Measurement of the Negative Muon Anomalous Magnetic Moment to 0.7 ppm

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Motivation

- 異常磁気モーメント
  - 磁気モーメント

$$\vec{\mu} = g \frac{e}{2mc} \vec{S}$$

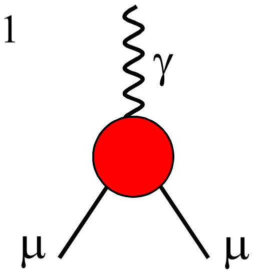
磁気モーメントのポテンシャル項

  - g = 2 (spin 1/2) : from Dirac equation

$$H = \frac{1}{2m}\left(\frac{\hbar}{i}\nabla + e\mathbf{A}(x)\right)^2 - e\phi(x) + \frac{e\hbar}{2m}\boldsymbol{\sigma}\cdot\mathbf{B}(x)$$

  - In SM, radiative correction changes g

$$a_\mu^{theory} = a_\mu^{QED} + a_\mu^{hadronic} + a_\mu^{weak} = 116\,591\,881\,(176) \times 10^{-11}$$

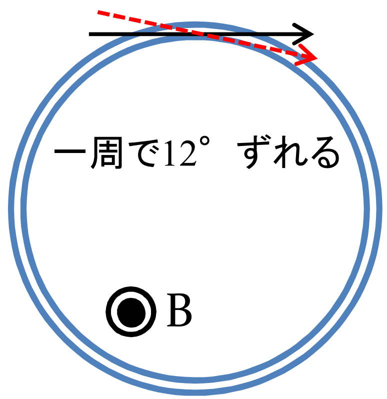


※ $a_\mu = \frac{g-2}{2}$ anomalous magnetic moment

⇨ If there are new particles or substructure for leptons, gauge bosons, quarks ,a_μ would be changed

Measurement principle

- 偏極したμをstorage ring に入射
- 磁場からトルク ⇒ 歳差運動
  - Spin precession frequency : $\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{mc\gamma}$
- Storage ring 中を回転
  - Cyclotron frequency : $\omega_c = \frac{eB}{mc\gamma}$



⇨ $\omega_a = \omega_s - \omega_c = \frac{e}{mc} a_\mu B$

- ビームの収束にelectric quadrupole を使っている

⇒ 電場を考慮する

Measurement principle

$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right]$$

邪魔

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0$$ となるγをとる

⇨ $\gamma = 29.3,\ \ p_\mu = 3.094 GeV/c$ "magic gamma"

- $\omega_a : a_\mu$ に比例、μのmomentum から独立

⇨ ω_a , B , e/mc からa_μ が求まる

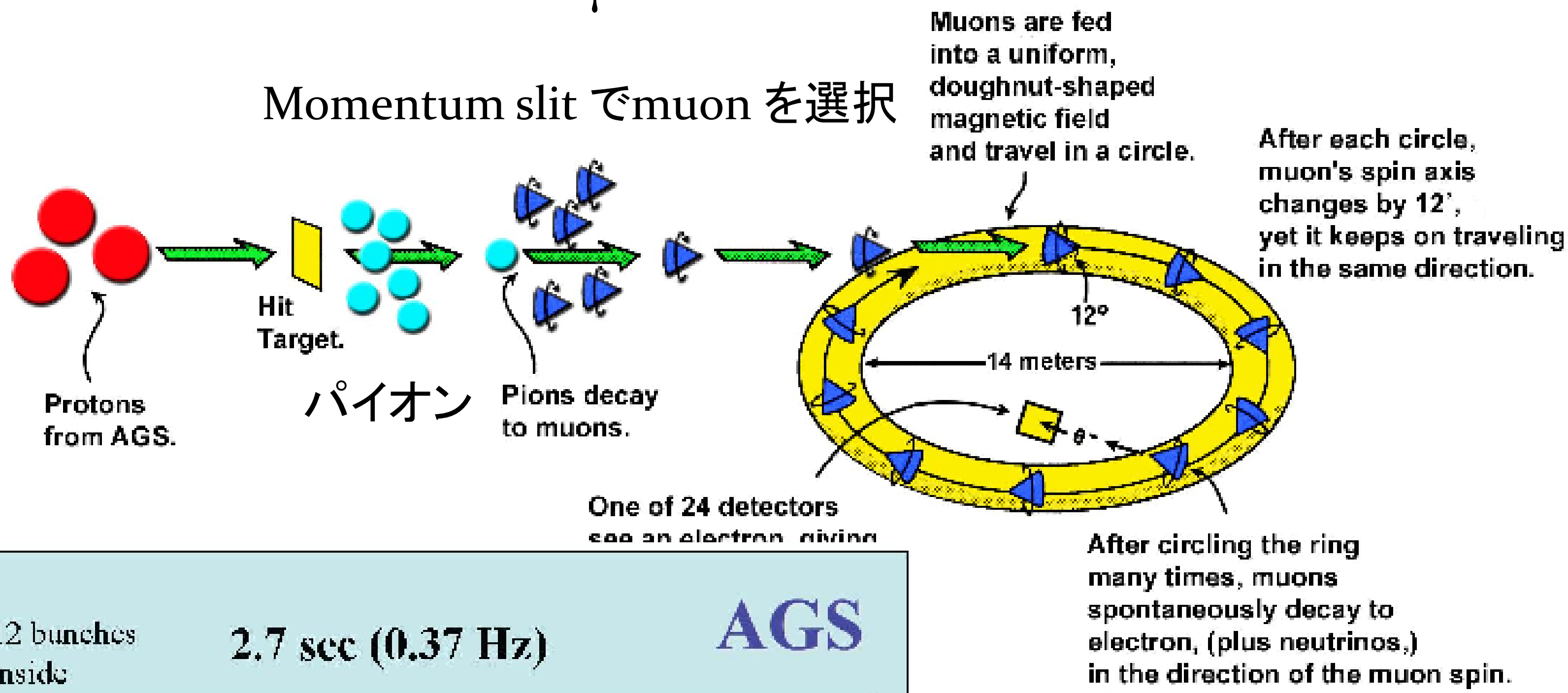
Setup : muon injection

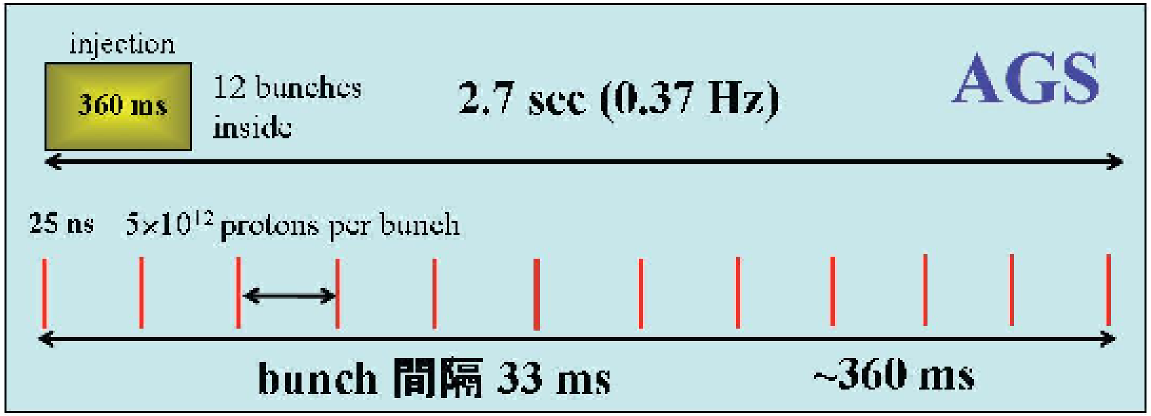
スピン 静止系

$$\bar{\nu} \longleftarrow \pi^- \longrightarrow \mu^-$$

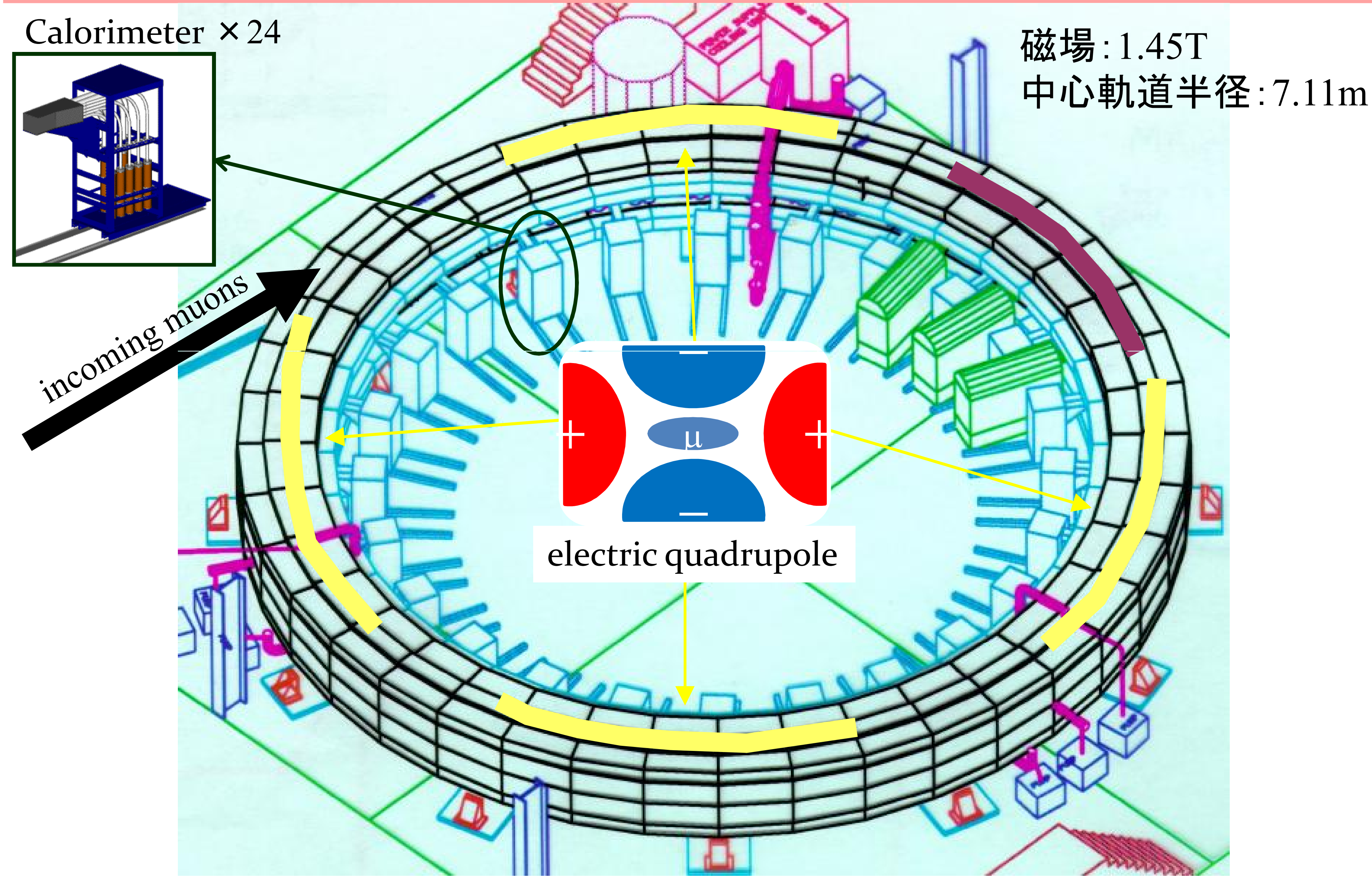
偏極 ~95%

Momentum slit でmuon を選択





Setup : muon storage ring



ω_a Measurement

- ω_a の測定
  - Muon spin によりdecay する方向が回転
  - ω_a was determined by fitting the time distribution of decay electrons
  - High energy electrons(emitted in the forward direction) をカウント

$$N(t) = N_0 e^{-\frac{t}{\gamma\tau}}\left[1 - A\cos(\underline{\omega_a} t + \phi)\right]$$

N_0 : *normalization constatnt*

$\gamma\tau$: *muon laboratory lifetime*

τ : *muon mean life in its rest frame*

A : *muon decay asymmetry parameter*

ω_a Measurement

- 2001年のデータ
- n=0.122, 0.142 について測定
  - $f_{CBO} \sim f_{g-2} \times 2$ を回避 : CBO由来の不確かさを減少
- Five independent analysis
  - 1,2
    - 少し違う関数でfit
    - energy range 1.8-3.4GeV
  - 3
    - energy-dependent modulation asymmetry でカウントに重み
    - Energy range 1.5-3.4GeV

ω_a Measurement

– 4,5

- データをランダムに4分割 : n_1-n_4
- rejoined

$$u(t) = n_1(t) + n_2(t),\ v(t) = n_3(t - \tau_a/2) + n_4(t + \tau_a/2)$$

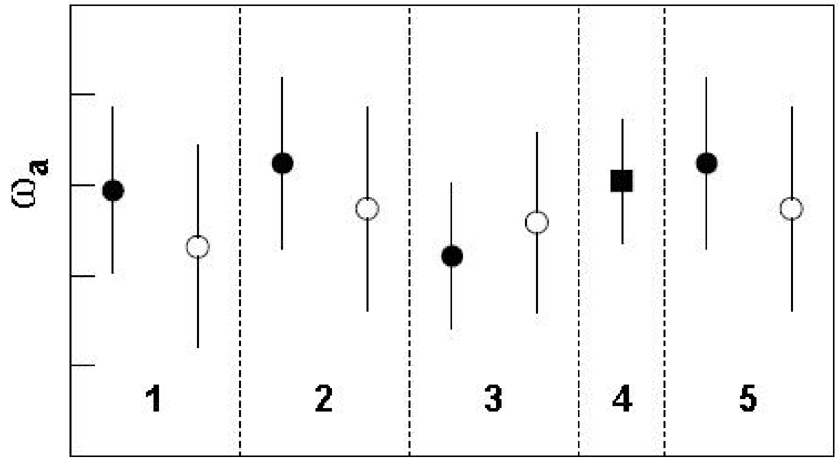
※ τ_a : 予測されるg-2 周期

$$r(t) = \frac{u(t) - v(t)}{u(t) + v(t)} = A(E)\sin\left[\omega_a t + \phi_a(E)\right] + \varepsilon$$

- 4
  - fit 前に両n values, 全detectors のデータを統合
- 5
  - 別々にfit

ω_a Measurement

- ω_a for two n values are consistent
- Five analyses の違いは statistical
- 平均をとる



$$\frac{\omega_a}{2\pi} = 229\ 073.59(15)(5) Hz\ (0.7\, ppm)$$

B Measurement

- 磁場 の測定(NMR)
  - Measured by a proton resonance frequency ω_p

$$\frac{\omega_p}{2\pi} = 61\,791\,400(11) Hz \;\; (0.2\,ppm)$$

- 定数　e/mc ⇒ λ
  - ω_p をつかうので必要な定数はλ

$$\lambda = \frac{\mu_\mu}{\mu_p} = 3.1183\,345\,39(10)$$

$$\mu = \frac{e\hbar}{2mc}$$

- ω_p, λ をつかって ⇒ $$a_\mu = \frac{R}{\lambda - R}$$

$$R = \frac{\omega_a}{\omega_p}$$

Anomalous magnetic moment

$$a_{\mu^-} = 11\ 659\ 214\ (8)(3) \times 10^{-10}\ \ (0.7\, ppm)$$

$$R_{\mu^-} = 0.003\ 707\ 208\ 3\ (26)$$

- $R_{\mu+}$とよく一致する
- 平均をとる

$$R_{\mu} = 0.003\ 707\ 206\ 3\ (20)$$

$$a_{\mu}(\exp) = 11\ 659\ 208\ (6) \times 10^{-10}\ \ (0.5\, ppm)$$

Summary

- This is the final analysis of the anomalous magnetic moment from experiment E821 at the Brookhaven Alternating Gradient Synchrotron
- $a_{\mu-}$を0.7ppmで測定

$$a_{\mu^-} = 11\ 659\ 214\ (8)(3) \times 10^{-10}\ \ (0.7\,ppm)$$

- $a_{\mu+}$ のデータとあわせて

$$a_{\mu}(\exp) = 11\ 659\ 208\ (6) \times 10^{-10}\ \ (0.5\,ppm)$$

- a_{μ}(SM) との差 : 2.7σ(e^+e^-), 1.4σ(τ)

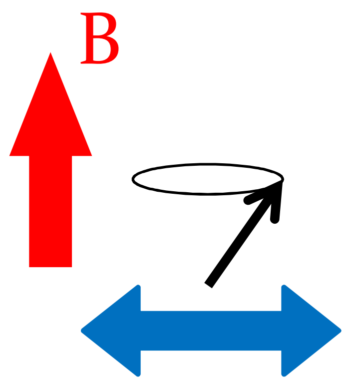
Buck up

Nuclear Magnetic Resonance

ラーモア歳差運動の周波数 $\omega_l = g_l \dfrac{eB}{2mc}$

$\Downarrow$

ω_1 からBが求められる



Bと垂直方向にω_1 の周波数の磁場をかけると共鳴する ⇒ ω_1が求まる

a_μ

$$\frac{\omega_a}{\omega_\mu} = \frac{a_\mu \frac{eB}{mc}}{g_\mu \frac{eB}{2mc}} = \frac{a_\mu}{\frac{g_\mu}{2}} = \frac{a_\mu}{a_\mu + 1}$$

$$= \frac{\omega_a}{\omega_p}\frac{\omega_p}{\omega_\mu} = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_\mu} = \frac{R}{\lambda}$$

$$\Rightarrow \qquad a_\mu = \frac{R}{\lambda - R}$$

ω_μ, ω_p : μ,p の軌道角運動量に対するラーモア歳差運動の周波数

$$\omega_l = g_l \frac{eB}{2mc}$$

Fit function

1. $f(t) = N(t)b(t)l(t)$

$$N(t) = N_0(E)e^{-t/(\gamma\tau)}\{1 + A(E)\sin[\omega_a t + \phi_a(E)]\}$$

$$b(t) = 1 + A_b e^{-t^2/\tau_b^2}\cos(\omega_b t + \phi_b)$$

$$l(t) = 1 + n_l e^{-t/\tau_l}$$

2. $N(t) = N_0(t;E)e^{-t/(\gamma\tau)}\{1 + A(t;E)\sin[\omega_a t + \phi_a(t;E)]\}$

$1 + A_i(t)\sin(\omega_{CBO,h}t + \phi_i)$ でN_0, A, ϕ_a をmodulate