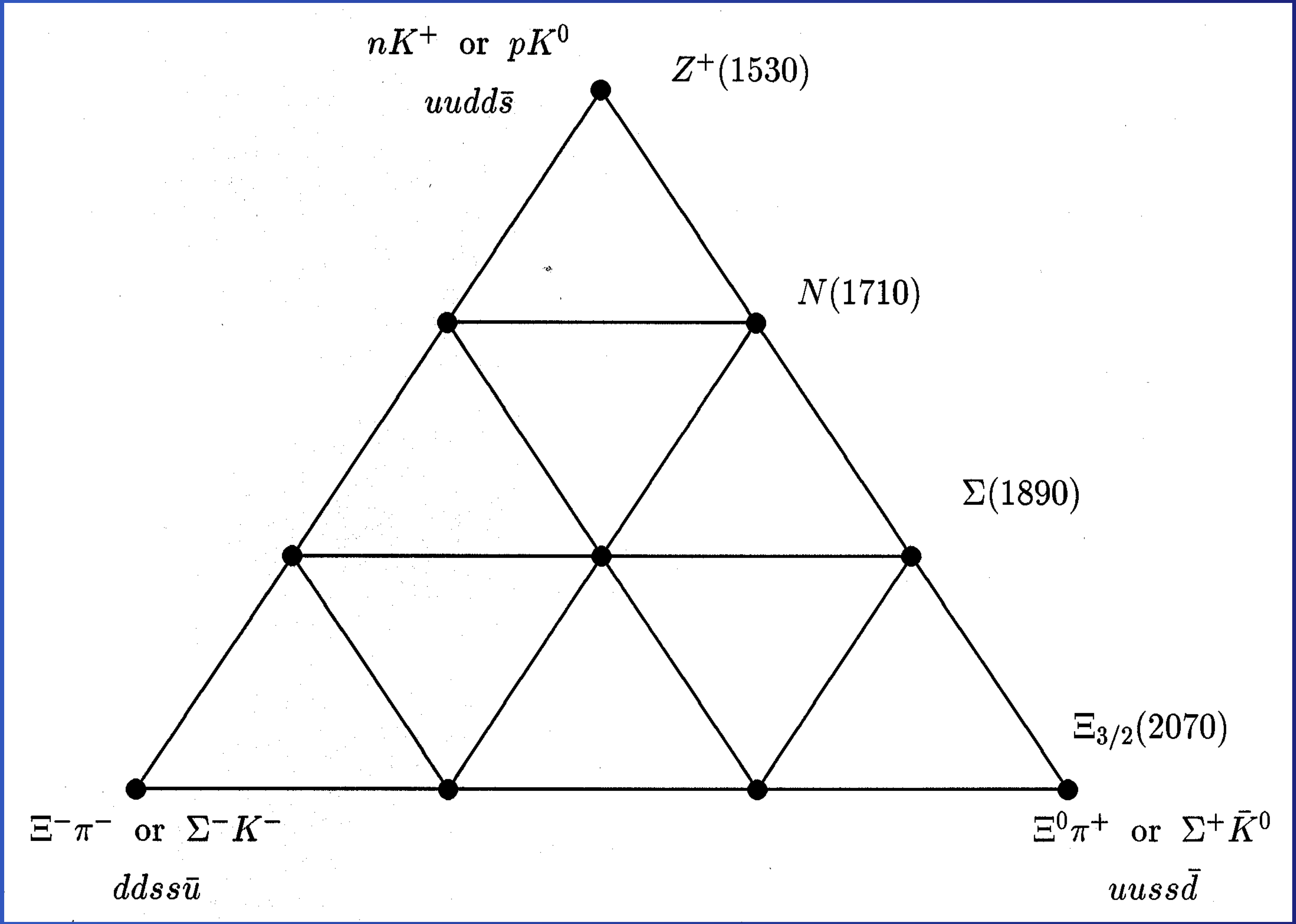
$$\begin{aligned} \Gamma(\theta^+ \to NK) &= 15\,\text{MeV} \\ \Gamma(N_{\bar{10}} \to N\eta, \Delta\pi, \Lambda K, \text{etc.}) &= 41\,\text{MeV} \end{aligned}$$

Absolute Massenskala:

Identifiziere $N_{\bar{10}}$ mit $N(1710, \frac{1}{2}^+)$-Resonanz

$\Rightarrow$ abstract (s.o.)

Theoretisches Modell



Theoretisches Modell

Alternative Beschreibungen

Problem im Quarkmodell:
Niedrige Resonanzbreite nicht unmittelbar zu erklären

Lösungsansatz von R.Jaffe, F.Wilczek (MIT):
(arXiv:hep-ph/0307341)
θ^+ als gebundener Zustand von 2 ud *Diquarks* + $\bar{s}$

Vorhersage aus diesem Modell:
Ξ’s etwa 300 MeV leichter als bei *Diakonov et al.*

Experimentelle Belege

Q: In den 1960ern und 70ern gab es eine systematische Suche nach seltsamen Teilchen. Warum wurde das θ^+ nicht gefunden?

A: Streuung von K^+ an N bei 440 MeV problematisch, da

- Niedriger Lorentzfaktor (Kaon-Lebenszeit: 10 ns)
- $p + p$ Reaktionen unsauber (kein klar def. K^+-Impuls)
- Niedrige Flussdichten

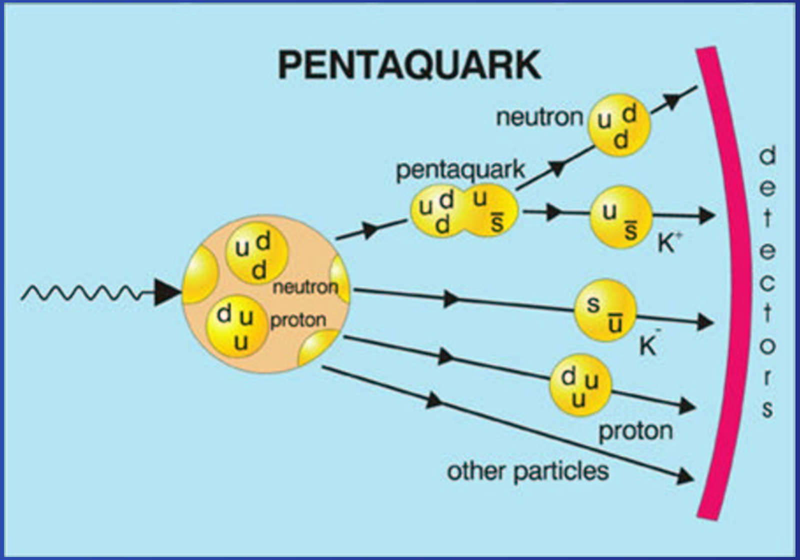
$\Rightarrow$ Erster Nachweis: Januar 2003

Experimentelle Belege

SPring-8 Anlange in Osaka, Japan

Nakano et al. (arXiv:hep-ex/0301020)

- Photonen aus Comptonstreuung $\gamma + e^- \rightarrow \gamma + e^-$
- Targets: Plastik-Szintilator (C,H) und Wasserstoff (LH$_2$)



Experimentelle Belege

SPring-8 Anlange in Osaka, Japan

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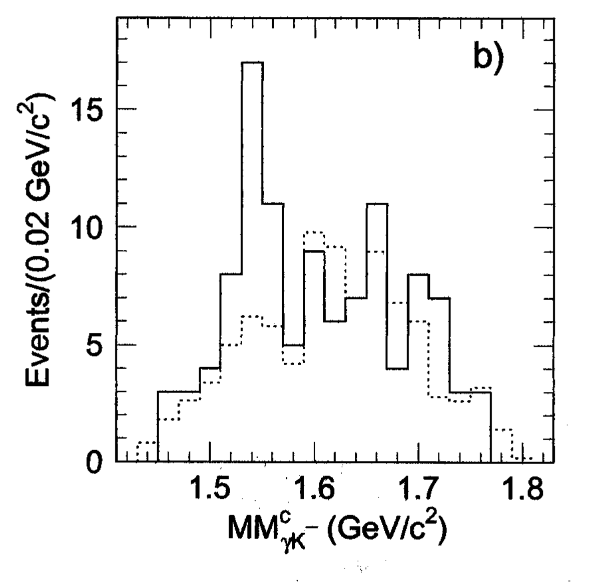


SC Peak: 4.6 σ, Signalbreite < 25 MeV

Experimentelle Belege

DIANA Kollaboration, ITEP Moskau (1986)

Barmin et al. (arXiv:hep-ex/0304040)

- Blasenkammer: $\mathrm{K}^+ + \mathrm{Xe} \rightarrow \mathrm{K}^0 + \mathrm{p} + \mathrm{Xe}'$
- $\mathrm{K}^0 \rightarrow \pi^+ + \pi^-$

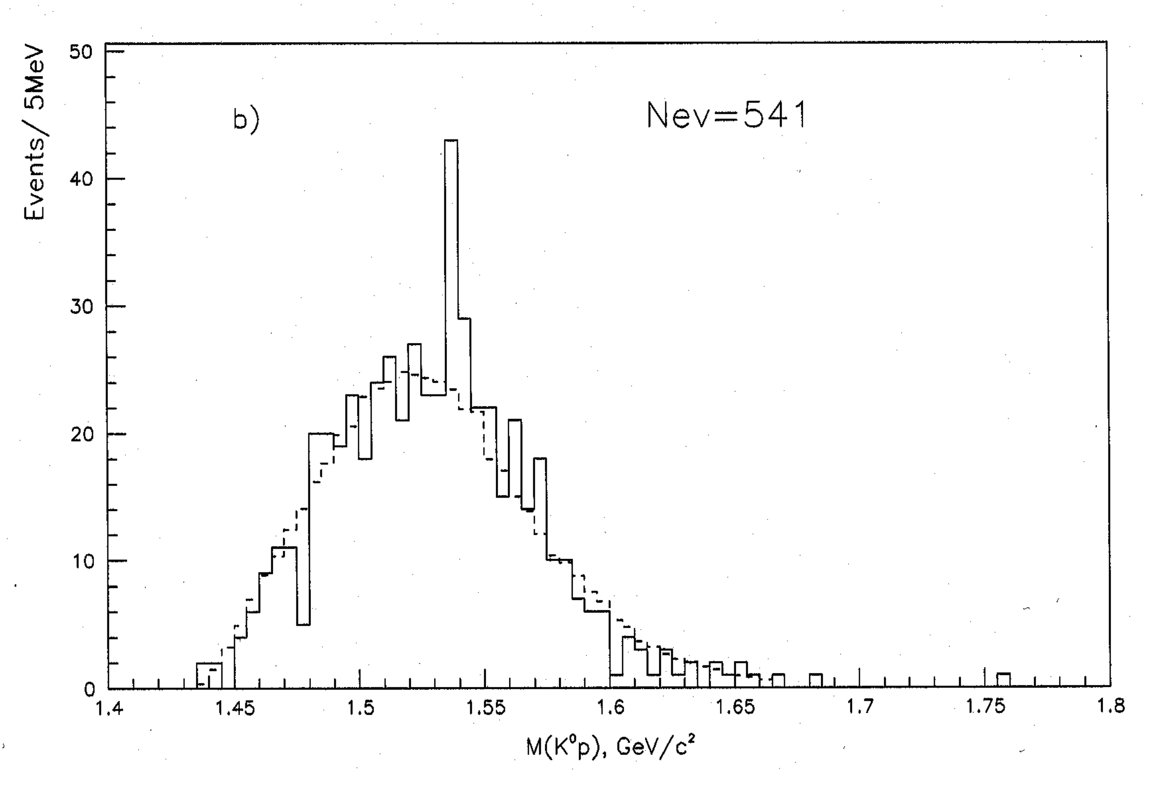
Ergebnisse:

- Peak bei 1539 ± 2 MeV
- Signifikanz: $4.4\ \sigma$
- Signalbreite: < 9 MeV

Experimentelle Belege

DIANA Kollaboration, ITEP Moskau (1986)

Barmin et al. (arXiv:hep-ex/0304040)

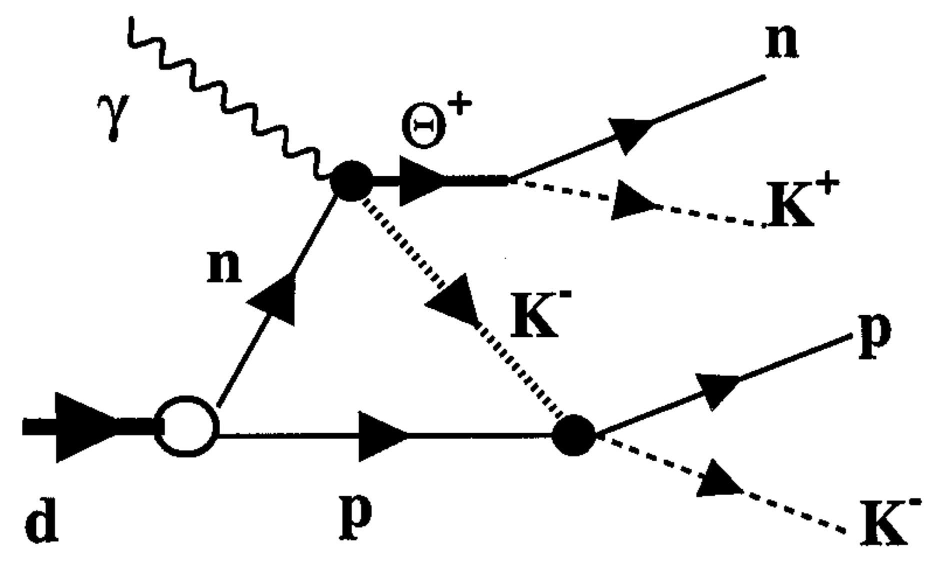


Experimentelle Belege

CLAS Kollaboration, Thomas Jefferson Lab., VA

Stepanyan et al. (arXiv:hep-ex/0307018)

γ aus e^- Bremsstrahlung, LD$_2$ Target



Experimentelle Belege

CLAS Kollaboration, Thomas Jefferson Lab., VA

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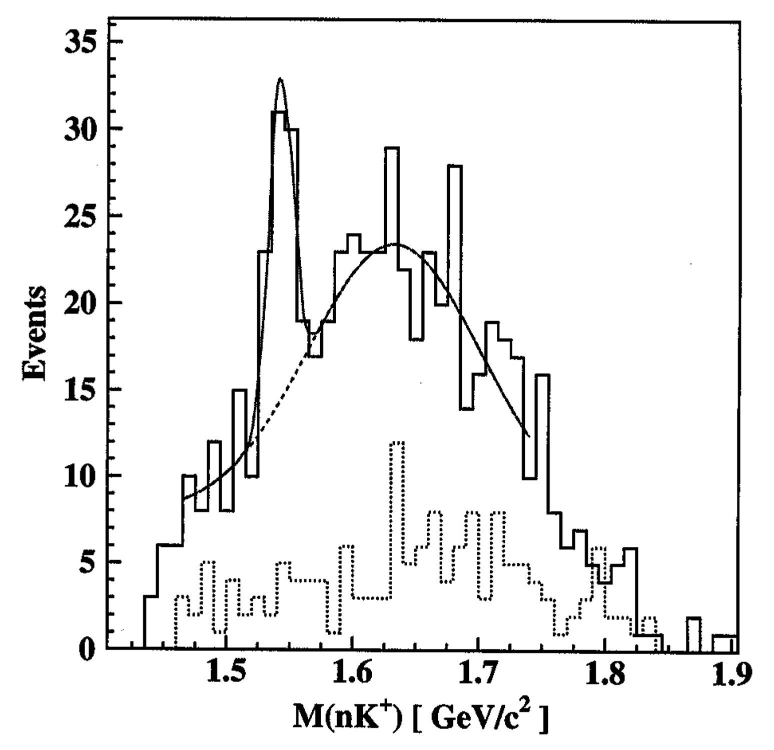

Experimentelle Belege

CLAS Kollaboration, Thomas Jefferson Lab., VA

Stepanyan et al. (arXiv:hep-ex/0307018)

Ergebnis:

- Peak bei 1542 $\pm$ 5 MeV
- Signifikanz: 5.3 σ
- Signalbreite: 21 MeV

Inzwischen weitere “Sichtungen” bei ELSA(Bonn), HERMES(DESY), etc.

Offene Fragen

Theorie:

- Einbau ins Quarkmodell?
- Erklärung für geringe Resonanzbreite?

Experiment:

- Wirklich Isospin-Singlet?
- Intrinsische Resonanzbreite?
- Spin-Messung?
- Andere Teilchen des Anti-Dekuplets?