Influences of halo-type and skin-type neutron distributions on the parity-violating electron scattering

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- **研究背景**

  皮型以及晕型中子密度分布的定义

  关于中子皮厚度以及中子密度分布的最新实验进展

- **皮型以及晕型中子密度分布对宇称不守恒电子散射的影响。**

- **基于Helm模型分析JLab宇称不守恒电子散射实验的结果**

- **结论**

I. 研究背景

皮型以及晕型密度分布的定义：

The nuclear neutron and proton distributions are often described with the two parameters Fermi (2PF) distributions:

$$\rho(r) = \frac{\rho_0}{1 + \exp[\frac{r-c}{a}]}$$

c is the half-density parameter and *a* is the diffuseness parameter.

考虑中子密度分布两种极端的情况：

Neutron **halo-type** distributions: $c_n = c_p, a_n > a_p$

Neutron **skin-type** distributions: $c_n > c_p, a_n = a_p$

原子核中子皮的定义：

$$R_{\mathrm{skin}} = R_n - R_p$$

Determination of R_{skin} has led to much experimental interest in recent years.

By analyzing the data measured in antiprotonic ^{208}Pb atom, the authors obtained

$$R_{\mathrm{skin}} = 0.16 \pm (0.02)_{\mathrm{stat}} \pm (0.04)_{\mathrm{syst}} \ \mathrm{fm}$$

B. Kłos, *et al.*, Phys. Rev. C 76, 014311 (2007) .

Another study of the antiprotonic data of ^{208}Pb leads to

$$R_{\mathrm{skin}} = 0.20 \pm (0.04)_{\mathrm{exp}} \pm (0.05)_{\mathrm{theo}} \ \mathrm{fm}$$

B. Brown, *et al.*, Phys. Rev. C 76, 034305 (2007).

Recent analysis of proton scattering data gave:

$$R_{\mathrm{skin}} = 0.211 \pm 0.06 \ \mathrm{fm}$$

J. Zenihiro, *et al.*, Phys. Rev. C 82, 044611 (2010).

Analysis of poin scattering data gave:

$$R_{\mathrm{skin}} = 0.16 \pm 0.07 \ \mathrm{fm}$$

E. Friedman, Nucl. Phys. A 896, 46 (2012).

采用电磁相互作用探针和弱相互作用探针的实验比强相互作用探针理论误差更小

With the electroweak probes, the parity-violating electron scattering experiment in PREx gave:

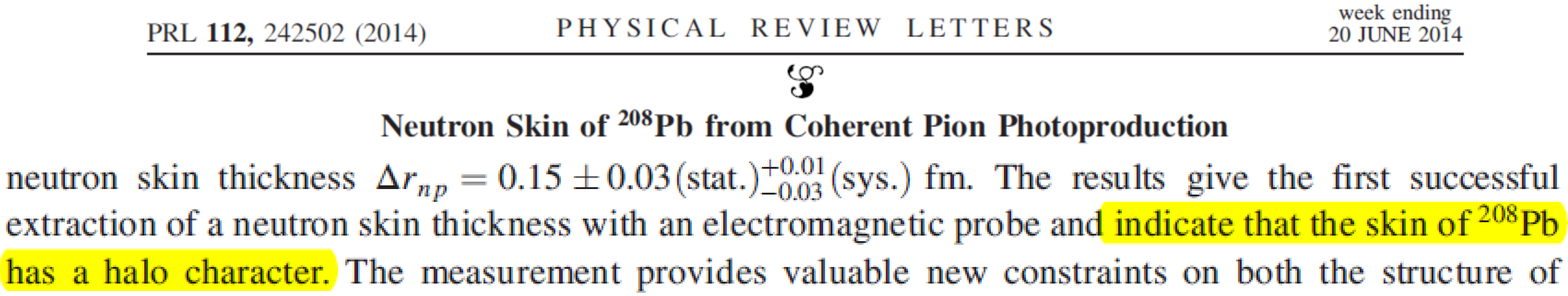
$$R_{\text{skin}} = 0.33^{+0.16}_{-0.18}\ \text{fm}$$

S. Abrahamyan *et al.*, Phys. Rev. Lett. 108, 112502 (2012).

With the electromagnetic probes, the coherent pion photoproduction experiments gave:

$$R_{\text{skin}} = 0.15\ \pm 0.03(\text{stat.})^{+0.02}_{-0.03}(\text{sys.})\ \text{fm}$$

C.M. Tarbert *et al.*, Phys. Rev. Lett. 112, 242502 (2014).



PRL **112,** 242502 (2014) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Neutron Skin of ^{208}Pb from Coherent Pion Photoproduction

neutron skin thickness $\Delta r_{np} = 0.15 \pm 0.03(\text{stat.})^{+0.01}_{-0.03}(\text{sys.})$ fm. The results give the first successful extraction of a neutron skin thickness with an electromagnetic probe and indicate that the skin of ^{208}Pb has a halo character. The measurement provides valuable new constraints on both the structure of

Experiments by measuring the data of antiprotonic ^{208}Pb atom and coherent pion photoproduction indicate that the skin of ^{208}Pb has a halo character.

The parameters for $\rho_p(r)$ are well determined by the electron scattering.

$$c_p = 6.680\ \text{fm},\ a_p = 0.447\ \text{fm}$$

质子2pF分布参数

From measuring the data of antiprotonic ^{208}Pb atom, the authors obtain:

$$c_n = 6.684\ \text{fm},\ a_n = 0.571\ \text{fm}$$

B. Kłos, *et al.*, Phys. Rev. C 76, 014311 (2007) .

From the coherent pion photoproduction experiment, the authors obtain:

$$c_n = 6.70 \pm 0.03(\text{stat.})\ \text{fm}$$

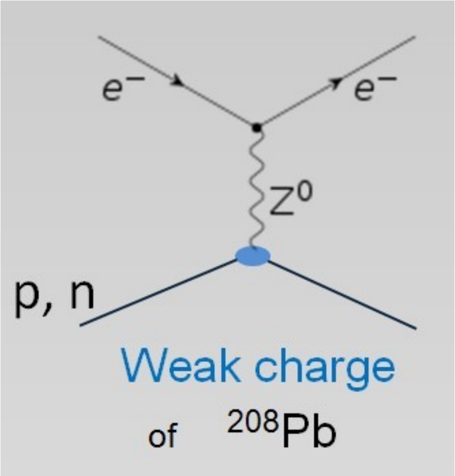
$$a_n = 0.55 \pm 0.01(\text{stat.})^{+0.02}_{-0.03}\ \text{fm}$$

C.M. Tarbert *et al.*, Phys. Rev. Lett. 112, 242502 (2014).

两个实验都表明原子核中子密度分布为晕型

II. 皮型以及晕型中子密度分布对宇称不守恒电子散射的影响

宇称不守恒电子散射



Z^0 玻色子是一种很有效的探针，它首先和中子耦合：

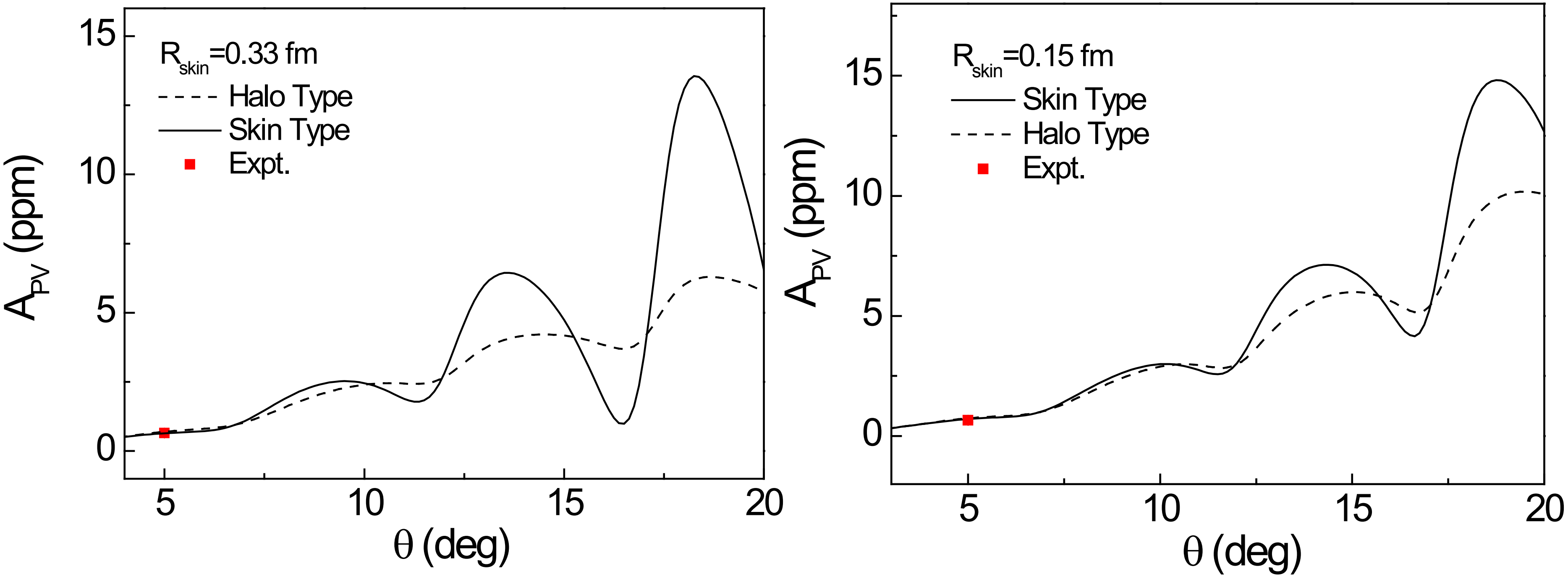
$$A_{\mathrm{pv}} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_N(Q^2)}{F_P(Q^2)}\right]$$

考虑到库仑扭曲效应： $A_{\mathrm{pv}} = \dfrac{2\,\mathrm{Re}[M_\gamma^* M_Z]}{|M_\gamma|^2}$

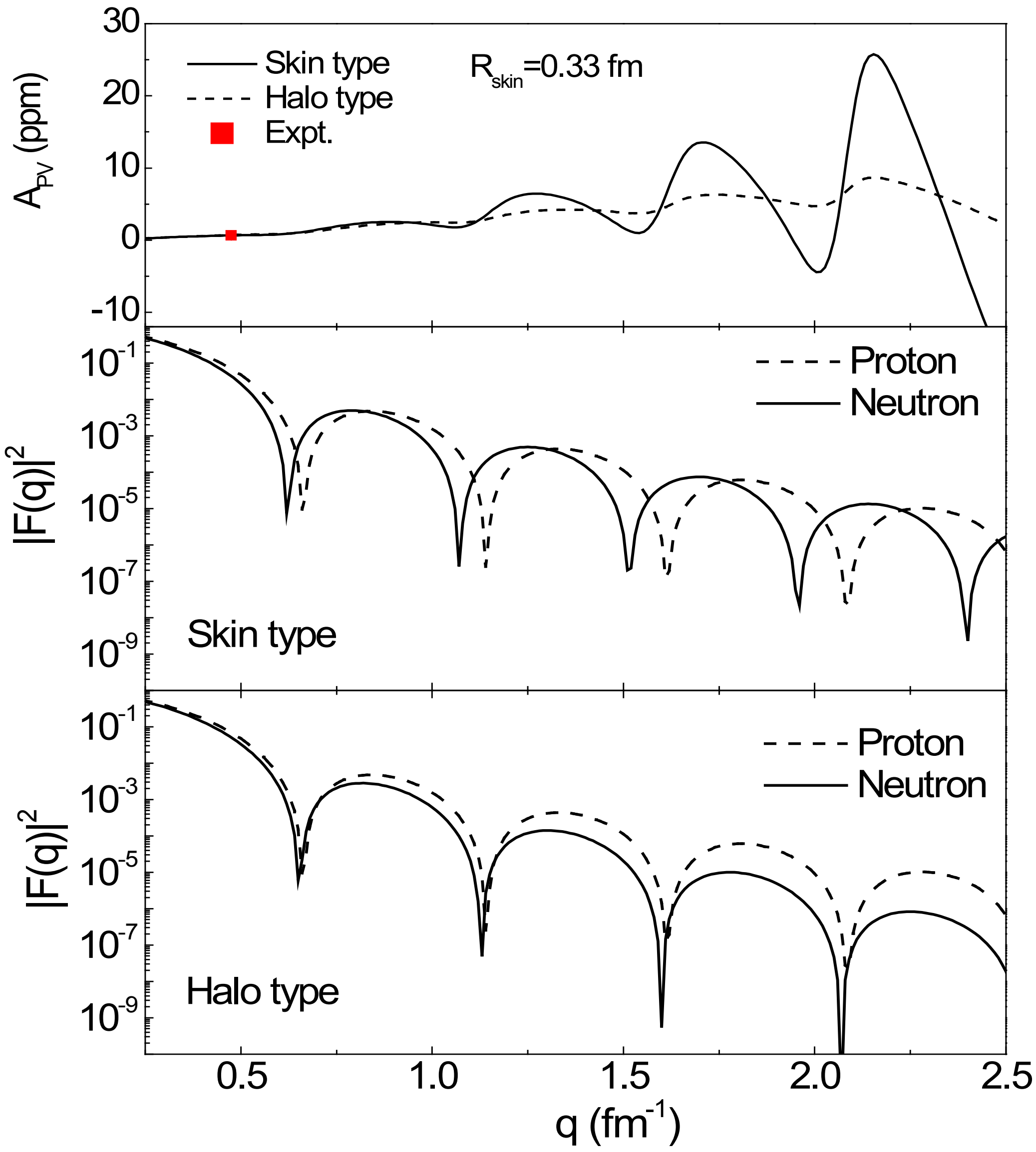
宇称不守恒电子散射理论最早是1989年由 Donnelly, Dubach 以及Sick 提出的。其物理思想是，在低转移动量区域Z^0玻色子主要和中子相耦合。因此可以通过实验测量到的宇称不守恒度来得到原子核内中子密度分布的性质。宇称不守恒度A_{pv}被定义为正宇称的电子与负宇称电子散射截面之差。

在 Jefferson 实验室， 最新的实验PREX-II and CREX 正在进行之中。

我们可以从这些宇称不守恒散射实验中得到什么中子分布的信息？



Assuming the neutron skin thickness are 0.33 fm and 0.15 fm respectively, the theoretical Apv for halo type and skin type of neutron distributions are calculated.



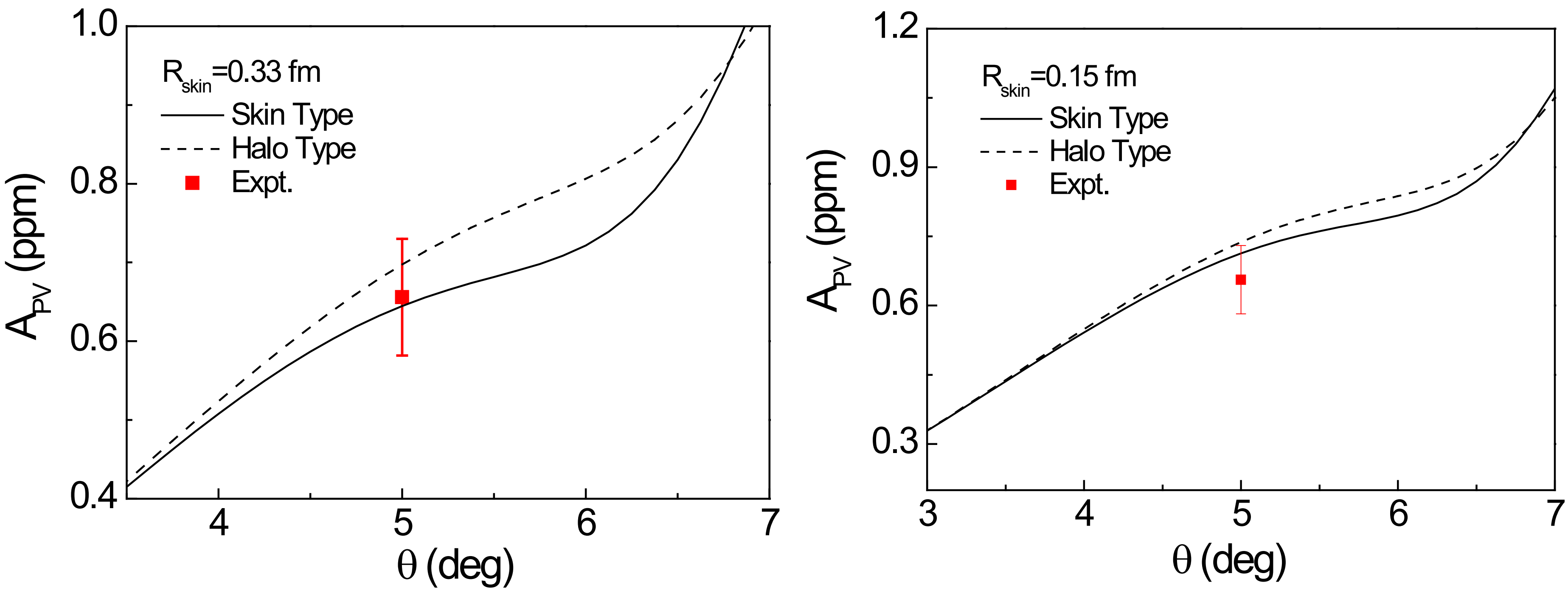
Upper panel: Apv of ^{208}Pb for skin-type and halo-type of neutron distributions.

Middle panel: the proton and neutron form factors for skin-type neutron distributions.

Lower panel: the proton and neutron form factors for halo-type neutron distributions.

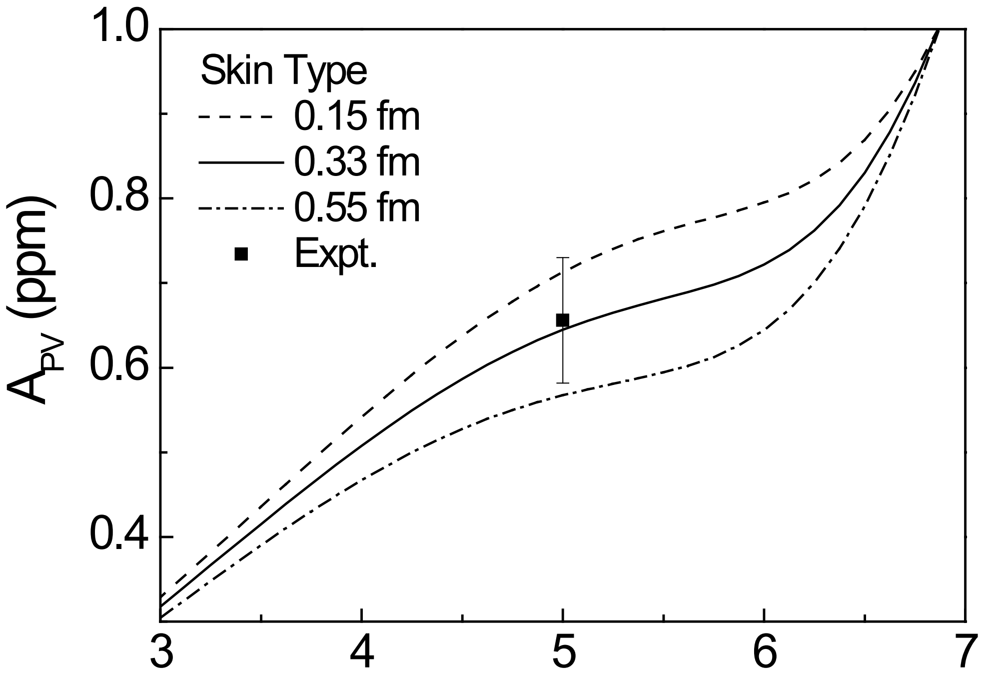
平面波波恩近似公式

$$A_{\text{pv}}(q)=\frac{G_F q^2}{4\pi\sqrt{2}\alpha}\left[\frac{F_n(q)}{F_p(q)}+4\sin^2\theta_W-1\right]$$



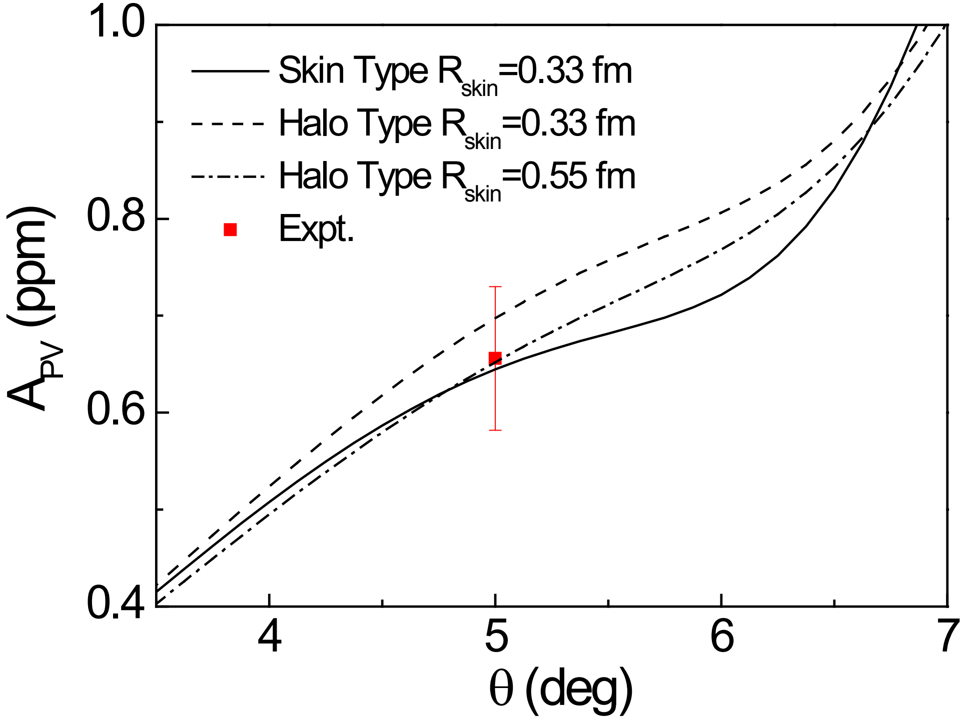
The theoretical Apv for halo type and skin type of 2pF neutron distributions

和之前的测量反质子原子以及Pi介子光致作用的实验结果不同，Jlab宇称不守恒散射的实验给出^{208}Pb中子密度分布更倾向于皮型的分布。



不同原子核中子密度分布给出的理论Apv值以及和PREx实验Apv值的对比。

If ^{208}Pb has a halo-type neutron density distributions, its neutron skin thickness needs to be as large as **0.55 fm** to meet the experiment results.



III. 基于Helm模型分析JLab宇称不守恒电子散射实验的结果

Helm model 密度分布的定义：

$$\rho^H(r) = \int d\vec{r}' f_G(\vec{r}-\vec{r}')\rho_0\Theta(R_0 - r)$$

where: $f_G(r) = \left(2\pi\sigma^2\right)^{-3/2} e^{-r^2/2\sigma^2}$

Helm模型有非常好的解析性质

它的形状因子可以解析的求出：

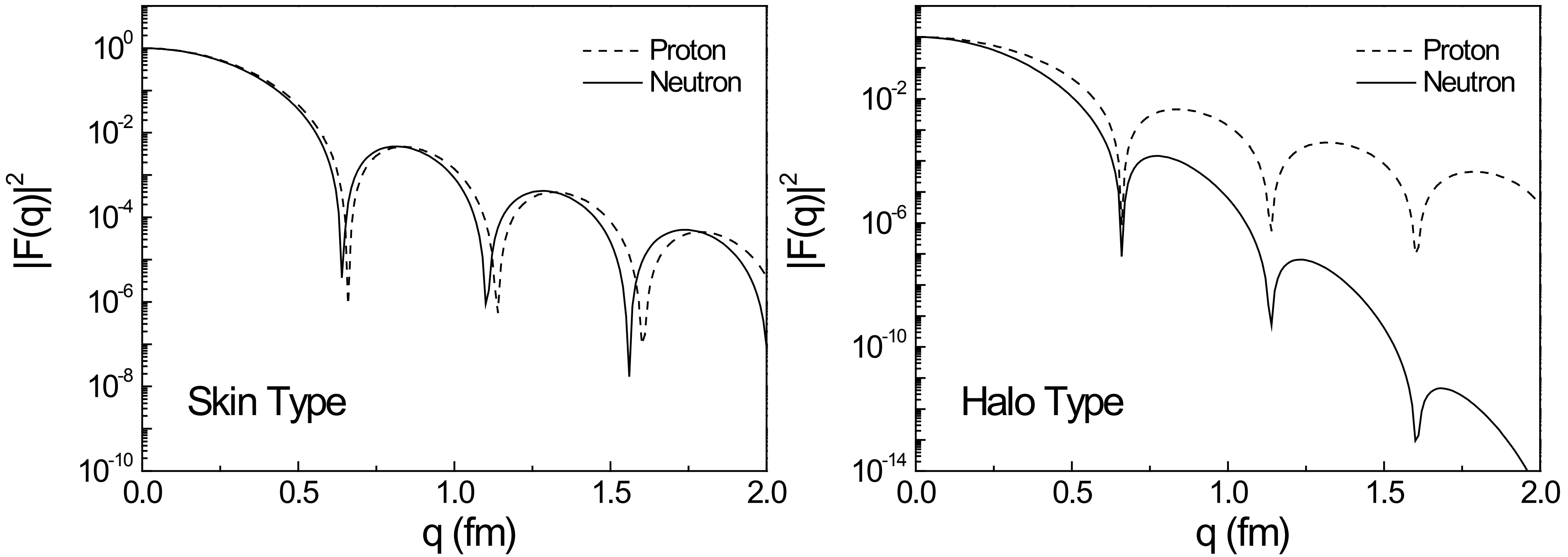
$$F^H(q) = \int e^{i\vec{q}\cdot\vec{r}} \rho^H(\vec{r}) d\vec{r} = \frac{3}{qR_0} j_1(qR_0)\, e^{-\sigma^2 q^2/2}$$

方均根半径以及四极半径也可以解析求得：

$$\left\langle r^2 \right\rangle = \frac{3}{5}\left(R_0^2 + 5\sigma^2\right) \qquad \left\langle r^4 \right\rangle = \frac{3}{7}\left(R_0^4 + 14R_0^2\sigma^2 + 35\sigma^4\right)$$

Neutron **halo-type** distributions: $R_{0n} = R_{0p}, \sigma_n > \sigma_p$

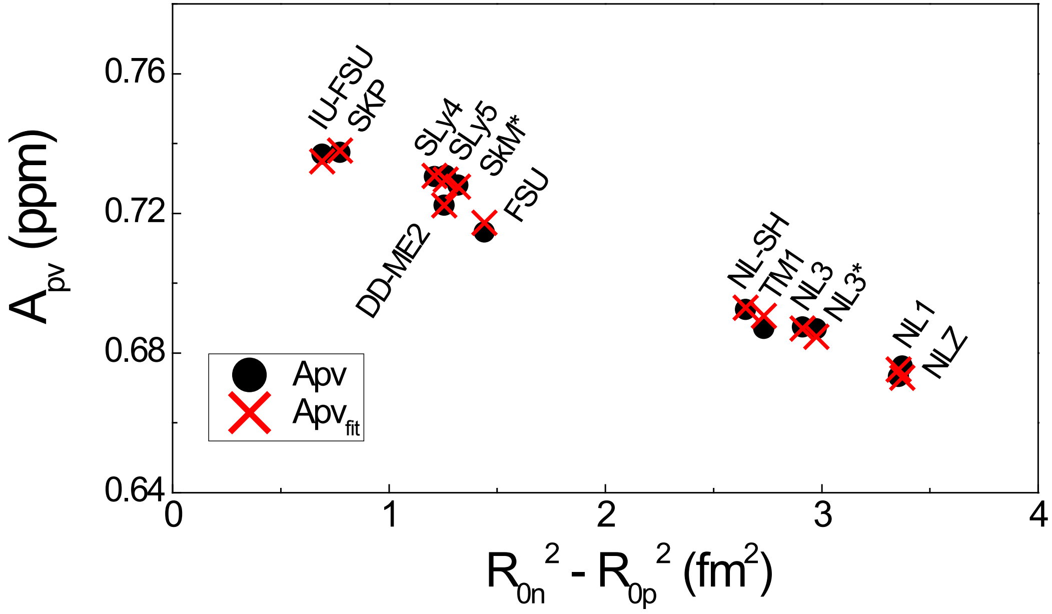
Neutron **skin-type** distributions: $R_{0n} > R_{0p}, \sigma_n = \sigma_p$



采用Helm模型描述^{208}Pb 的质子和中子密度分布，其分别为皮型和晕型分布时的形状因子差别

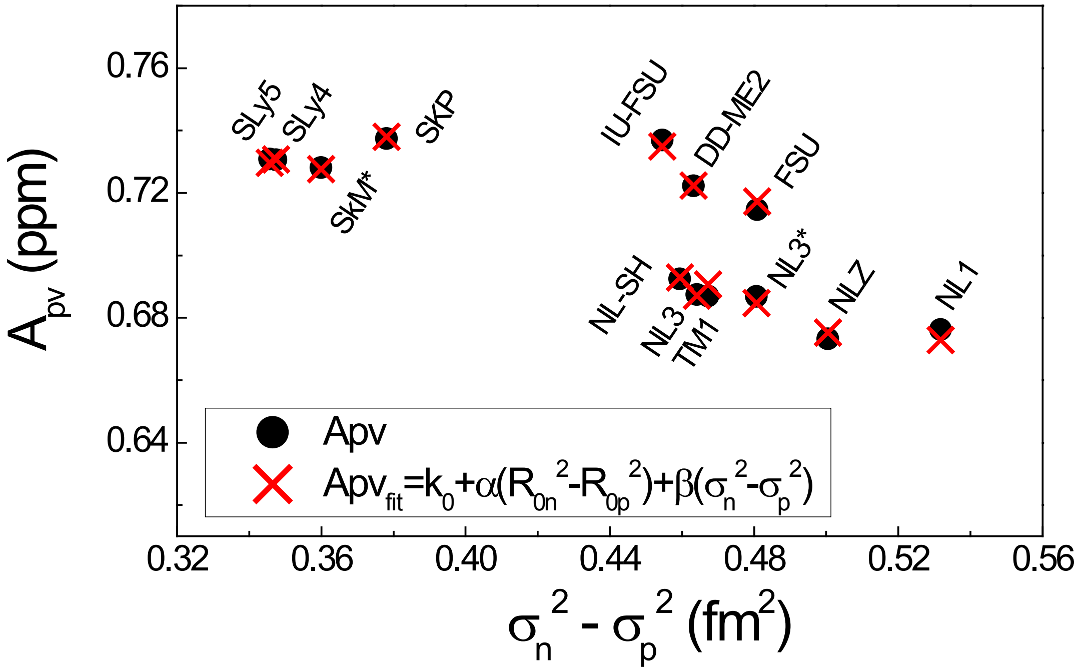
$$F^{H}(q)=\int e^{i\vec{q}\cdot\vec{r}}\rho^{H}(\vec{r})d\vec{r}=\frac{3}{qR_0}j_1(qR_0)\,e^{-\sigma^2q^2/2}$$

Half density radius R_0 determines the locations of the minima of the form factors and the diffuseness parameter σ describes the attenuation of the form factor.



在我们上一篇论文中(J. Liu, Z. Ren, and C. Xu, PRC **88**, 054321, 2013), 我们理论上给出了Helm模型密度分布的参数和理论计算的宇称不守恒度满足下面关系：

$$A_{\text{pv}} = k_0 + \alpha(R_{0n}^2 - R_{0p}^2) + \beta(\sigma_n^2 - \sigma_p^2)$$



通过拟合不同的Helm模型密度分布，我们得到：

$$A_{\text{pv}} = 0.779 - 0.0213\,(R_{0n}^2 - R_{0p}^2) - 0.0639\,(\sigma_n^2 - \sigma_p^2)$$

where the corresponding Adj. R-square is 0.992.

根据弹性电子散射实验，我们可以提取出 ^{208}Pb Helm模型质子密度分布的参数为：

$$R_{0p} = 6.797 \text{ fm}, \ \sigma_p = 0.813 \text{ fm}$$ **Expt.**

通过Jlab宇称不守恒散射实验的结果，我们可以得到 ^{208}Pb 中子皮的厚度为：

$$R_{\text{skin}} = 0.33 \ \text{ fm}$$

假设中子密度分布为皮型的分布，根据半径公式：

$$\langle r^2 \rangle = \frac{3}{5}\left(R_0^2 + 5\sigma^2\right)$$

我们可以得到： $R_{0n} = 7.237 \text{ fm}, \ \sigma_n = 0.813 \text{ fm}$ **Skin type**

带入之前的公式中

$$A_{\text{pv}} = 0.779 - 0.0213\,(R_{0n}^2 - R_{0p}^2) - 0.0639\,(\sigma_n^2 - \sigma_p^2)$$

我们可以提取出 $A_{\text{pv}}(\text{skin}) = 0.647 \text{ ppm}$ 对于皮型中子密度分布。

假设中子密度分布为晕型的分布，根据半径公式我们可以得到：

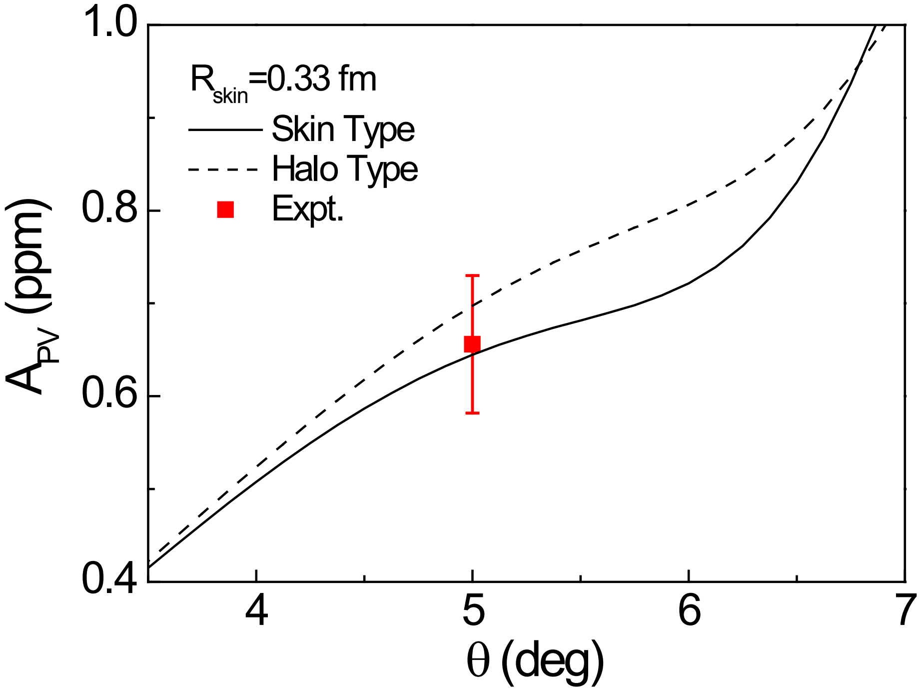
$R_{0n} = 6.797 \text{ fm}, \ \sigma_n = 1.377 \text{ fm}$ **Halo type**

$A_{\text{pv}}(\text{halo}) = 0.700 \text{ ppm}$

Helm模型的理论结果：

$$A_{\mathrm{pv}}(\mathrm{skin}) = 0.647\ \mathrm{ppm}$$

$$A_{\mathrm{pv}}(\mathrm{halo}) = 0.700\ \mathrm{ppm}$$



Theoretical Apv for halo type and skin type of 2pF neutron distributions

For small angles (for example 5 deg):

$$A_{\mathrm{pv}}(\mathrm{halo}) - A_{\mathrm{pv}}(\mathrm{skin}) = 0.0213(R^2_{0n(\mathrm{skin})} - R^2_{0p}) - 0.0639\,(\sigma^2_{n(\mathrm{halo})} - \sigma^2_p)$$

$$= 0.0213 \cdot \left(\frac{5}{3}\Delta\right) - 0.0639 \cdot \left(\frac{1}{3}\Delta\right) \approx 0.05\ \mathrm{ppm} > 0$$

$$\Delta = \left(R_{\mathrm{skin}} + R_p\right)^2 - R_p^2 = 3.706\ \mathrm{fm}^2$$

IV. 结论

1. 宇称不守恒散射的振幅和相应的质子中子密度分布形状因子极小值的位置有关。在中子皮厚度一样的基础上，对于皮型中子密度分布，其宇称不守恒散射的振幅要大于晕型分布的振幅。

2. 不同于之前实验的结果，Jlab 宇称不守恒散射实验表明 ^{208}Pb 原子核中子密度分布为皮型。

3. 通过Helm模型的分析，我们可以得到，半密度参数 R_0 只决定了形状因子极小值的位置，而弥散系数 σ 决定了形状因子的衰减。

4. 借助于Helm模型，在小角度时，皮型中子密度分布的宇称不守恒度小于晕型中子密度分布的宇称不守恒度。理论上我们也可以说明，如果宇称不守恒散射振幅很大时，原子核中子密度分布为皮型。

Thanks for your attention