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Reading Phys. Lett. B 809, 135748 (2020)

Probing the Z = 6 spin-orbit shell gap with (p,2p) quasi-free scattering reactions

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Three questions

Basic picture of QFS ?

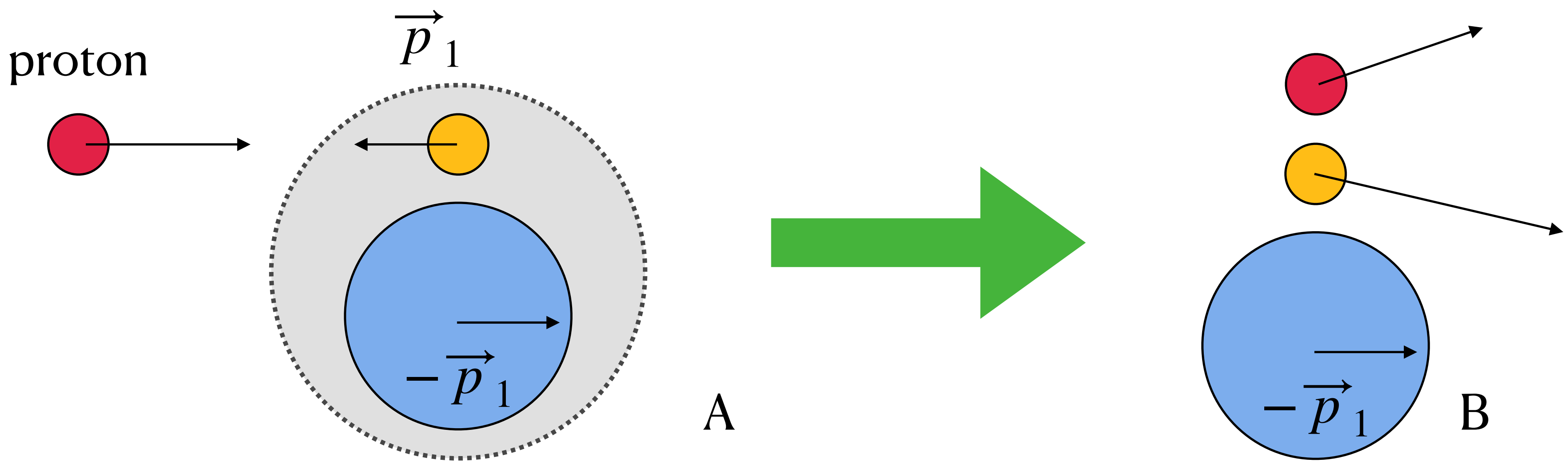
Theoretical framework of QFS ?

How can the experiment reveal
the reduction of the shell gap?

Quasi-free scattering

Used to describe (p, pn) reactions

$$p + A(n + B) \rightarrow p + n + B$$



The projectile only interacts only with the removed nucleon, leaving the state of B unchanged.

Calculation

T matrix: $T_{p,pN} = \sqrt{S(lj)} \left\langle \chi^{(-)}_{\mathbf{k}'_p} \chi^{(-)}_{\mathbf{k}_N} \middle| \tau_{pN} \middle| \chi^{(+)}_{\mathbf{k}_p} \psi_{jlm} \right\rangle$

Fourier transform of the interaction

$$T_{p,pN} = \sqrt{S(lj)} \int d^3\mathbf{r}'_{pB} d^3\mathbf{r}'_{NB} d^3\mathbf{r}_{pA} d^3\mathbf{r}_{NB} \times \tau\left(\mathbf{r}'_{pB}, \mathbf{r}'_{NB}; \mathbf{r}_{pA}, \mathbf{r}_{NB}\right) \times \chi^{(-)*}_{\mathbf{k}'_p}\left(\mathbf{r}'_{pB}\right) \chi^{(-)*}_{\mathbf{k}_N}\left(\mathbf{r}'_{NB}\right) \times \chi^{(+)}_{\mathbf{k}_p}\left(\mathbf{r}_{pA}\right) \psi_{jlm}\left(\mathbf{r}_{NB}\right)$$

$\mathbf{r}_{pA} = \mathbf{r}_{pN} + \mathbf{r}_{NB}$

"the range of the pN interaction is much smaller than the nuclear size"

$$T_{p,pN} = \sqrt{S(lj)}\, \tau\left(\mathbf{k}'_{pN}, \mathbf{k}_{pN}; E\right) \int d^3\mathbf{r}_{NB} \times \chi^{(-)*}_{\mathbf{k}'_p}\left(\mathbf{r}_{NB}\right) \chi^{(-)*}_{\mathbf{k}_N}\left(\mathbf{r}_{NB}\right) \times \chi^{(+)}_{\mathbf{k}_p}\left(\alpha \mathbf{r}_{NB}\right) \psi_{jlm}\left(\mathbf{r}_{NB}\right)$$

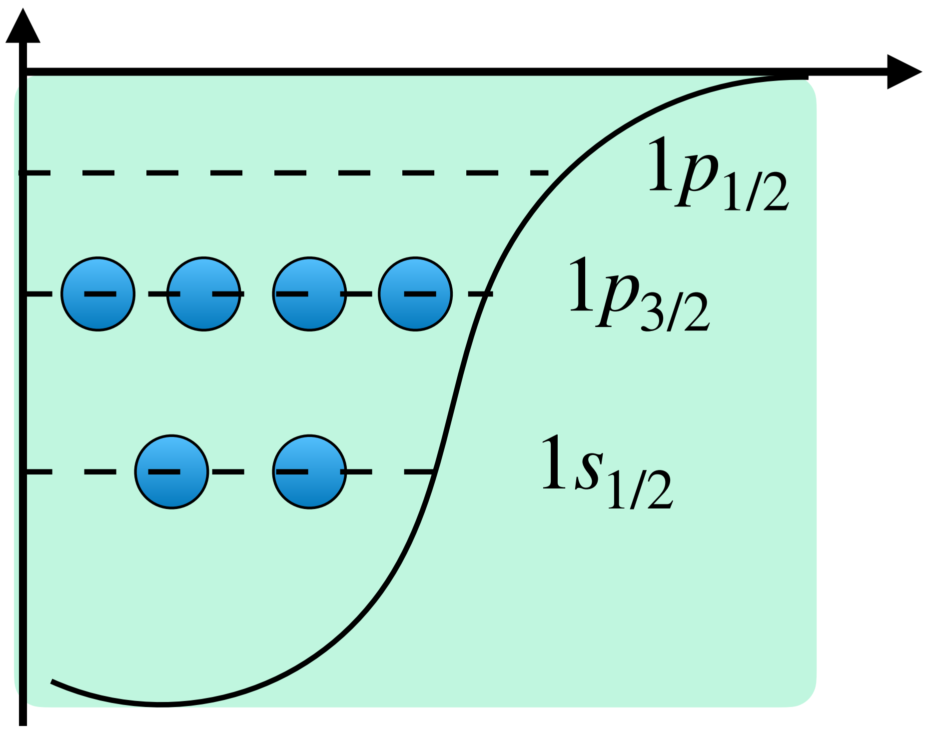
Zero-range approximation ?

Eikonal approximation:

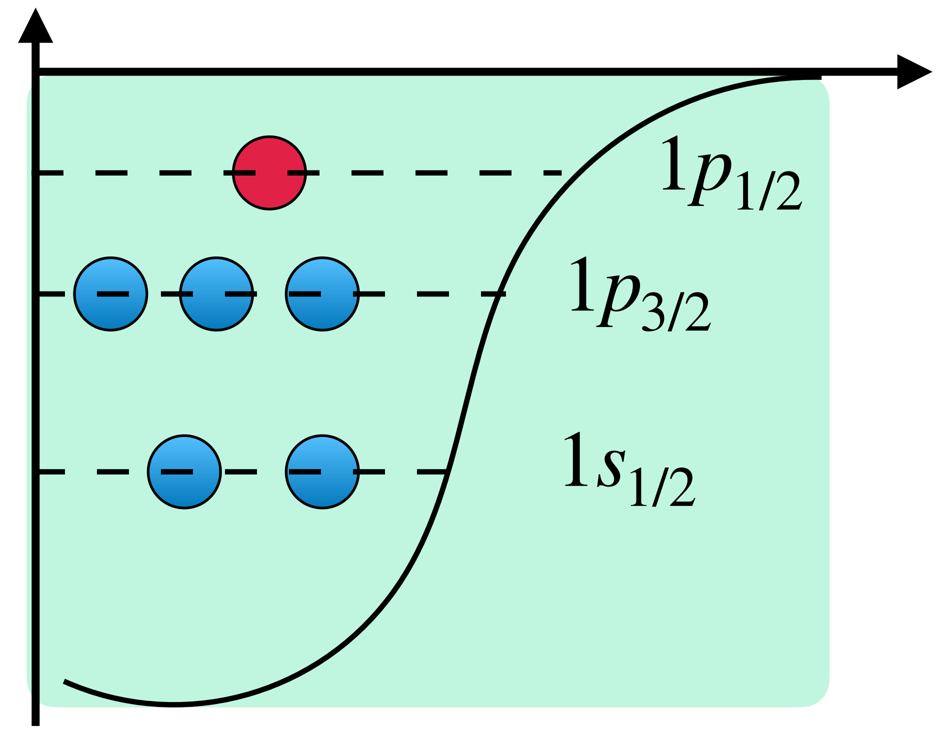
$$\chi_i(\mathbf{r})^{\mathrm{in(out)}} = \exp\left[i \mathbf{k}_{\mathbf{i}}^{\mathrm{in(out)}} \cdot \mathbf{r}\right] \times \exp\left[-\frac{i}{\hbar v} \int_{a_{in(out)}}^{b_{in(out)}} dz' U_i^{\mathrm{in(out)}}(\mathbf{r}')\right]$$

[1]T. Aumann, C.A. Bertulani, J. Ryckebusch, Phys. Rev. C 88 (2013) 064610

A simple shell model picture



Ground state of O



Proton excitation of O

0^+_1State of O: $|0^+_1, {}^{A-1}\mathrm{C}\rangle \approx |\nu(sd)^n; J=0\rangle \otimes |\pi(1p_{3/2})^4; J=0\rangle$

2^+_1State of O: $|2^+_1, {}^{A-1}\mathrm{C}\rangle \approx \alpha|\nu(sd)^n; J=2\rangle \otimes |\pi(1p_{3/2})^4; J=0\rangle$

$$+\beta|\nu(sd)^n; J=0\rangle \otimes |\pi(1p_{3/2})^3(1p_{1/2})^1; J=2\rangle$$

Ground state of ${}^A N$:

$$|1/2^-, {}^{A}\mathrm{N}\rangle \approx |\nu(sd)^n; J=0\rangle \otimes |\pi(1p_{3/2})^4(1p_{1/2})^1; J=1/2\rangle$$

Some results

	State	Orbital	σ_{exp}[mb]	σ_{theo}[mb]	$C^2 S_{exp}$
^{17}N(p,2p)^{16}C	inclusive		3.82(19)		
	0^+	$1p_{1/2}$	2.83(20)	6.171	0.46(3)
	2^+	$1p_{3/2}$	0.68(9)	5.929	0.11(2)
^{19}N(p,2p)^{18}C	inclusive		3.66(14)		
	0^+	$1p_{1/2}$	2.53(15)	5.267	0.48(3)
	2^+	$1p_{3/2}$	0.45(7)	5.193	0.09(1)
^{21}N(p,2p)^{20}C	inclusive		2.65(34)		
	0^+	$1p_{1/2}$	1.87(38)	4.554	0.41(8)
	2^+	$1p_{3/2}$	0.78(17)	4.458	0.17(4)

inclusive cross section and
exclusive cross section for a particular single-particle state

How experiment separates cross section induced by different s.p. state?

Data reduction

Reduction of β^2 [2]:

$$\frac{\sigma_{exp}(2_1^+)}{\sigma_{exp}(0_1^+)} \times \frac{\sigma_{theo}(p_{1/2})}{\sigma_{theo}(p_{3/2})} = \frac{C^2S(2_1^+)}{C^2S(0_1^+)} = \beta^2 \times \frac{5}{2}$$

	State	Orbital	σ_{exp}[mb]	σ_{theo}[mb]	C^2S_{exp}	β^2 [%]
^{17}N(p,2p)^{16}C	inclusive		3.82(19)			
	0^+	$1p_{1/2}$	2.83(20)	6.171	0.46(3)	
	2^+	$1p_{3/2}$	0.68(9)	5.929	0.11(2)	10.0(15)
^{19}N(p,2p)^{18}C	inclusive		3.66(14)			
	0^+	$1p_{1/2}$	2.53(15)	5.267	0.48(3)	
	2^+	$1p_{3/2}$	0.45(7)	5.193	0.09(1)	7.2(12)
^{21}N(p,2p)^{20}C	inclusive		2.65(34)			
	0^+	$1p_{1/2}$	1.87(38)	4.554	0.41(8)	
	2^+	$1p_{3/2}$	0.78(17)	4.458	0.17(4)	17.0(51)

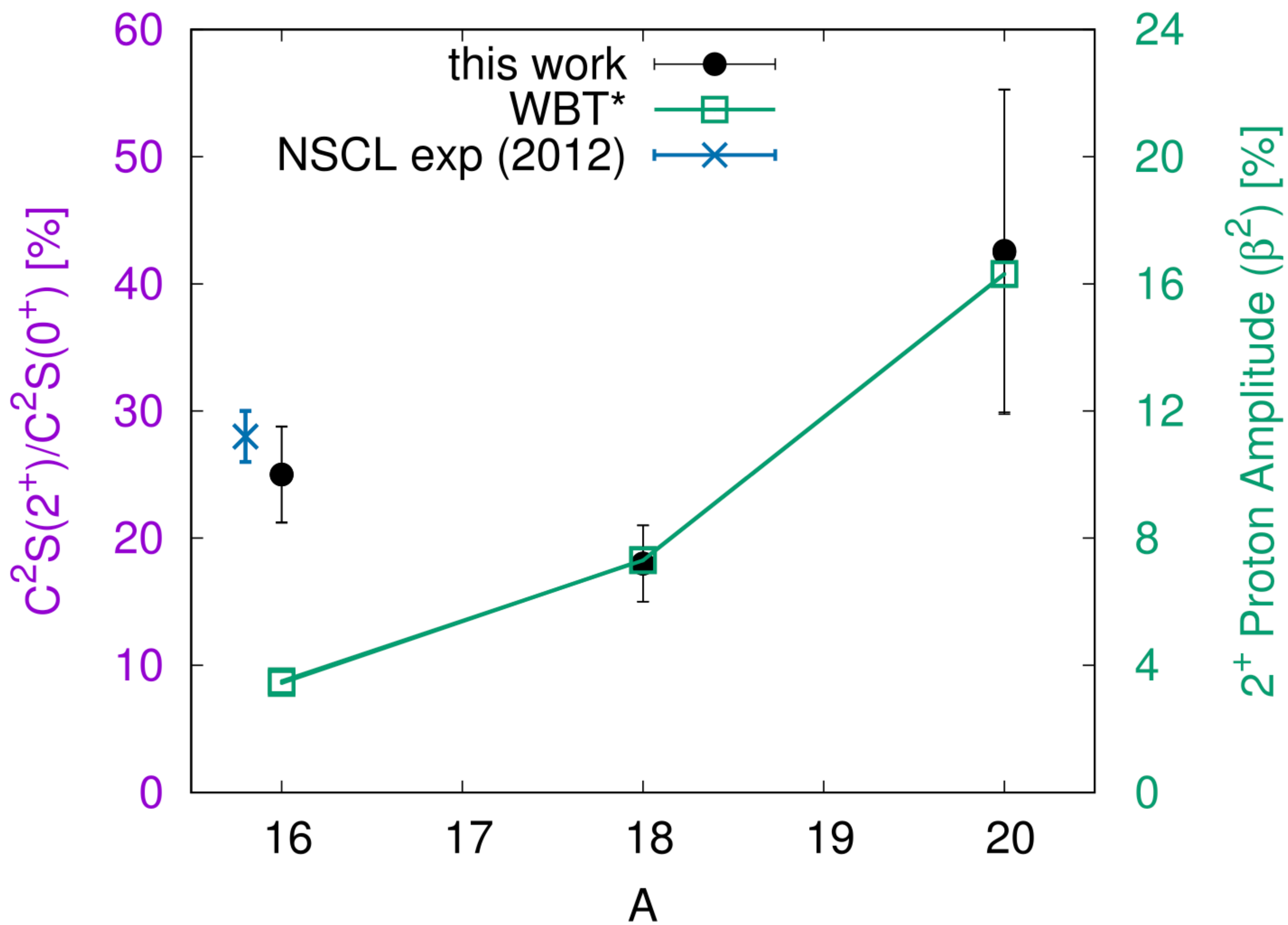
[2] M. Petri, … Structure of ^{16}C: testing shell model and ab initio approaches, Phys. Rev. C 86 (4) (2012) 044329,

Comparison with shell model results

$$\frac{C^2S(2_1^+)}{C^2S(0_1^+)} = \beta^2 \times \frac{5}{2}$$

Scale factor

Ratios from experiment



β^2 from shell models

A decline is observed in the experiment

Some results

In first order perturbation theory, the proton amplitude is given by:

$$\beta \sim \frac{V_{\pi\nu}}{E_{2^+_\pi} - E_{2^+_\nu}} \qquad ?$$

$V_{\pi\nu}$: matrix element mixing the unperturbed 2^+_π and 2^+_ν states

The denominator is dominated by the difference between the proton $1p_{1/2}$ and $1p_{3/2}$ level energies $\Delta E_{so} = e_{1/2} - e_{3/2}$

$$\beta \nearrow \qquad \Delta E_{so} \searrow$$

"The driving mechanism behind the evolution of the $\pi 1p_{1/2}$ and $\pi 1p_{3/2}$ orbits as function of isospin is the combined effect of the tensor (mainly) and two-body spin-orbit forces acting on the $1p$ protons when neutrons are added in the $d_{5/2}$ and $s_{1/2}$ orbits."

Summary

1. Carry out QFS experiment of $N(p,2p)C$, get the inclusive and exclusive cross section.
2. Calculate cross sections for different s.p. state based on eikonal approximation.
3. Set up a shell model picture to describe the structure of N and C.
4. Derive the proton amplitude β from ratios of SFs.
5. An increase of β towards the drip line indicates a moderate quenching of $Z = 6$ $1p$ spin-orbit splitting gap.