Physics
OSAKA UNIVERSITY

人工原子における
電子間相互作用によるパリティーの破れ

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日本物理学会 第76回年次大会, オンライン, 2021/03/14

Atomic parity violation

Weiman et al.
PRL55, 2680 (1985); PRA34,792 (1986);
PRL61, 310 (1988); Science 275,1759 (1997)

^{133}Cs 6s-7s transition

Parity violating (PV) E1

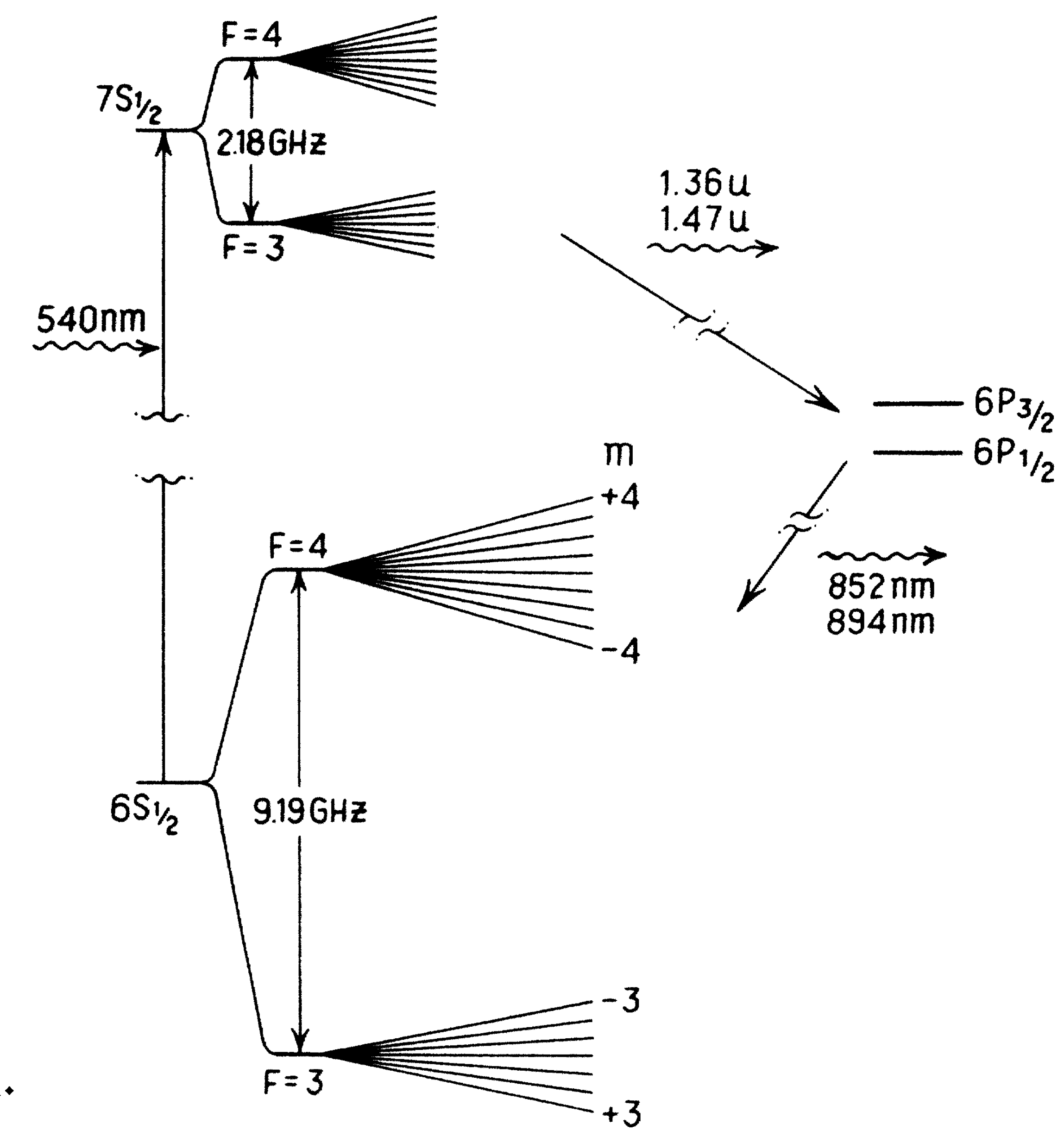
$$\sim G_F \bar{q}\gamma^\mu q\, \bar{e}\gamma_\mu\gamma_5 e$$

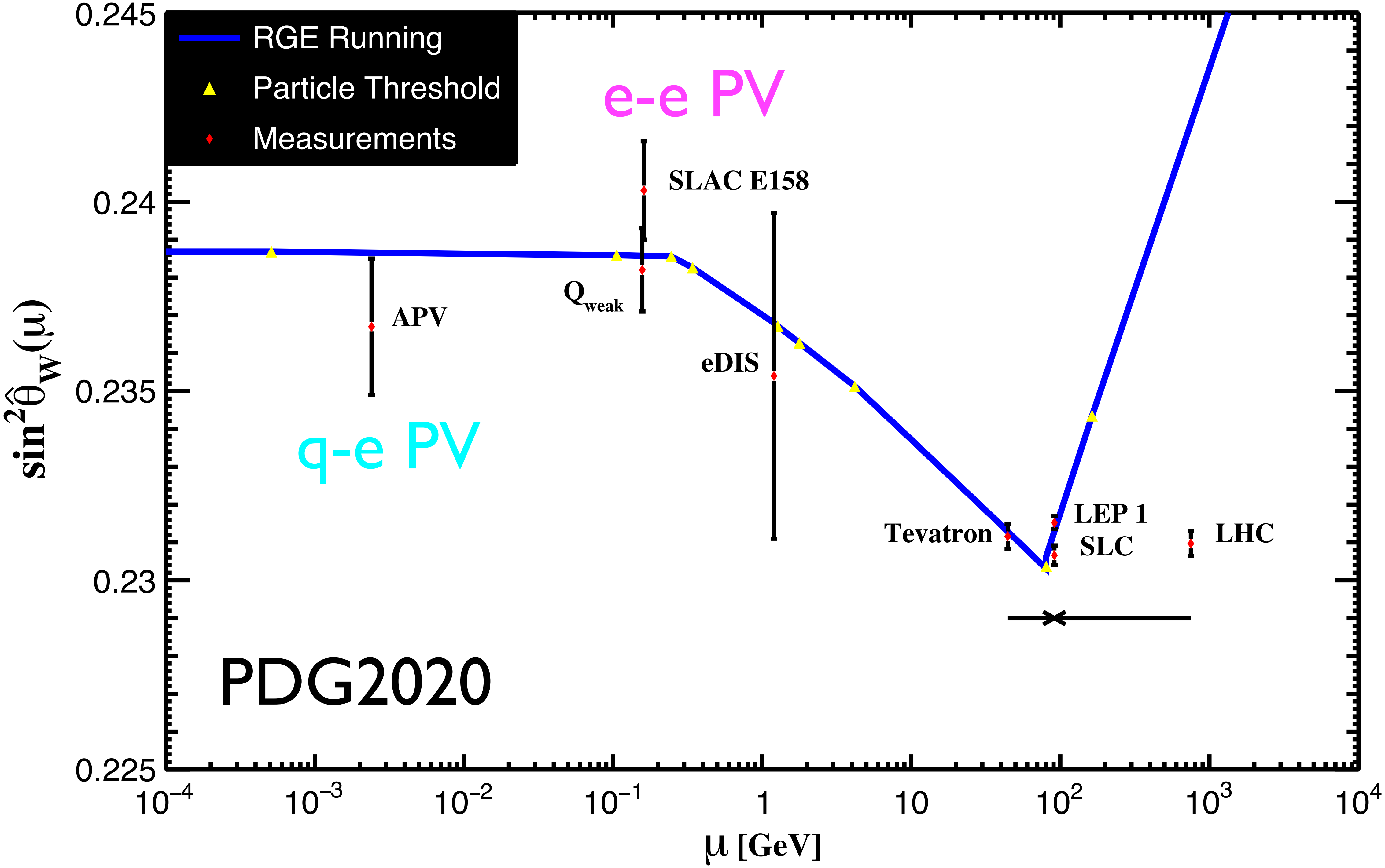
Stark induced E1

$$\Gamma = |A_{\rm ST} + A_{\rm PV}|^2$$

ST-PV interference

$$\sin^2\theta_{\rm w} = 0.2261(12)_{\rm exp}\ (41)_{\rm theory}.$$



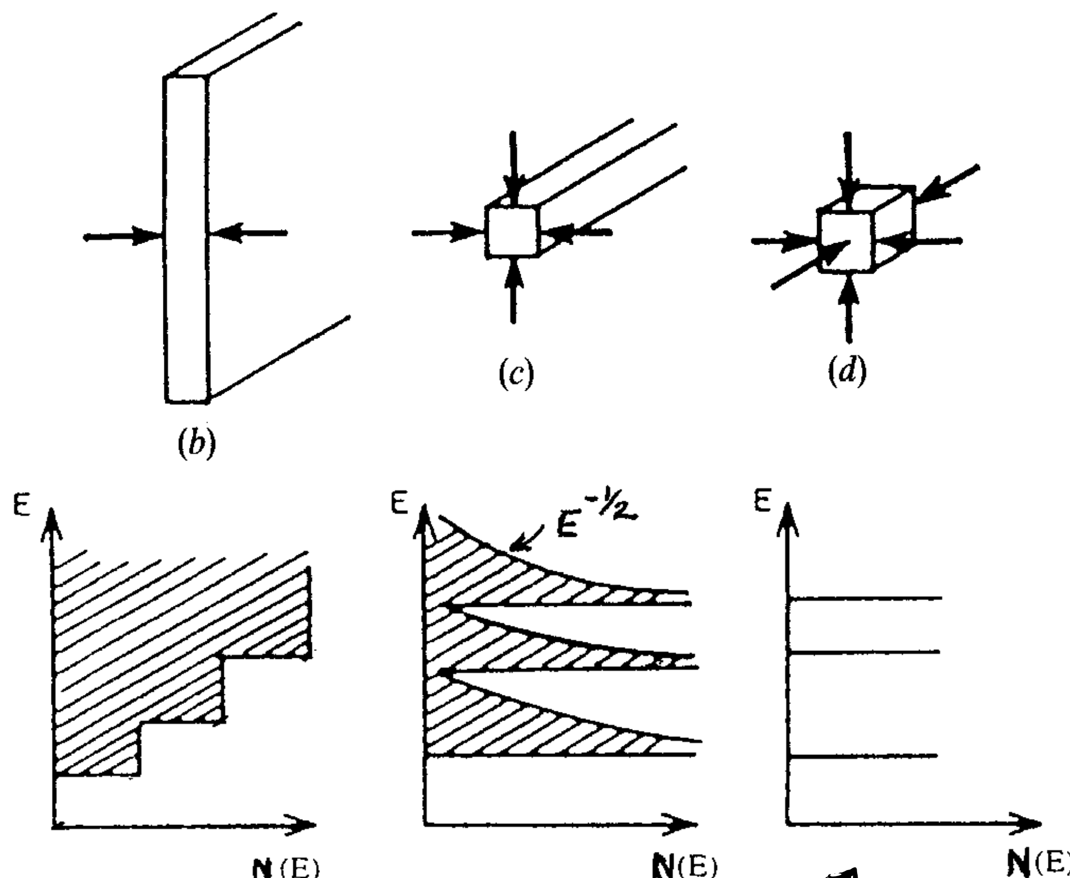


RGE Running
Particle Threshold
Measurements
e-e PV
q-e PV
SLAC E158
APV
Q weak
eDIS
Tevatron
LEP 1
SLC
LHC
PDG2020
0.245
0.24
0.235
0.23
0.225
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
μ [GeV]
$\sin^2\hat{\theta}_W(\mu)$

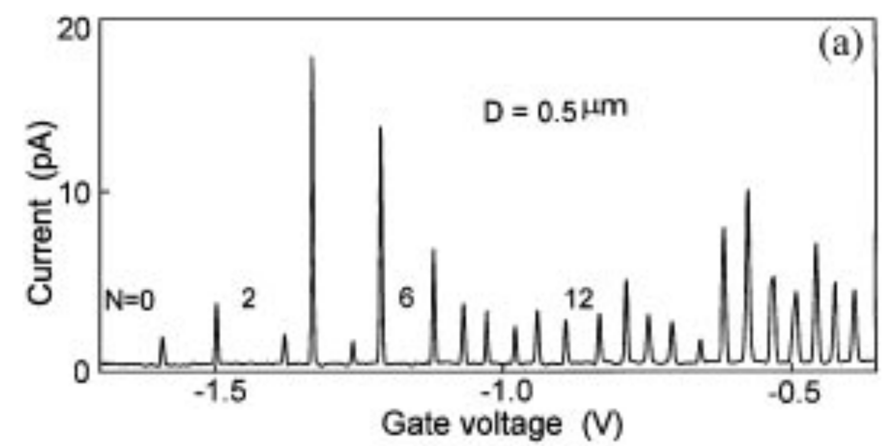
Artificial atoms

Semiconductor nanostructure

quantum well   wire   dot



A.D.Yoffe,
Adv. Phys. , 42, 173 (1993)



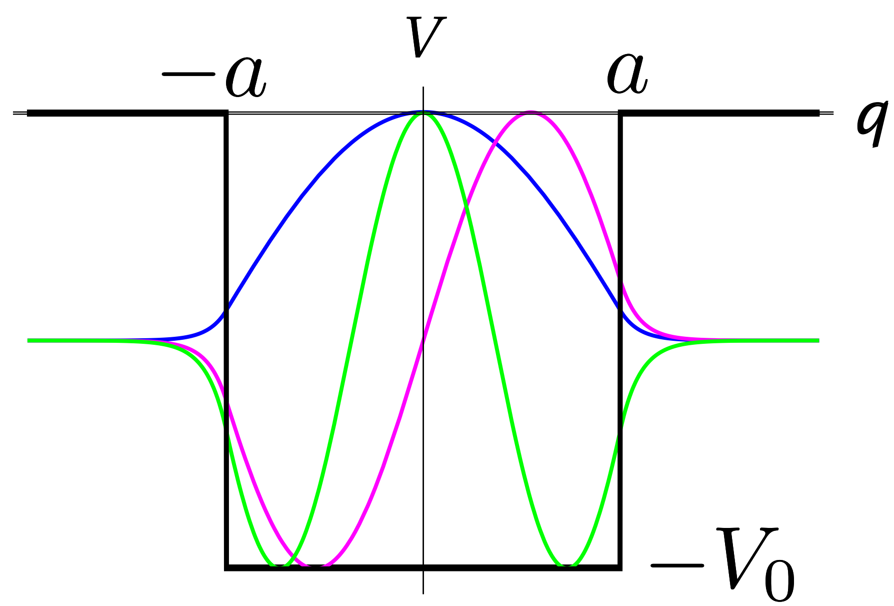
S.Tarucha et al.,
PRL 77, 3613 (1996)

quantized energy levels like natural atoms

Quantum box: 3-dim. square-well potential

$$\psi_{\boldsymbol{n}}(x,y,z)=\varphi_{n_x}(x)\varphi_{n_y}(y)\varphi_{n_z}(z)$$

One-dim. potential



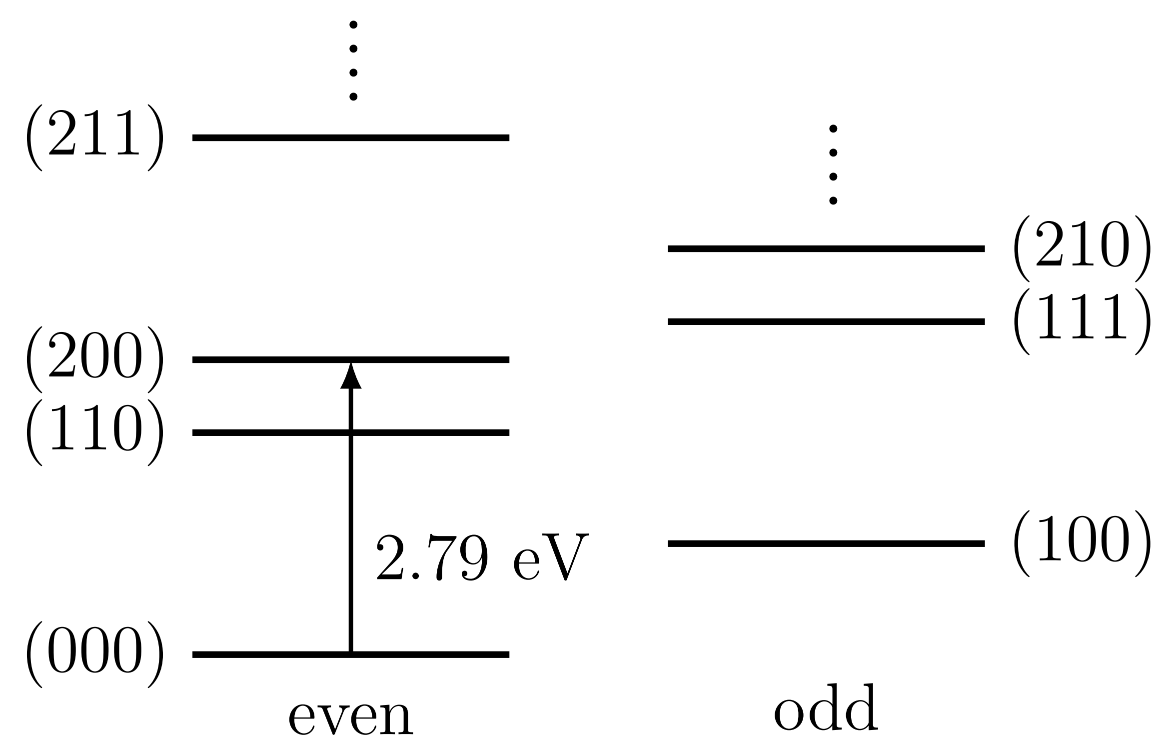
$$2a = 3\ \mathrm{nm}$$

$$V_0 = 20\ \mathrm{eV}$$

$$m = 0.1 m_e$$

7 bound states $n_{x,y,z} = 0 - 6$

Low-lying 3-dim. levels



Parity violation in e-e neutral current

$$\mathcal{H}_{\mathrm{PV}}^{(\mathrm{NC})} = \frac{G_F}{2\sqrt{2}}(-1+4\sin^2\theta_w)\bar{e}\gamma^\mu e\,\bar{e}\gamma_\mu\gamma_5 e$$

Two electrons in the 3-dim. well

One of them is a spectator in the ground state.

Non-relativistic quantum mechanical hamiltonian

$$H_{\mathrm{PV}} = \frac{G_F}{2\sqrt{2}m_e}(-1+4\sin^2\theta_w) \times \left[\boldsymbol{\sigma}\cdot\boldsymbol{p}\rho_s(\boldsymbol{r}) + \rho_s(\boldsymbol{r})\boldsymbol{\sigma}\cdot\boldsymbol{p} - 2\boldsymbol{p}_s(\boldsymbol{r})\cdot\boldsymbol{\sigma}\right]$$

$\rho_s(\boldsymbol{r})\,,\ \boldsymbol{p}_s(\boldsymbol{r})$: spectator number, momentum densities

NB $\rho_s(\boldsymbol{r}) \sim \delta^3(\boldsymbol{r})\,,\ \boldsymbol{p}_s(\boldsymbol{r}) \simeq 0$ in atomic PV

Principle of PV experiment

E1 forbidden transition: (000)→(200)

induced by the weak PV and Stark effect

even-odd state mixing

$$A = A_{\mathrm{ST}} + A_{\mathrm{PV}}$$

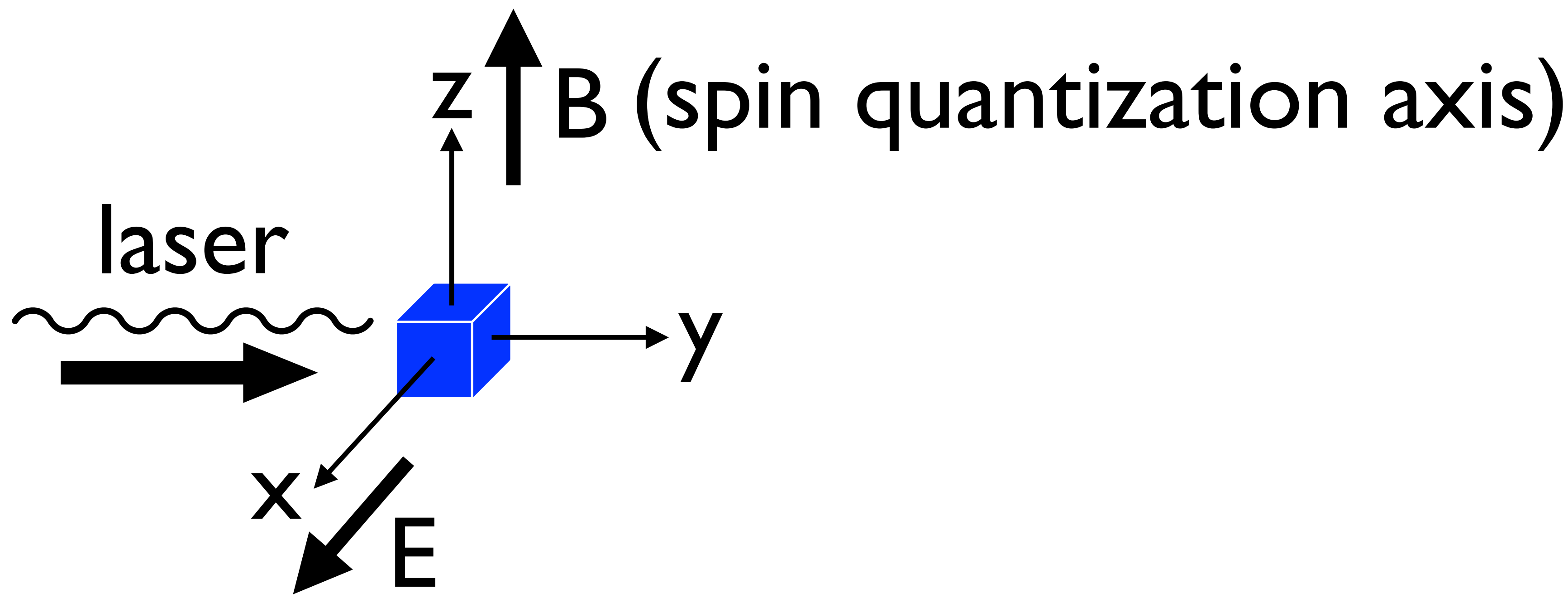
$$\Gamma = |A_{\mathrm{ST}}|^2 + 2\mathrm{Re}(A^*_{\mathrm{ST}} A_{\mathrm{PV}}) + O(G_F^2)$$

interference between Stark and PV

the same as Cs atomic PV experiment

Numerical illustration

Setup



Stark field along the x axis: $\boldsymbol{E}_{\rm ST} = E_{\rm ST}\hat{\boldsymbol{x}}$

Laser beam along the y axis:

$$\boldsymbol{E}_L = E_{\rm L}(i\cos\theta\hat{\boldsymbol{x}} + \sin\theta\hat{\boldsymbol{z}})e^{i(ky-\omega t)}$$

Amplitudes and rates

$$A_{\mathrm{ST}} = i\cos\theta \cdot \delta_{m_f m_i} e^2 E_{\mathrm{L}} E_{\mathrm{ST}}\, a^2 C_{\mathrm{ST}}$$

$$C_{\mathrm{ST}} = 7.2 \times 10^{-2}\ \mathrm{eV}^{-1}$$

$$A_{\mathrm{PV}} = ieE_{\mathrm{L}} \frac{G_F}{2\sqrt{2}} (-1 + 4\sin^2\theta_w) \frac{1}{m_e a^3}$$
$$\times \left[i\cos\theta (\delta_{m_f, m_i+1} + \delta_{m_f+1, m_i}) C_{\mathrm{PV}}^{(x)} + \sin\theta \cdot 2m_i \delta_{m_f, m_i} C_{\mathrm{PV}}^{(z)} \right]$$

$$C_{\mathrm{PV}}^{(z)} = -0.11\ \mathrm{eV}^{-1}$$

$$\Gamma_{\mathrm{ST}} = 2.3 \times 10^5/\mathrm{sec}\ \cos^2\theta \cdot \delta_{m_f m_i} \left(\frac{E_{\mathrm{ST}}}{100\ \mathrm{V/cm}} \right)^2 \left(\frac{E_{\mathrm{L}}^2}{1\ \mathrm{W/mm^2}} \right) \left(\frac{1\ \mathrm{kHz}}{\gamma_L} \right)$$

$$\Gamma_{\mathrm{int}} = 1.1 \times 10^{-11}/\mathrm{sec}\ \cos\theta \sin\theta \cdot 2m_i \delta_{m_f m_i} \left(\frac{E_{\mathrm{ST}}}{100\ \mathrm{V/cm}} \right) \left(\frac{E_{\mathrm{L}}^2}{1\ \mathrm{W/mm^2}} \right) \left(\frac{1\ \mathrm{kHz}}{\gamma_L} \right)$$

Summary

- ✶ Semiconductor nanostructure
    - artificial atoms, quantized energy levels
- ✶ Parity violation in the e-e neutral current
    - illustration with a quantum box
    - Stark-PV interference $\sim 10^{-11}/\mathrm{sec}$
- ✶ Possible rate enhancement mechanism
    - closely degenerate parity even-odd states
        - symmetry consideration
            - the present setup: C_{4h} point group

関連する講演: 吉見さん(岡大) 15pV1-11