CP violation in B-meson decays and matter-antimatter asymmetry

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Lecture 1

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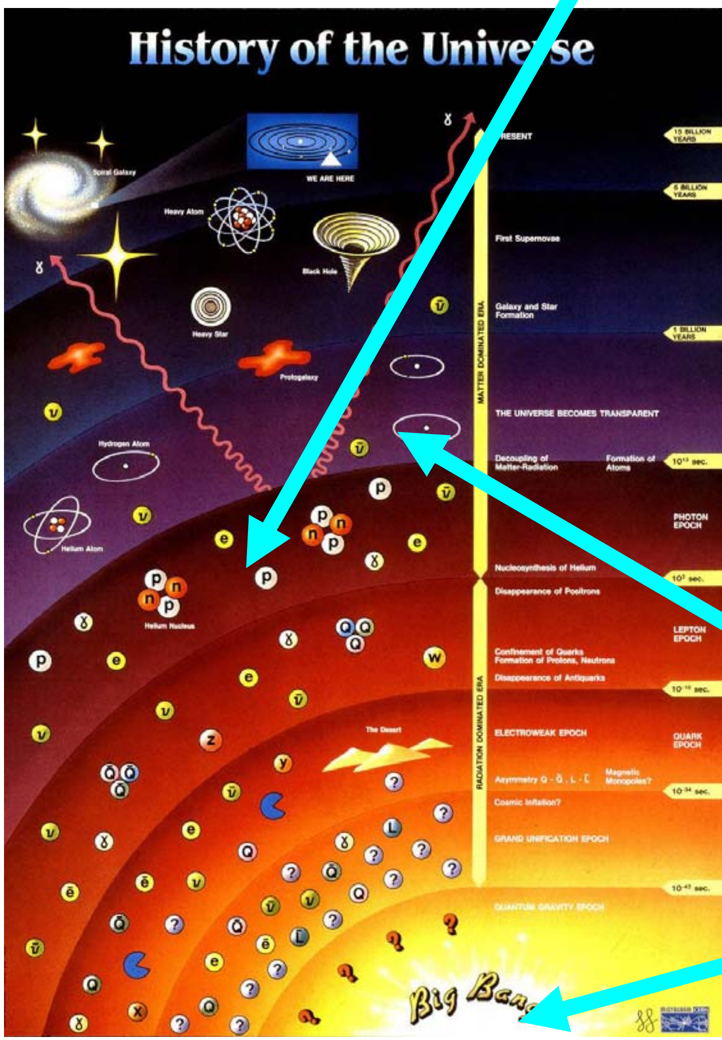
Why do we study CP violation at all?

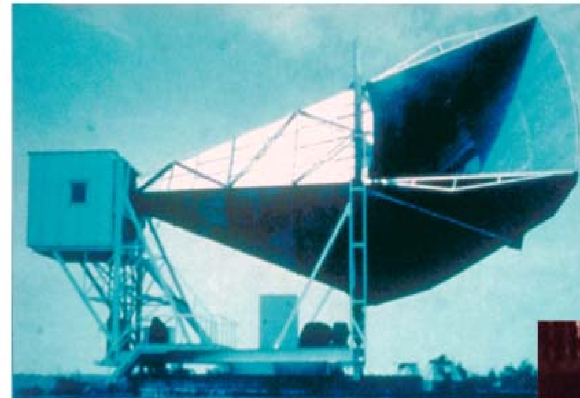
Its goes back the basic question: "Why do we exist?"

Big-Bang scenario

Generation of light elements

Discovery of Cosmic Background





Microwave Receiver

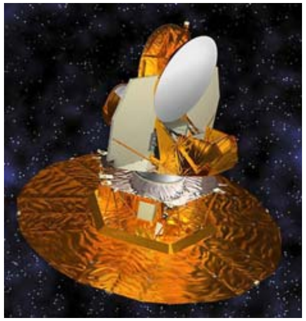
Robert Wilson

Arno Penzias

Black-body radiation
The universe is filled with 3 °K photons

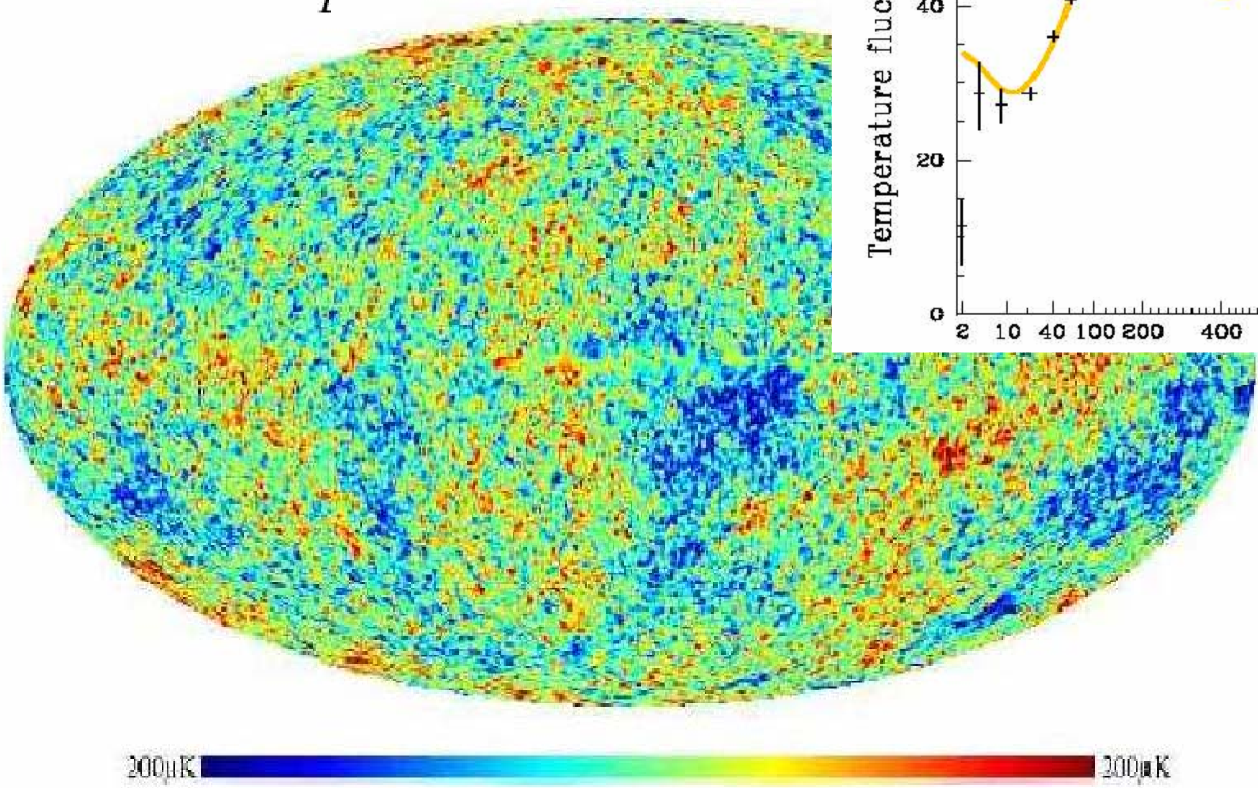
Expanding universe

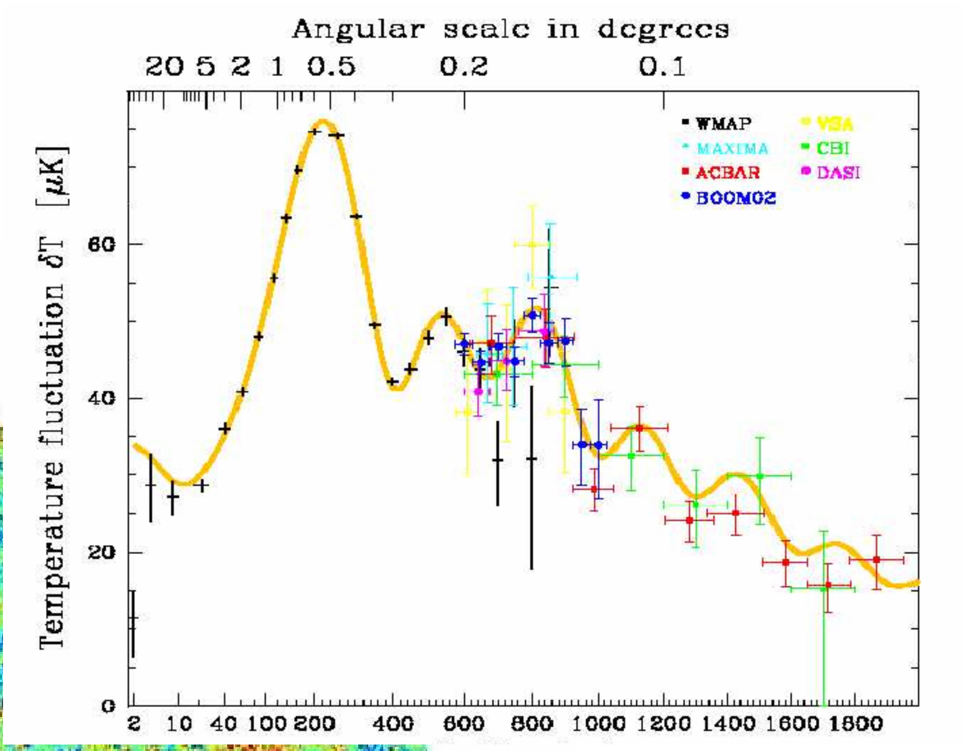
Structure of the Microwave Radiation



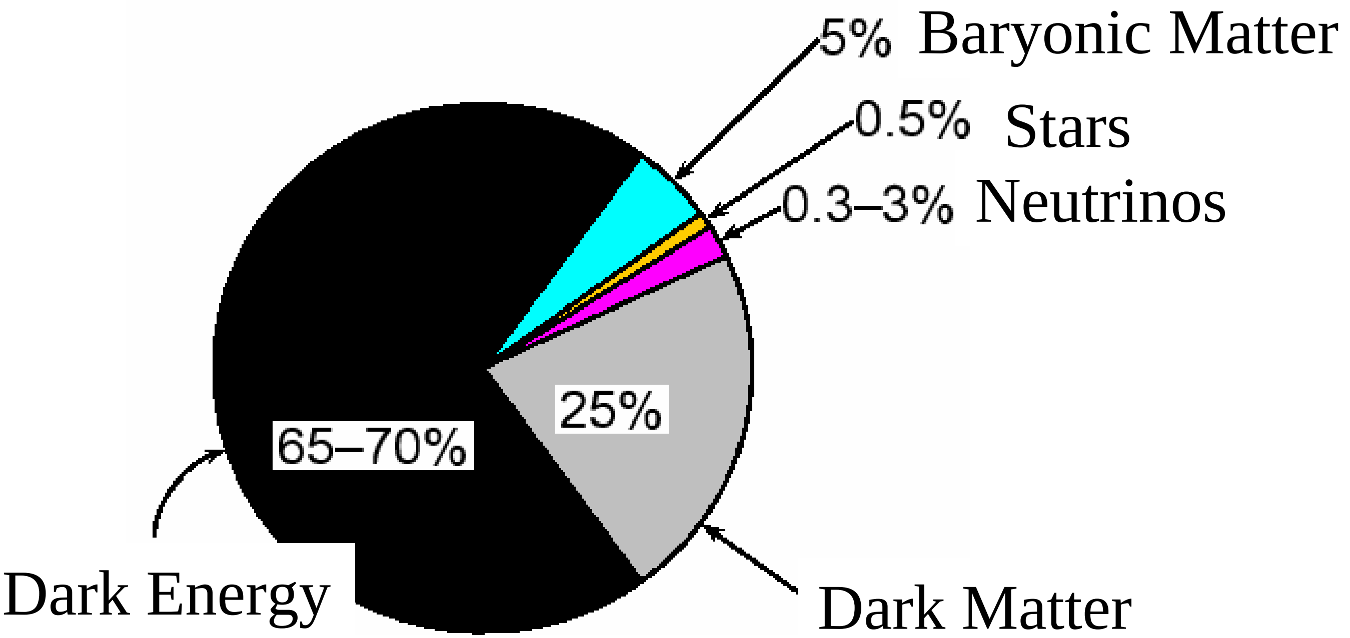
Wilkinson Microwave Anisotropy Probe

$$T = 2.725^{\circ}K, \quad \frac{\delta T}{T} \sim 10^{-5}$$

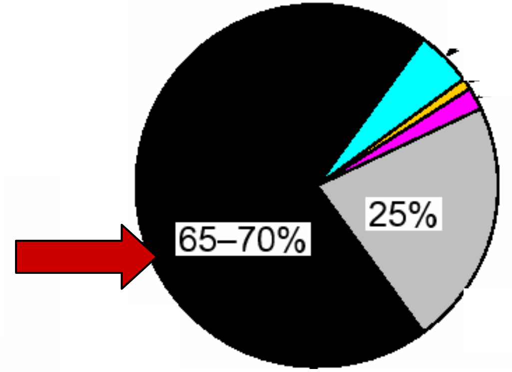




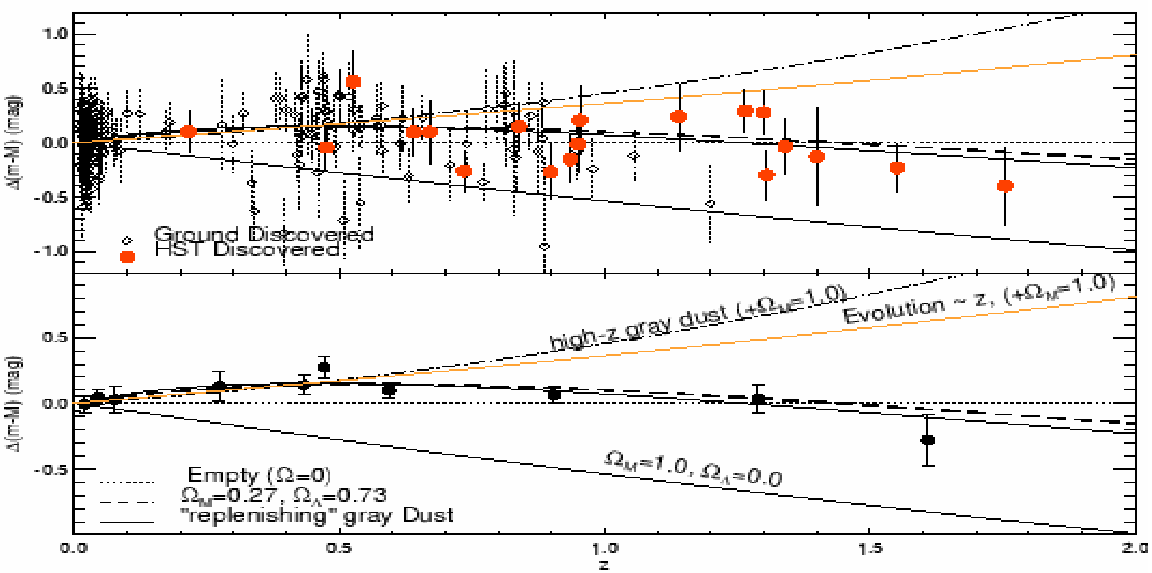
$$\frac{\delta T}{T} = \sum_{l,m} C_{lm} Y_{lm}(\theta, \varphi)$$


5% Baryonic Matter
0.5% Stars
0.3–3% Neutrinos
25%
65–70%
Dark Energy
Dark Matter

Dark Energy

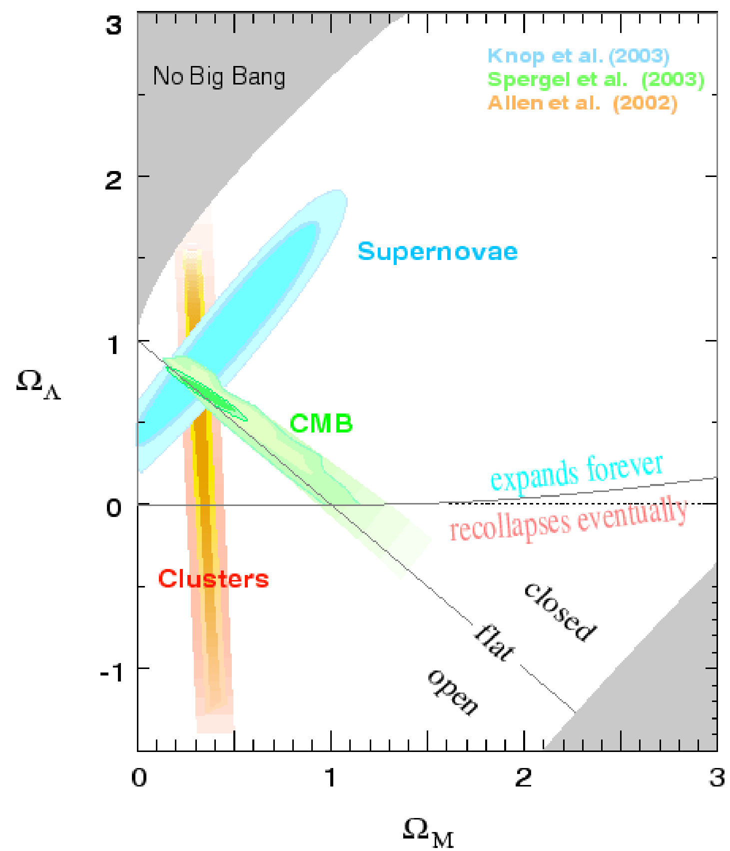


- Type Ia supernova are standard candles for cosmological observations
- Expansion of the Universe is accelerating
- Nature of Dark Energy is a matter of speculations



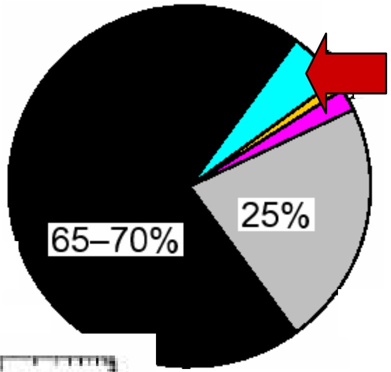
$$\Omega_M = \frac{\varepsilon_{\text{matter}}}{\varepsilon_{\text{tot}}}$$

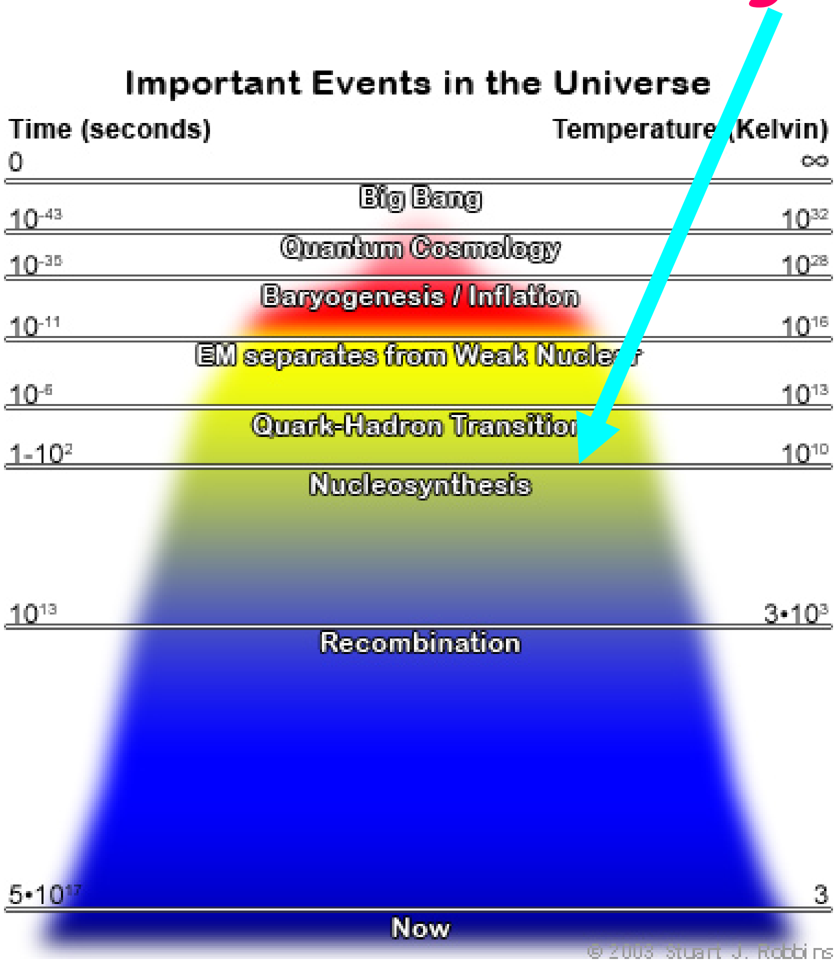
$$\Omega_\Lambda = \frac{\varepsilon_{\text{dark energy}}}{\varepsilon_{\text{tot}}}$$

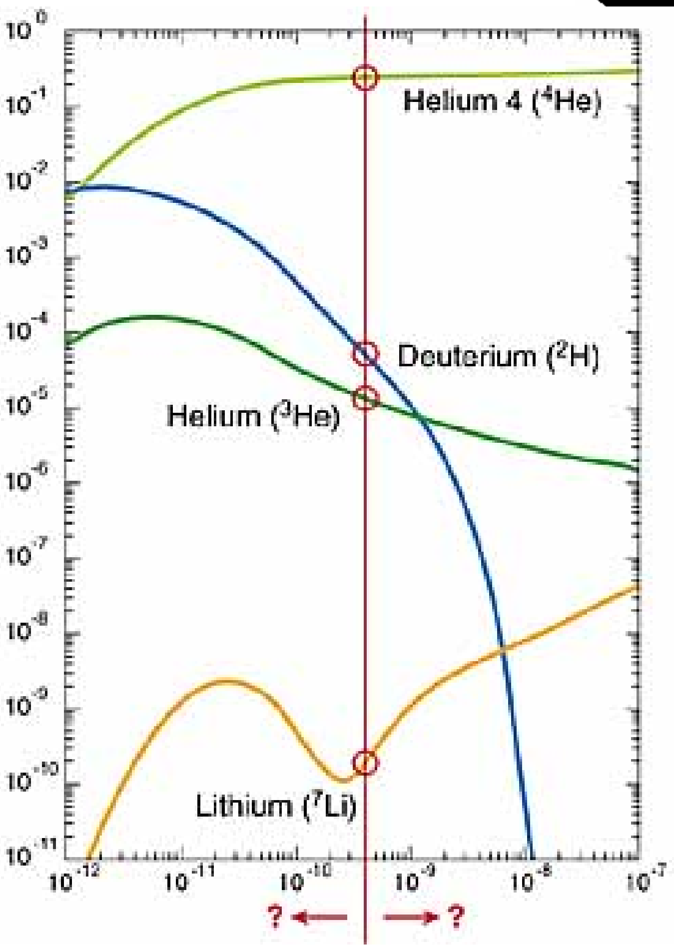


Big Bang Nucleosynthesis

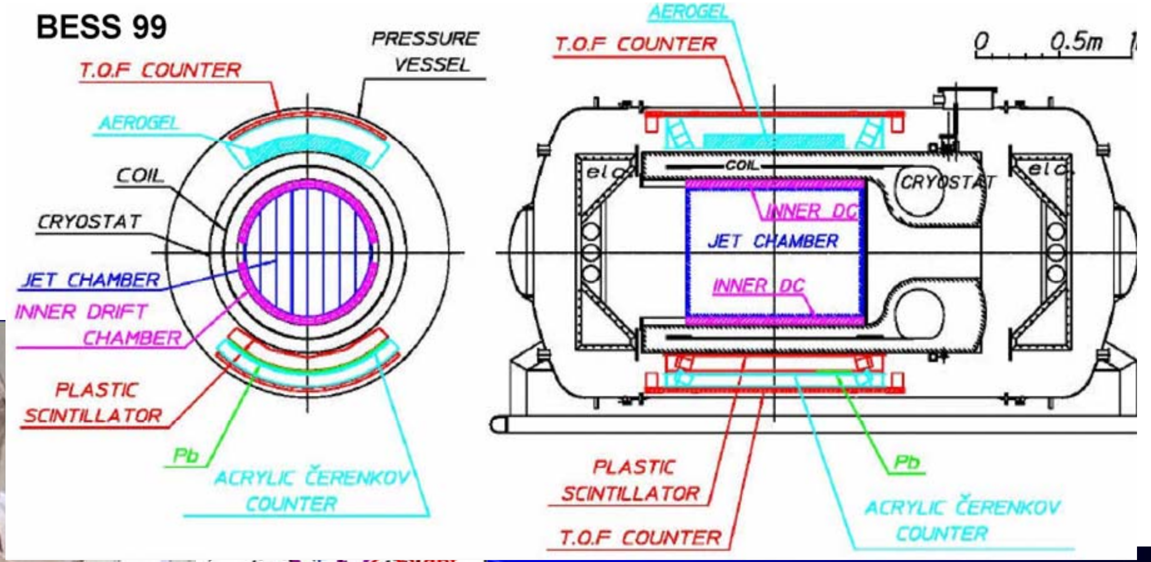
Generation of light elements

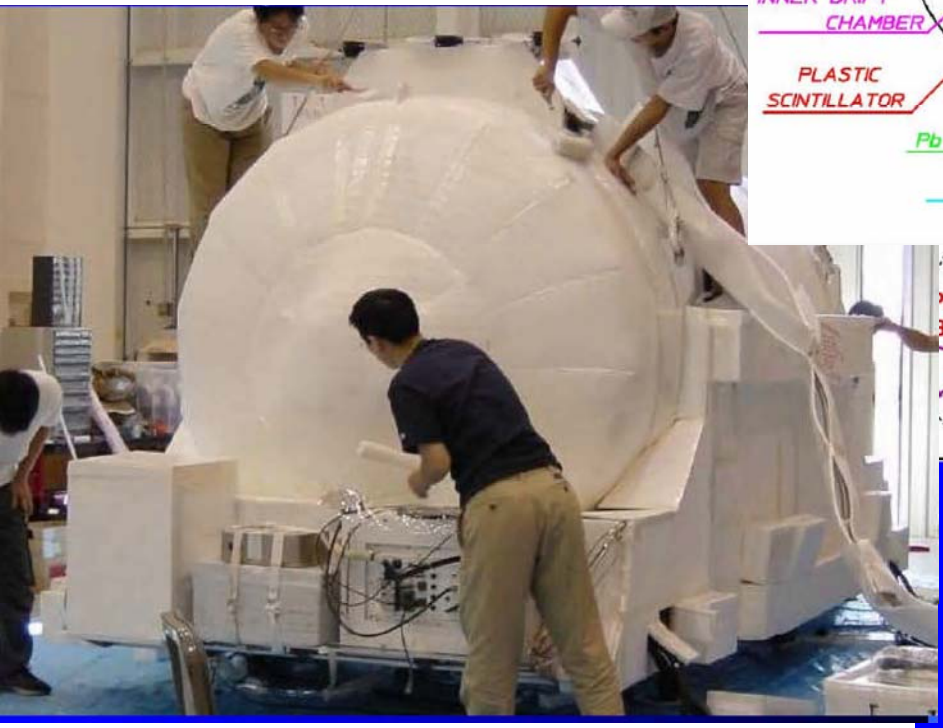






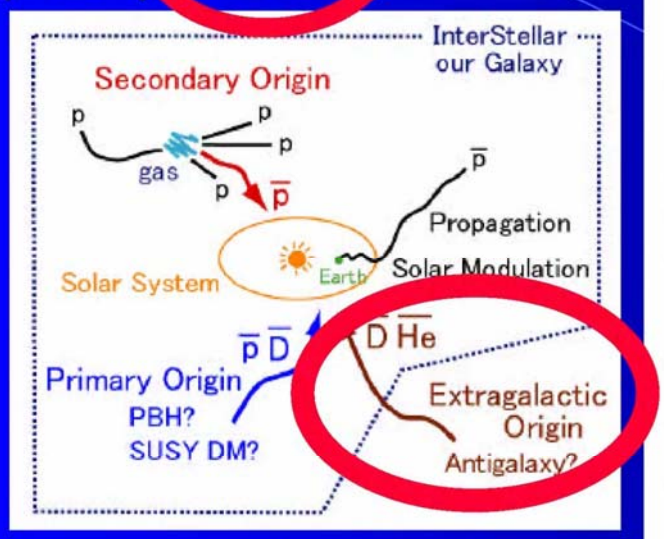
Anti-matter search





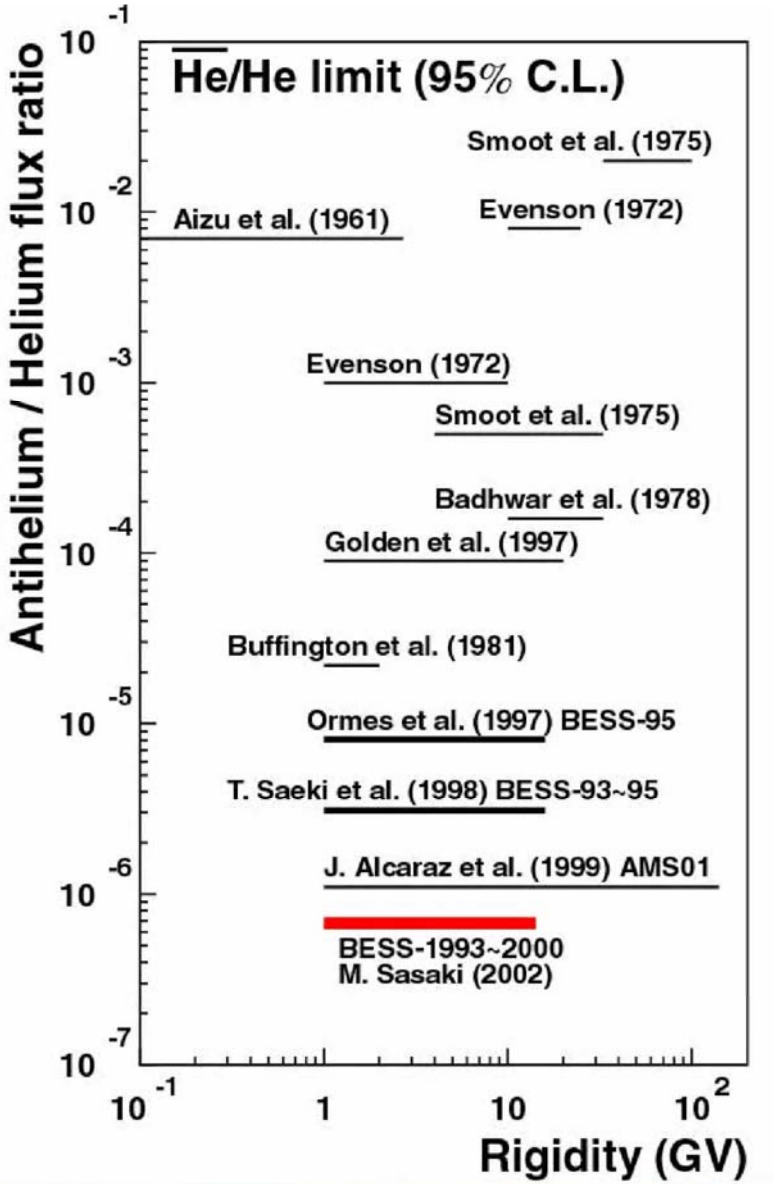
Where is anti-matter?

$\bar{p}$, $\bar{D}$, $\overline{He}$



- ✓ Extra-galactic origin ?
- ✓ $\overline{He}/He < 6.8 \times 10^{-7}$

Most direct evidence that our neighbour space is made of matter.



Particles and Antiparticles

- The relativistic wave equation proposed by Dirac (1928) was able to account for the intrinsic angular momentum (spin) of the electron.

$$(\gamma_\mu \frac{\partial}{\partial x_\mu} + m)\psi = 0$$

- Where ψ four component wave function, γ_μ - 4x4 matrices.
- Writing the plane-wave solution as

$$\psi(\vec{r},t) = u_j e^{ip_\mu x_\mu}, \quad or \quad \psi(\vec{r},t) = u_j e^{-ip_\mu x_\mu} \qquad j = 1,\dots,4$$

- Two possible solution with "positive energy" and two more with "negative"

$$u_{++} = \begin{bmatrix} 1 \\ 0 \\ \frac{p}{|E|+m} \\ 0 \end{bmatrix} \quad u_{+-} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ \frac{-p}{|E|+m} \end{bmatrix} \qquad u_{-+} = \begin{bmatrix} \frac{-p}{|E|+m} \\ 0 \\ 1 \\ 0 \end{bmatrix} \quad u_{--} = \begin{bmatrix} 0 \\ \frac{p}{|E|+m} \\ 0 \\ 1 \end{bmatrix}$$

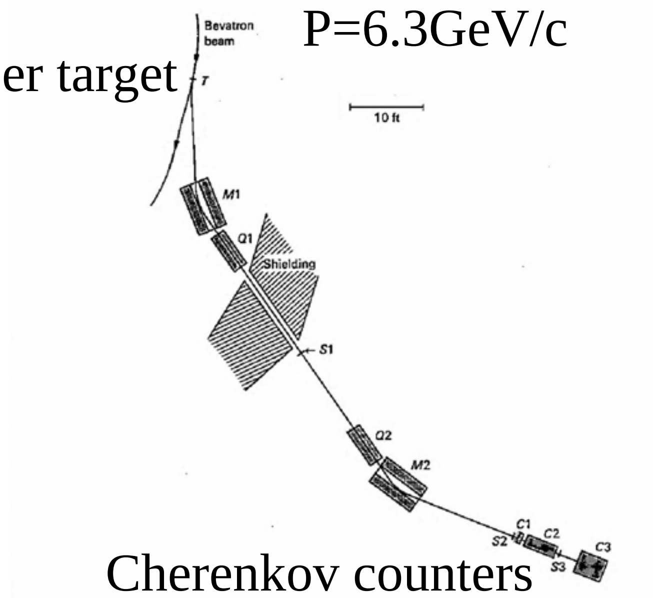
- Dirac supposed that there was a completely filled sea of negative-energy states; a "hole" in this sea of the electrons was interpreted as ***positron***

Particles and Antiparticles

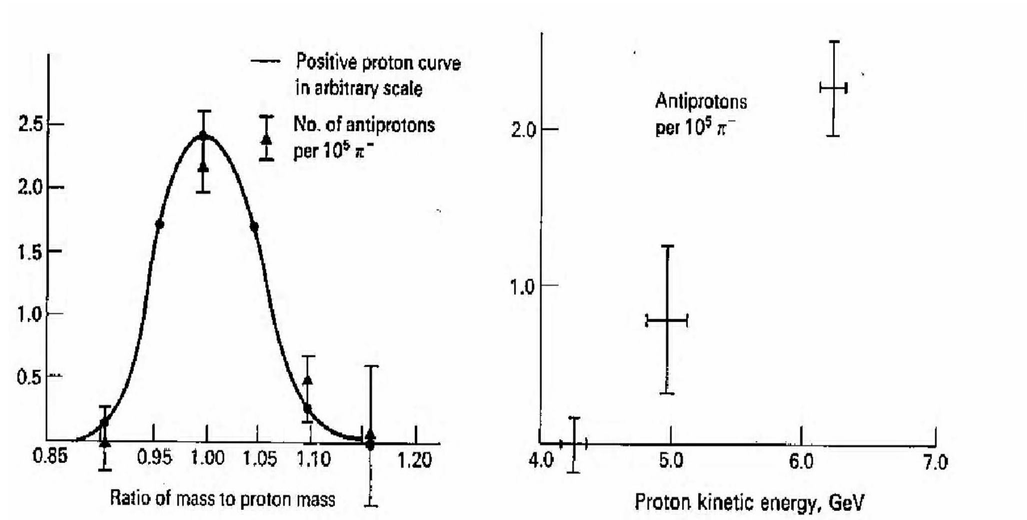
- Positron was discovered in the cosmic rays by Andersen and by Blackett and Occhialini in 1933
- The antiproton was discovered in the experiments at Berkeley by Chamberlain, Segre, Wiegand, and Ypsilantis in 1955.

P=6.3GeV/c

Copper target



Cherenkov counters



- The existence of antiparticles is a general property of both fermions and bosons.
- The antiparticle having the same mass as the particle, but opposite charge and magnetic moment.

Invariance in quantum mechanics

- Result of a measurement corresponds to expectation value of some operator Q $\quad q = \int \psi^* Q \psi dt$
- The Schrodinger equation of motion for ψ $\quad i\hbar \frac{\partial}{\partial t}\psi_s(t) = H\psi_s(t)$

  where H is the total energy operator (Hamiltonian)
- It gives the energy eigenvalues E of stationary state $\quad H\psi = E\psi$
- Time dependence of vector state ψ_s, $\quad \psi_s(t) = T(t,t_0)\psi_s(t_0)$

  where $\quad T(t,t_0) = \exp[-i(t-t_0)H/\hbar]$
- Operator T preserves the norm of wavefunction and is unitary $\quad T^{-1} \equiv T^*, T^{-1}T = 1$
- Heisenberg description attributes the time dependence to operator Q $\quad Q = T^{-1}Q_0 T,$

$$i\hbar\frac{dQ}{dt} = i\hbar\frac{\partial Q}{\partial t} + i\hbar\frac{dT^{-1}}{dt}Q_0 T + i\hbar T^{-1}Q_0\frac{dT}{dt} =$$

$$i\hbar\frac{\partial Q}{\partial t} - HT^{-1}Q_0 T + T^{-1}Q_0 TH = \boxed{i\hbar\frac{\partial Q}{\partial t} + [Q, H]}$$

Conserved quantum numbers are associated with operators commuting with the Hamiltonian

Simple examples: translations

- Translation in space – continuous transformation

- Infinitesimal translation in space δr

$$\psi' = \psi(r+\delta r) = \psi(r) + \delta r \frac{\partial \psi(r)}{\partial r} = (1+\delta r \frac{\partial}{\partial r})\psi = D\psi$$

- Since the momentum operator is $p = -i\hbar \frac{\partial}{\partial r}$

$$D = (1 - \partial r \cdot p / i\hbar)$$

- A finite translation Δr can be obtained by making n steps in succession

$$D = \lim_{n\to\infty} (1 - \partial r \frac{p}{i\hbar})^n = \exp(\frac{ip\Delta r}{\hbar})$$

- So if Hamiltonian commutes with D, so also does with p

$$[\, p \,, H \,] = 0$$

Simple examples: rotations

- Infinitesimal rotations in space $\delta\phi$ $$R = 1 + \delta\phi \frac{\partial}{\partial\phi}.$$

- The operator of the z-component of angular momentum

$$J_z = -i\hbar\left(x\frac{\partial}{\partial y} - y\frac{\partial}{\partial x}\right) = -i\hbar\frac{\partial}{\partial\phi} \quad \Rightarrow \quad R = 1 + \frac{i}{\hbar}J_z\delta\phi.$$

- A finite rotation $\Delta\phi$ can be obtained by making n steps in succession

$$R = \lim_{n\to\infty}\left(1 + \frac{i}{\hbar}J_z\partial\phi\right)^n = \exp\left(\frac{i}{\hbar}J_z\Delta\phi\right)$$

- So if Hamiltonian commutes with R, so also does with J_z

$$[J_z, H] = 0$$

- Conservation of angular momentum about an axis corresponds to invariance of the Hamiltonian under rotations about that axis

Parity

- Operation of spatial inversion of coordinates is an example of a discrete transformation $(x, y, z \rightarrow -x, -y, -z)$
- Repetition of this operation implies $P^2=1$ and the eigenvalue of the operator will be $\pm$ 1, this is called the parity P of the system
- Any spherically symmetric potential has the property $H(\vec{r}) = H(-\vec{r}) = H(r)$

  so that [P,H]=0: the bound states have definite parity
- A familiar example is provided by the hydrogen atom wave functions:

$$\psi(r,\theta,\phi) = \chi(r) Y_l^m(\theta,\phi)$$

$$l = 0 \qquad Y_0^0 = \tfrac{1}{\sqrt{4\pi}}; \quad l = 1 \qquad Y_1^0 = \sqrt{\tfrac{3}{4\pi}} \cos\theta \qquad Y_1^1 = \sqrt{\tfrac{3}{8\pi}} \sin\theta e^{i\phi};$$

$$l = 2 \qquad Y_2^0 = \sqrt{\tfrac{5}{16\pi}} (3\cos^2\theta - 1) \qquad Y_2^1 = \sqrt{\tfrac{15}{8\pi}} \sin\theta \cos\theta e^{i\phi}$$

$$Y_2^2 = \sqrt{\tfrac{15}{32\pi}} \sin^2\theta e^{2i\phi}$$

$$Y_l^m(\theta,\phi) \rightarrow Y_l^m(\pi-\theta, \pi+\phi) = (-1)^l Y_l^m(\theta,\phi)$$

- Thus the spherical harmonic functions have $P = (-1)^l$

Charge-Conjugation Invariance

- The operation of charge conjugation reverses the sign of charge and magnetic moment of a particle (leaving all other coordinates unchanged).

- For baryons and leptons, a reversal of charge entails a change in sign of the baryon or lepton number.

- Charge-Conjugation of the fermion anti-fermion bound state. The total wave function is a product of the three wave functions:

$$\psi(total) = \Phi(space) \cdot \alpha(spin) \cdot \chi(charge)$$

$$\alpha(1,1) = \psi_1(\tfrac{1}{2},\tfrac{1}{2})\psi_2(\tfrac{1}{2},\tfrac{1}{2})$$

$$\alpha(1,0) = \tfrac{1}{\sqrt{2}}[\psi_1(\tfrac{1}{2},\tfrac{1}{2})\psi_2(\tfrac{1}{2},-\tfrac{1}{2}) + \psi_2(\tfrac{1}{2},\tfrac{1}{2})\psi_1(\tfrac{1}{2},-\tfrac{1}{2})]$$

$$\alpha(1,-1) = \psi_1(\tfrac{1}{2},-\tfrac{1}{2})\psi_2(\tfrac{1}{2},-\tfrac{1}{2})$$

$$\alpha(0,0) = \tfrac{1}{\sqrt{2}}[\psi_1(\tfrac{1}{2},\tfrac{1}{2})\psi_2(\tfrac{1}{2},-\tfrac{1}{2}) - \psi_2(\tfrac{1}{2},\tfrac{1}{2})\psi_1(\tfrac{1}{2},-\tfrac{1}{2})]$$

- Fermion anti-fermion wave function is anti-symmetrical under particle interchange (Fermi statistics)

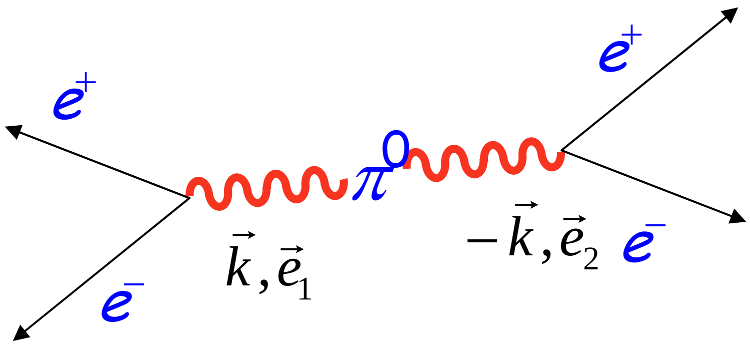
$$-1 = C \cdot (-1)^{S+1} \cdot (-1)^{l} \Rightarrow C = (-1)^{S+l}$$

Eigenstates of the Charge-Conjugation Operator

- Consider the operation of charge conjugation performed on a charged-pion $C|\pi^+\rangle \to |\pi^-\rangle \neq \pm|\pi^+\rangle$
- However, for neutral system $C|\pi^0\rangle = \eta|\pi^0\rangle, \quad \eta^2 = 1$
- Remember for $\langle q\bar{q}|$ state $C = (-1)^{S+l}$ so $C|\pi^0\rangle = +|\pi^0\rangle.$
- Note that electromagnetic fields are produced by moving charge which change sign under charge conjugation. As a consequence, the photon has C=-1. Since the charge-conjugation quantum number is multiplicative, this means that a system of n photons has $C=(-1)^n$.
- As a result $\pi^0 \to 2\gamma$

Parity of the pion

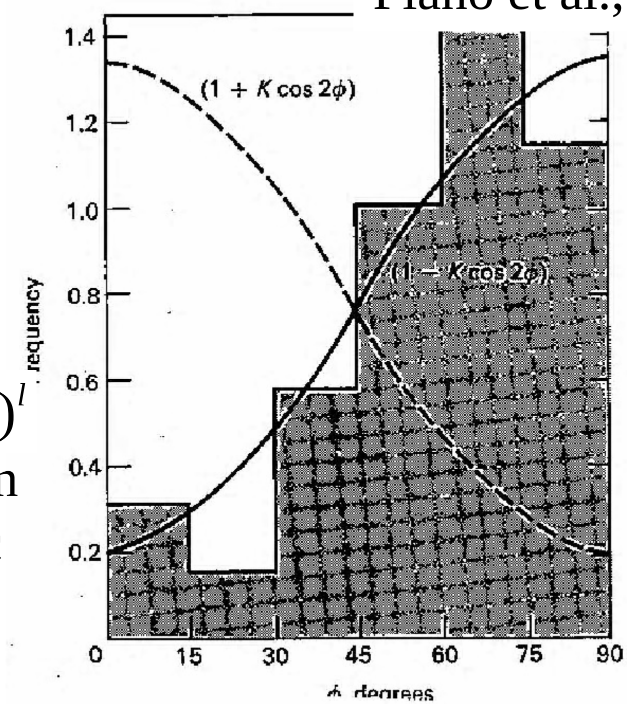
- The parity of the neutral pion has been established from observations of the γ-ray polarization in the double Dalitz decay $\pi^0 \to e^+e^-e^+e^-$.



$$\psi(2\gamma) \sim (\vec{e}_1 \cdot \vec{e}_2) \quad \text{- scalar}$$

$$\psi(2\gamma) \sim (\vec{e}_1 \times \vec{e}_2) \cdot \vec{k} \quad \text{- pseudoscalar}$$

Plano et al.,1959



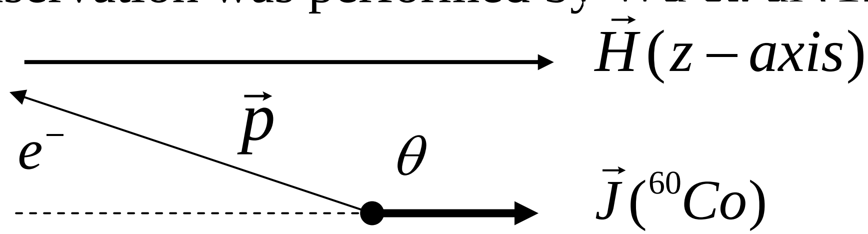
- Since the plane of e+e- lies predominantly in the plane of the E-vector, measurement of the angular distribution between the plane of the pairs demonstrates the odd parity of the neutral pion.
- Spherical harmonic functions have $P = (-1)^l$ and if we will take into account that fermion and anti-fermion have the opposite intrinsic parity the parity of the $q\bar{q}$ pair is

$$P = (-1)^{l+1}$$

Parity Nonconservation in weak decays

- In 1956 Lee and Yang came to conclusion that the weak interactions did not conserved parity – largely on the basis of the fact that the K^+ could decay in two decay modes $K^+ \to 2\pi$ and $K^+ \to 3\pi$, in which the final states have opposite parities.

- The test parity conservation was performed by Wu et. al (1957).



- 60Co(J=5) decays to 60Ni*(J=4). The relative electron intensities allon and against the field direction were measured.

- As a result $$I(\theta) = 1 + \alpha \frac{\vec{\sigma} \cdot \vec{p}}{E} = 1 + \alpha \frac{v}{c} \cos\theta$$

Where $\alpha = -1$

Historical remarks

P violation was suggested by Lee and Yang to resolve θ-τ paradox	PR 104, 256 1956
Ioffe, Okun and Rudik showed that Lee and Yang way leads to C violation	JETP 5,328 1957
Landau introduced CP	JETP 5,336 1957
Wu and collaborators observed the angular asymmetry in the polarized nuclear β-decays	PR 105,1413 1957

CP violation in the $K^0_L \rightarrow \pi^+\pi^-$ decay

Christenson, Cronin, Fitch and Turlay observed 40 events of the $K^0_L \rightarrow \pi^+\pi^-$ decay PRL 13, 138 1964

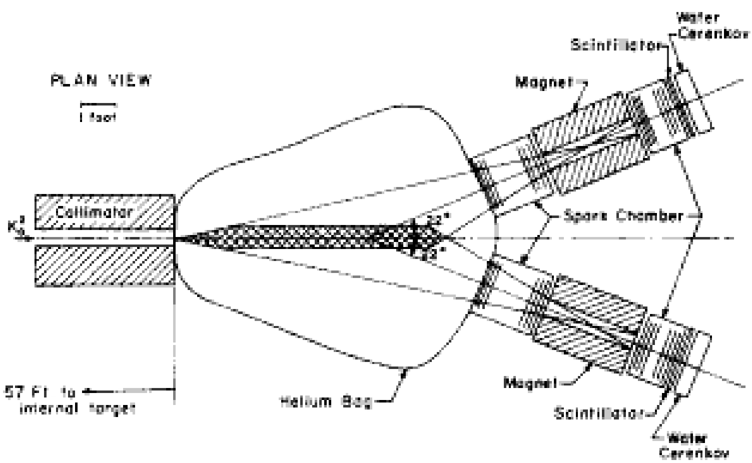


FIG. 1. Plan view of the detector arrangement.

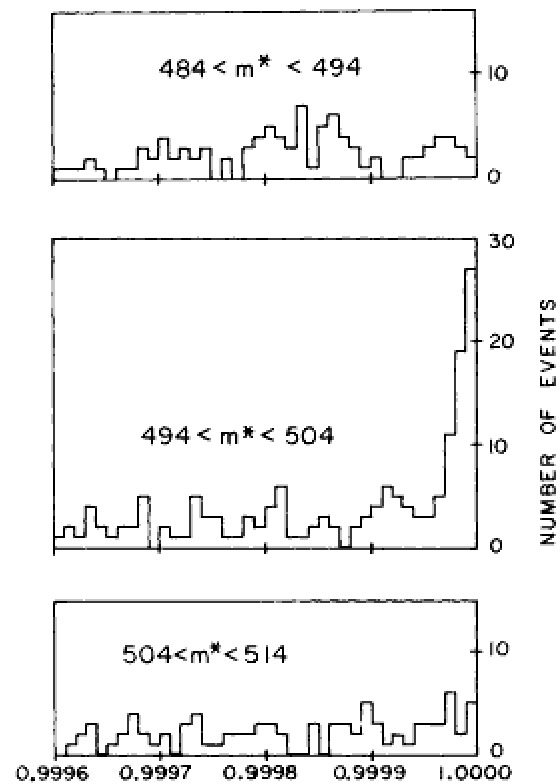


FIG. 3. Angular distribution in three mass ranges for events with cos θ > 0.9995.