PHYS 3446 – Lecture #21

Wednesday, Nov. 16, 2016

Dr. Jaehoon Yu

- Elementary Particle Properties
  - Strangeness Quantum Number
  - Isospin Quantum Number
  - Gell-Mann-Nishijima Relations
  - Summary of Quantum Numbers
- Symmetries
  - Why do we care about the symmetry?

Announcements

- Class on Wednesday, Nov. 23?
  – No class Wednesday, Nov. 23
- Quiz #4
  – Monday, Nov. 28
  – Covers up to what we learn coming Monday, Nov. 21
  – BYOF
- Reading assignments: 10.3 and 10.4

Physics Department
The University of Texas at Arlington
<u>COLLOQUIUM</u>

Design and Scalable Synthesis of Nanoscale Materials for Solar Energy Conversion

Wednesday November 16, 2016

4:00 Room 100 Science Hall

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My research is aimed at creating materials that will be the building blocks of economical, large-scale, clean energy technologies of the future. The key to creating effective energy conversion materials is controlling the flow of energy, matter and electricity at the nanoscale by careful design of the shape, size and composition of materials at the same scale. I am primarily interested in developing materials for cheap yet efficient solar cells that either generate electricity or directly generate chemical fuels. As an example, I will present semiconductor/liquid junction solar cells constructed on metal oxide nanowire scaffolds that achieved record photocurrents, and also new results on metal sulfide materials. Equally important is the development of methods for the rapid, economical synthesis of highly structured nanomaterials in quantities that match the scale of our energy problem. As an example, I will describe novel flame-synthesis methods for the bottom-up growth of arrays of single-crystal metal oxide nanowires and composites over large areas on electrically conductive substrates. Technologies like this may someday remove barriers to the practical implementation of nanotechnology in solar energy conversion devices.

Bio: Pratap Rao is an Assistant Professor in the Mechanical Engineering Department at the Worcester Polytechnic Institute (WPI). He received his PhD in 2013 from Stanford University, where he was a recipient of the Daniel W. MacDonald Memorial Fellowship (2007–2008) and the Link Foundation Energy Fellowship (2009–2011). He has co-authored 23 peer-reviewed papers that have appeared in Nano Letters, Nature Communications, Scientific Reports, and Proceedings of the Combustion Institute. His work on materials for solar energy conversion is currently funded by the National Science Foundation.

Refreshments will be served at 3:30 p.m. in the Physics Library

Strangeness

- From cosmic ray shower observations
  - K-mesons and Σ & Λ^0 baryons are produced strongly w/ large x-sec's
    - But their lifetimes are typical of weak interactions (~10^{-10} sec)
    - They are produced in pairs – a K with a Σ or a K with a Λ^0
  - Gave an indication of a new quantum number
- Consider the reaction $\pi^- + p \rightarrow K^0 + \Lambda^0$
  - K^0 and Λ^0 subsequently decay
  - $\Lambda^0 \rightarrow \pi^- + p$ and $K^0 \rightarrow \pi^+ + \pi^-$
- Observations on Λ^0
  - Always produced with a K^0 never with just a π^0
  - Produced with a K^+ but not with a K^-

$$\pi^- + p \rightarrow K^+ + \pi^- + \Lambda^0$$

$$\pi^- + p \not\rightarrow K^- + \pi^+ + \Lambda^0 \qquad \pi^- + p \not\rightarrow \pi^- + \pi^+ + \Lambda^0$$

Strangeness

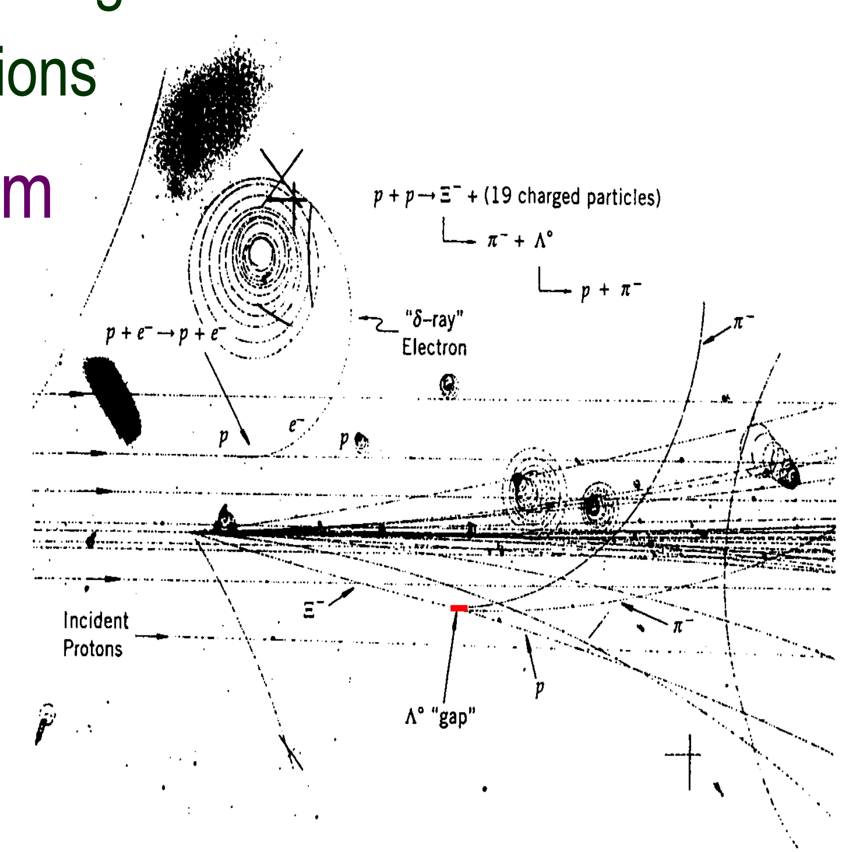
- Consider reactions $\pi^+ + p \to \Sigma^+ + K^+$ and $\pi^- + p \to \Sigma^- + K^+$
  - With the subsequent decays $\Sigma^{+(-)} \to n + \pi^{+(-)}$ and $K^+ \to \pi^+ + \pi^0$
- Observations from Σ^+
  - Σ^+ is always produced with a K^+ never with just a π^+
  - Σ^+ is also produced with a K^0 but with an additional π^+ for charge conservation
- Observations from Σ^-
  - Σ^- is always produced with a K^+ never with a K^-
- Thus,
  - Observed: $\pi^+ + p \to \Sigma^+ + \pi^+ + K^0$ $\quad \pi^- + p \to \Sigma^- + K^+$
  - Not observed: $\pi^- + p \not\to \Sigma^+ + K^-$ $\quad \pi^- + p \not\to \Sigma^- + \pi^+$

Strangeness

- Further observation from cross section measurements
  - The cross section for reactions $\pi^- + p \rightarrow K^+ + \pi^- + \Lambda^0$ and $\pi^- + p \rightarrow K^0 + \Lambda^0$ with 1GeV/c pion momenta are ~ 1mb
    - Whereas the total pion-proton scattering cross section is ~ 30mb
    - The interactions are strong interactions
  - Λ^0 at v~0.1c decays in about 0.3cm
    - Lifetime of Λ^0 baryon is

$$\tau_{\Lambda^0} \approx \frac{0.3cm}{3\times10^9 cm/s} = 10^{-10}\sec$$

    - The short lifetime of these strange particles indicate weak decay



Strangeness

- Strangeness quantum number
  - Murray Gell-Mann and Abraham Pais proposed a new additive quantum number that are carried by these particles in 1950's
  - **Conserved in strong and EM interactions**
  - Violated in weak decays
  - S=0 for all ordinary mesons and baryons as well as photons and leptons
  - For any strong associated-production reaction with the initial state S=0, the total strangeness of particles in the final state should also add up to 0.

Strangeness

- Based on experimental observations of reactions and with an arbitrary choice of S(K^0)=1, we obtain
  - S(K$^+$)= S(K^0)=1 and S(K$^-$)= S($\bar{\mathrm{K}}^0$)= -1
  - S(Λ^0)= S(Σ^+)= S(Σ^0)= S(Σ^-)= -1
  - Does this work for the following reactions?
  - $\pi^- + p \to K^+ + \pi^- + \Lambda^0$
  - $\pi^- + p \to K^0 + \Lambda^0$
- For strong production reactions $\mathrm{K}^- + p \to \Xi^- + \mathrm{K}^+$ and $\bar{\mathrm{K}}^0 + p \to \Xi^0 + \mathrm{K}^+$ we can determine that
  - cascade particles $S\left(\Xi^-\right) = S\left(\Xi^0\right) = -2$ if $\mathrm{S}\left(\bar{\mathrm{K}}^0\right) = S\left(\mathrm{K}^-\right) = -1$

More on Strangeness

- Let's look at the reactions again

$$\pi^- + p \rightarrow K^0 + \Lambda^0$$

  - This is a strong interaction
    - Strangeness must be conserved
    - S: 0 + 0 → +1 -1
- How about the decays of the final state particles?
  - $\Lambda^0 \rightarrow \pi^- + p$ and $K^0 \rightarrow \pi^+ + \pi^-$
  - These decays are weak interactions so S is not conserved
  - S: -1 → 0 + 0 and +1 → 0 + 0
- A not-really-elegant solution
  - S is only conserved in Strong and EM interactions → Unique strangeness quantum numbers cannot be assigned to leptons
- Leads into the necessity of the strange quark

Isospin Quantum Number

- Strong force does not depend on the charge of the particle
  - Nuclear properties of protons and neutrons are very similar
  - From the studies of mirror nuclei, the strengths of p–p , p–n and n–n strong interactions are essentially the same
  - If corrected by the EM interactions, the x-sec between n–n and p–p are the same
- Since the strong force is much stronger than any other forces, we could imagine a new quantum number that applies to all particles involved in the strong interaction
  - Protons and neutrons are two orthogonal mass eigenstates of the same particle like spin up and down states

$$p = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \text{and} \quad \mathrm{n} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Isospin Quantum Number

- Protons and neutrons are degenerate in mass because of some symmetry of the strong force
  - Isospin symmetry ➔ Under the strong force these two particles appear identical
  - Presence of the Electromagnetic or Weak force breaks this symmetry, distinguishing p from n
- Isospin works just like the spin
  - Protons and neutrons have isospin ½ ➔ Isospin doublet
  - Three pions, π+, π- and π^0, have almost the same masses
  - Strong interaction X-sec by these particles are almost the same after correcting for EM effects
  - Strong force does not distinguish these particles ➔ Isospin triplet

$$\pi^+ = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad \pi^0 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad \text{and} \quad \pi^- = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

Isospin Quantum Number

- This QN is found to be <u>conserved in strong interactions</u>
- But not conserved in EM or Weak interactions
- The third component of the isospin QN is assigned to be positive for the particles with larger electric charge
- Isospin is not a space-time symmetry
- Cannot be assigned uniquely to leptons and photons since they are not involved in strong interactions
  - There is something called weak-isospin for weak interactions

Iso-spin Assignments of some hadrons

hadrons	Mass (MeV/c^2)	Lifetime τ_0 (sec)	I	I_3
p				
n				
π^+, π^-, π^0				
K^+, K^0, K^0-bar, K^-				
η^0, Λ^0				
Σ^+, Σ^0, Σ^-				
Ω^-				

Gell-Mann-Nishijima Relation

- Strangeness assignment is based on Gell-Mann-Nishijima relation
  - Electric charge of a hadron can be related to its other quantum numbers

$$Q = I_3 + \frac{Y}{2} = I_3 + \frac{B+S}{2}$$

  - Where
    - Q: hadron electric charge
    - I_3: third component of isospin
    - Y=B+S, strong hypercharge
  - Quantum numbers of several long lived particles follow this rule

Gell-Mann-Nishijima Relation

- With the discovery of new flavor quantum numbers, charm and bottom, this relationship was modified to include these new additions ($Y=B+S+C+b$)
  - Since the charge and the isospin are conserved in strong interactions, the strong hypercharge, Y, is also conserved in strong interactions
- This relationship holds in all strong interactions

Quantum numbers for a few hadrons

$Hadron$	Q	I_3	B	S	$Y = (B + S)$
π^+	1	1	0	0	0
π^0	0	0	0	0	0
π^-	-1	-1	0	0	0
K^+	1	$1/2$	0	1	1
K^0	0	$-1/2$	0	1	1
η^0	0	0	0	0	0
p	1	$1/2$	1	0	1
n	0	$-1/2$	1	0	1
Σ^+	1	1	1	-1	0
Λ^0	0	0	1	-1	0
Ξ^-	-1	$-1/2$	1	-2	-1
Ω^-	-1	0	1	-3	-2

Violation of Quantum Numbers

- The QN we learned are conserved in strong interactions are but many of them are violated in EM or weak interactions
- Three types of weak interactions
  - Hadronic decays: Only hadrons in the final state

$$\Lambda^0 \to \pi^- + p$$

  - Semi-leptonic decays: both hadrons and leptons are present

$$n \to p + e^- + \bar{\nu}_e$$

  - Leptonic decays: only leptons are present

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Hadronic Weak Decays

- These decays follow selection rules: $|\Delta I_3|=1/2$ and $|\Delta S|=1$

QN	$\Lambda^0 \rightarrow$	π^-	p	$\|\Delta\|$
I_3	0	-1	½	1/2
S	-1	0	0	1

QN	$\Sigma^+ \rightarrow$	π^0	p	
I_3	1	0	½	1/2
S	-1	0	0	1

QN	$K^0 \rightarrow$	π^+	π^-	
I_3	- ½	1	-1	1/2
S	1	0	0	1

QN	$\Xi^- \rightarrow$	Λ^0	π^-	
I_3	- ½	0	-1	1/2
S	-2	-1	0	1

Semi-leptonic Weak Decays

These decays follow selection rules: $|\Delta I_3|=1$ and $|\Delta S|=0$ or $|\Delta I_3|=\frac{1}{2}$ and $|\Delta S|=1$

QN	$n \rightarrow$	p	$e^- + \bar{\nu}_e$	$\lvert\Delta\rvert$
I_3	-1/2	1/2		1
S	0	0		0

QN	$\pi^- \rightarrow$	μ^-	$\bar{\nu}_\mu$	
I_3	-1			1
S	0			0

QN	$K^+ \rightarrow$	π^0	$\mu^+ + \nu_\mu$	
I_3	½	0		1/2
S	1	0		1

QN	$\Sigma^- \rightarrow$	n	$e^- + \bar{\nu}_e$	
I_3	-1	-1/2		1/2
S	-1	0		1

Summary of Weak Decays

- Hadronic weak-decays
  - Selection rules are $|\Delta I_3|=1/2$ and $|\Delta S|=1$
  - $|\Delta I_3|=3/2$ and $|\Delta S|=2$ exists but heavily suppressed
- Semi-leptonic weak-decays
  - Type 1: Strangeness conserving
    - Selection rules are: $|\Delta S|=0$, $|\Delta I_3|=1$ and $|\Delta I|=1$
  - Type 2: Strangeness non-conserving
    - Selection rules are: $|\Delta S|=1$, $|\Delta I_3|=\frac{1}{2}$ and $|\Delta I|=\frac{1}{2}$ or $3/2$
    - $\Delta I=3/2$ and $|\Delta S|=1$ exist but heavily suppressed

EM Processes

QN	$\pi^0 \rightarrow$	γ	γ	$\lvert\Delta\rvert$
I_3	0			0
S	0			0

QN	$\eta^0 \rightarrow$	γ	γ	
I_3	0			0
S	0			0

QN	$\Sigma^0 \rightarrow$	Λ^0	γ	
I_3	0	0		0
S	-1	-1		0

- Strangeness is conserved but the total isospin is not
  - Selection rules are: $|\Delta S|=0$, $|\Delta I_3|=0$ and $\Delta I= 1$ or 0

Summary of Quantum Numbers

- Baryon Number
  - An additive and conserved quantum number, Baryon number (B)
  - This number is conserved in general but not absolute
- Lepton Number
  - Quantum number assigned to leptons
  - Lepton numbers by species and the total lepton numbers must be conserved
- Strangeness Numbers
  - Conserved in strong interactions
  - But violated in weak interactions
- Isospin Quantum Numbers
  - Conserved in strong interactions
  - But violated in weak and EM interactions

Quantum Numbers

- We've learned about various newly introduced quantum numbers as a patch work to explain experimental observations
  - Lepton numbers
  - Baryon numbers
  - Isospin
  - Strangeness
- Some of these numbers are conserved in certain situation but not in others
  - Very frustrating indeed….
- These are due to lack of quantitative description by an elegant theory