Gamma-ray production in neutral-current interactions

Artur Ankowski

University of Wrocław,
INFN & Dept. of Physics, ”Sapienza” Università di Roma

In collaboration with
O. Benhar, T. Mori, R. Yamaguchi, and **M. Sakuda**

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Outline

1. **Introduction**
   - Neutral current vs. charged current
   - How are the NC events detected?
   - Could nuclear deexcitation provide an additional signature?
2. **Case of NC neutrino-oxygen scattering**
   - Nuclear structure and deexcitation scheme
   - Estimate of the cross section
3. **Summary**

Introduction

Neutral current vs. charged current

Structure of the NC and CC is the same,

$$\langle N'(p')|\hat{J}^\mu|N(p)\rangle = \Big\langle N'(p')\Big|\gamma^\mu(F_1+F_2) - \frac{(p+p')^\mu}{2M}F_2 + \gamma^\mu\gamma_5 F_A + \gamma_5\frac{q^\mu}{M}F_P\Big|N(p)\Big\rangle$$

Both *n*'s and *p*'s may undergo NCE scattering

Neutral current elastic scattering

Structure of the NC and CC is the same, but

$$F_i^{z,(p)} = -\frac{1}{2}\left(F_i^{(n)} + F_i^s\right) + \left(\frac{1}{2} - 2\sin^2\theta_W\right) F_i^{(p)},$$

$$F_A^{z,(p)} = \frac{1}{2}\left(F_A + F_A^s\right),$$

$$F_i^{z,(n)} = -\frac{1}{2}\left(F_i^{(p)} + F_i^s\right) + \left(\frac{1}{2} - 2\sin^2\theta_W\right) F_i^{(n)},$$

$$F_A^{z,(n)} = -\frac{1}{2}\left(F_A - F_A^s\right),$$

W.M. Alberico, S.M. Bilenky, C.Maieron,
Phys. Rep. 358, 227 (2002)

Neutral current elastic scattering

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$$F_i^{z,(n)} = -\frac{1}{2}\left(F_i^{(p)} + F_i^s\right) + \left(\frac{1}{2} - 2\sin^2\theta_W\right) F_i^{(n)},$$

$$F_A^{z,(n)} = -\frac{1}{2}\left(F_A - F_A^s\right),$$

F_i^S are vanishing, see e.g.

D. Androić *et al.*, PRL 104, 012001 (2010);

Z. Ahmed *et al.,* arXiv:1107.0913

Neutral current elastic scattering

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$$F_i^{z,(p)} = -\frac{1}{2}F_i^{(n)} + \left(\frac{1}{2} - 2\sin^2\theta_W\right)F_i^{(p)},$$

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$$F_i^{z,(n)} = -\frac{1}{2}F_i^{(p)} + \left(\frac{1}{2} - 2\sin^2\theta_W\right)F_i^{(n)},$$

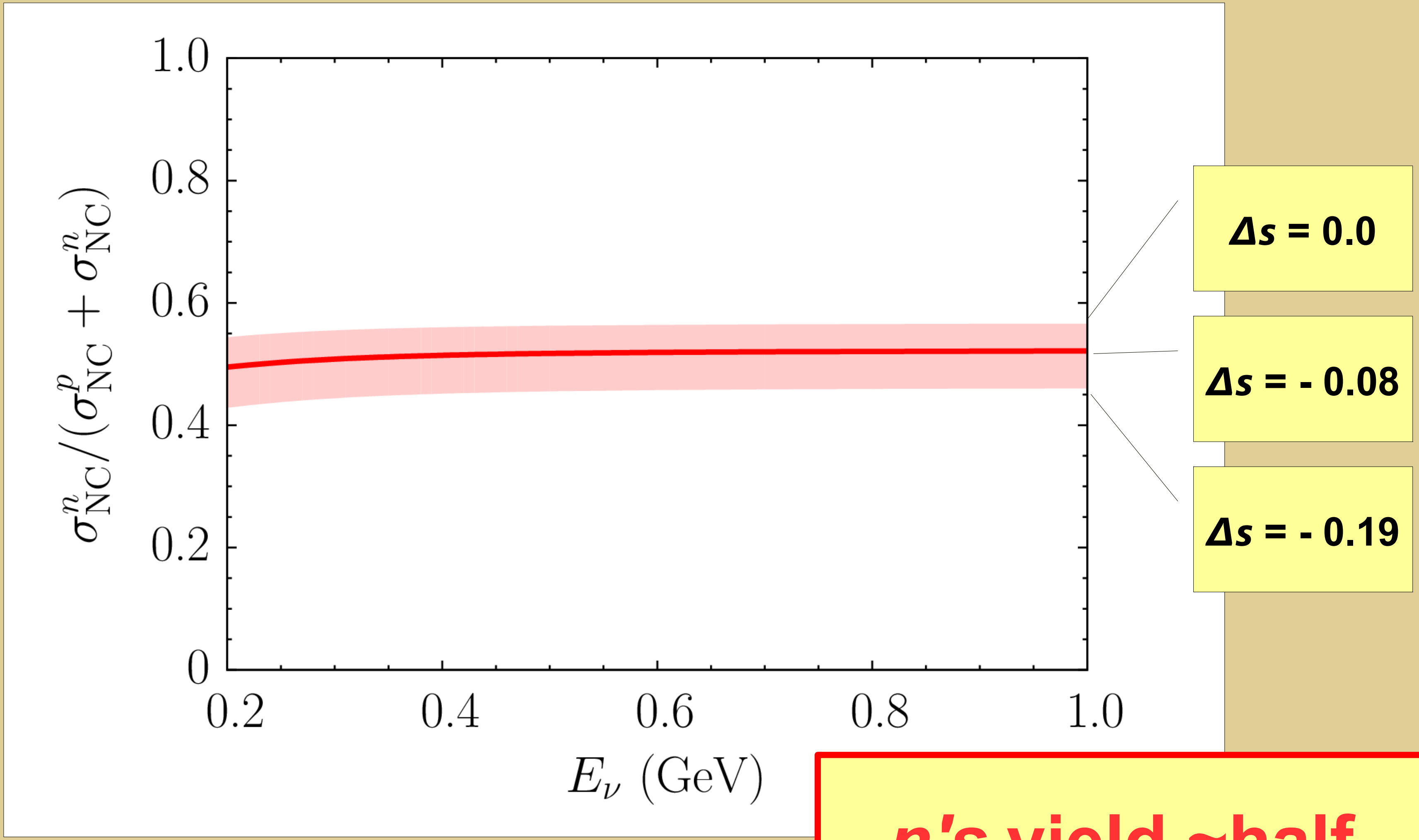
$$F_A^{z,(n)} = -\frac{1}{2}\left(F_A - F_A^s\right),$$

$$F_A^s = \frac{\Delta s}{(1 + \frac{Q^2}{M_A^2})^2}$$

Δs = -0.08±0.26, MiniBooNE

Δs = -0.12±0.09, BNL E734

Neutron contribution to the NC ^{16}O cross section



***n*'s yield ~half of the x-section**

Neutral current elastic scattering

- The total NC x-section of a symmetric nucleus is **largely independent of Δ*s***:

When Δs = 0.0 is used instead of Δs = -0.08, the cross section changes by **less than 0.3%** for 0.2 < E < 5 GeV.

- In the following **Δ*s* = 0.0**.

Detection

- Neutrons (~50% of NC events) do not emit Cherenkov light.

- In water Cherenkov detectors, the threshold momentum for observation of proton is 1.07 GeV/c.

- Hence, an additional signature for NC event might be very useful.

Nuclear deexcitation as a prompt signal of NC event

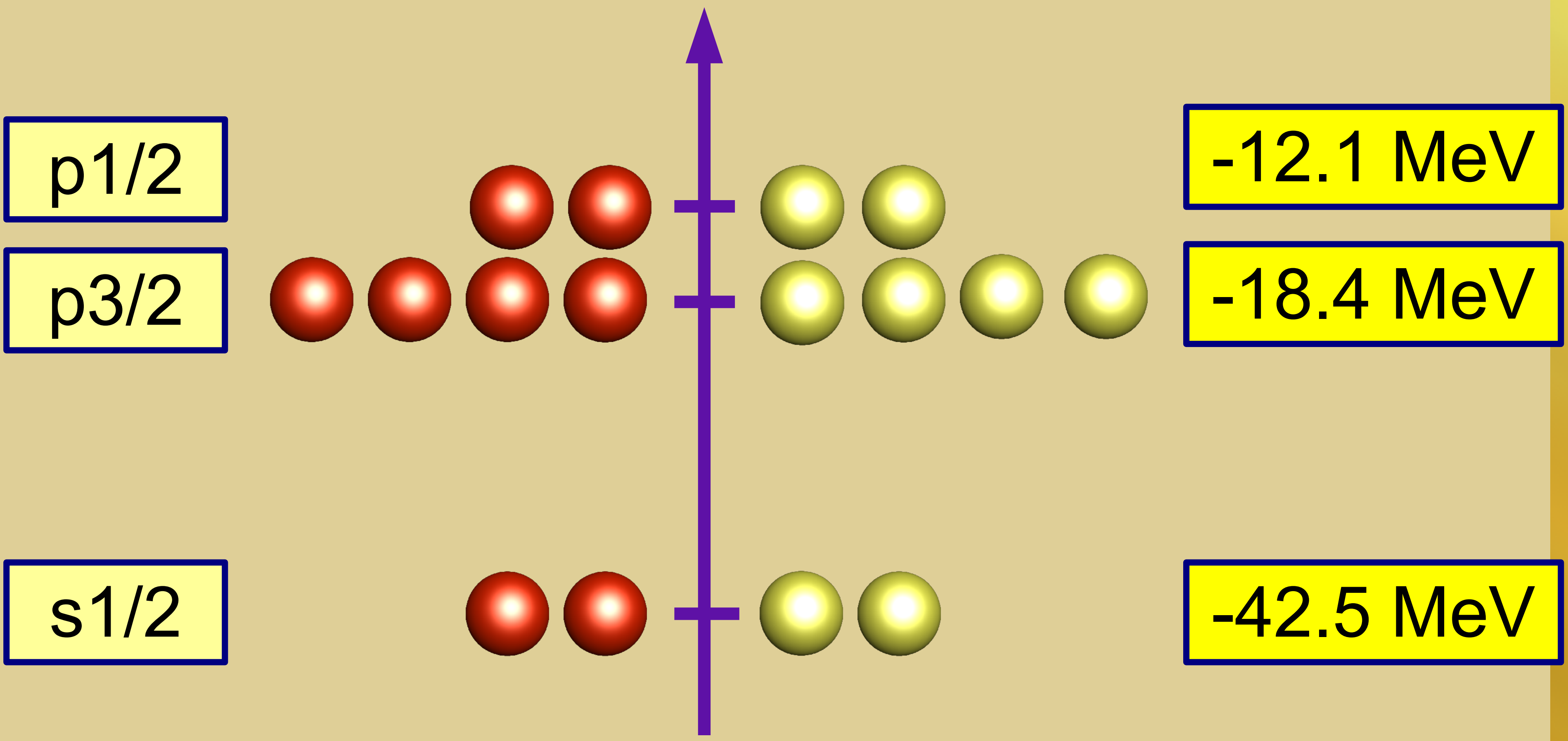
- Nucleon knockout often leaves residual nucleus in an **excited state**.

- **Deexcitation** may yield photons above detection threshold.

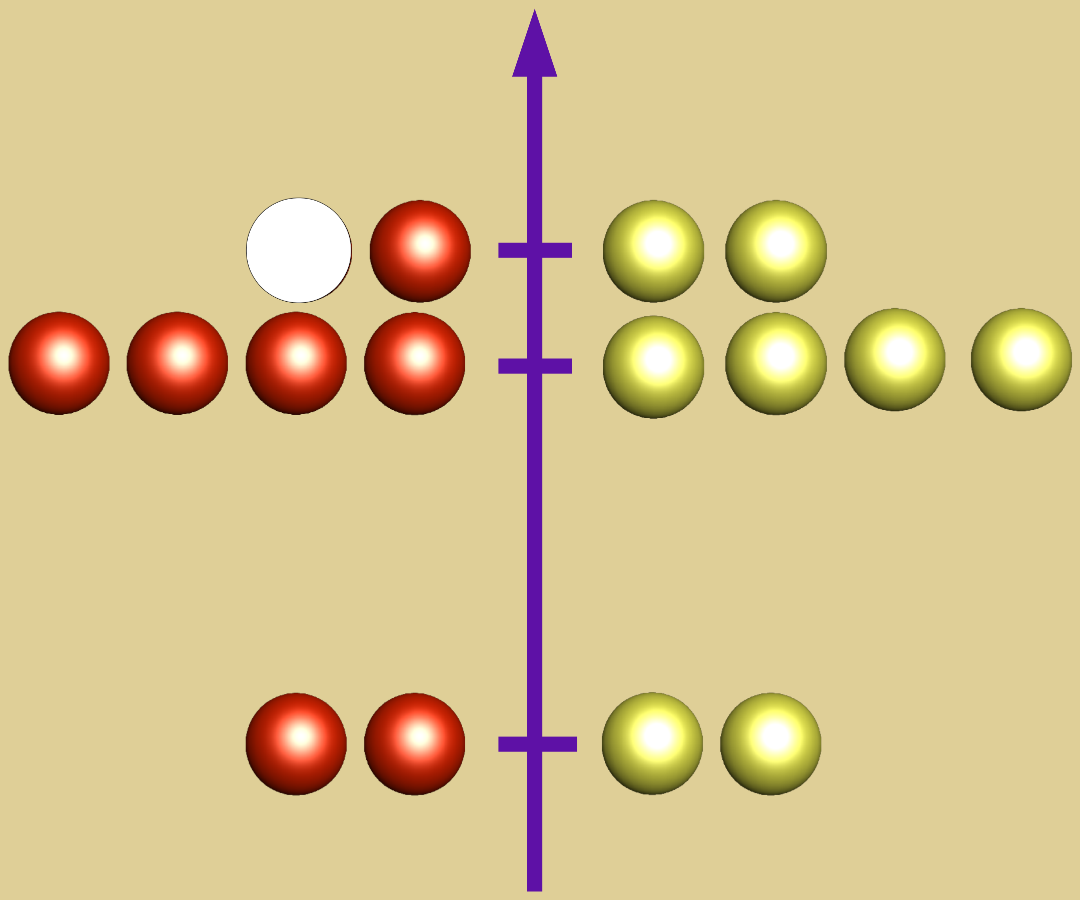
- Such photons could provide **useful signal**, especially for water Cherenkov detectors.

NC neutrino-oxygen scattering

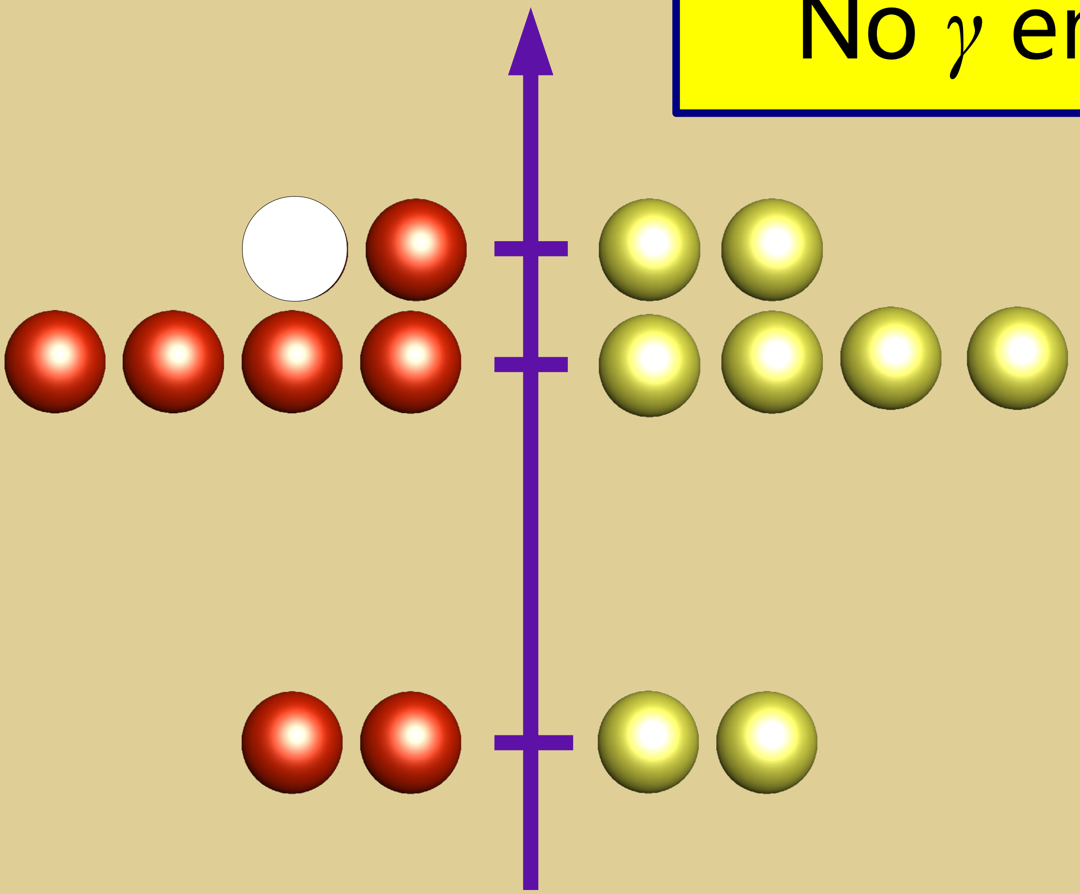
Structure of the oxygen nucleus



p1/2 knockout

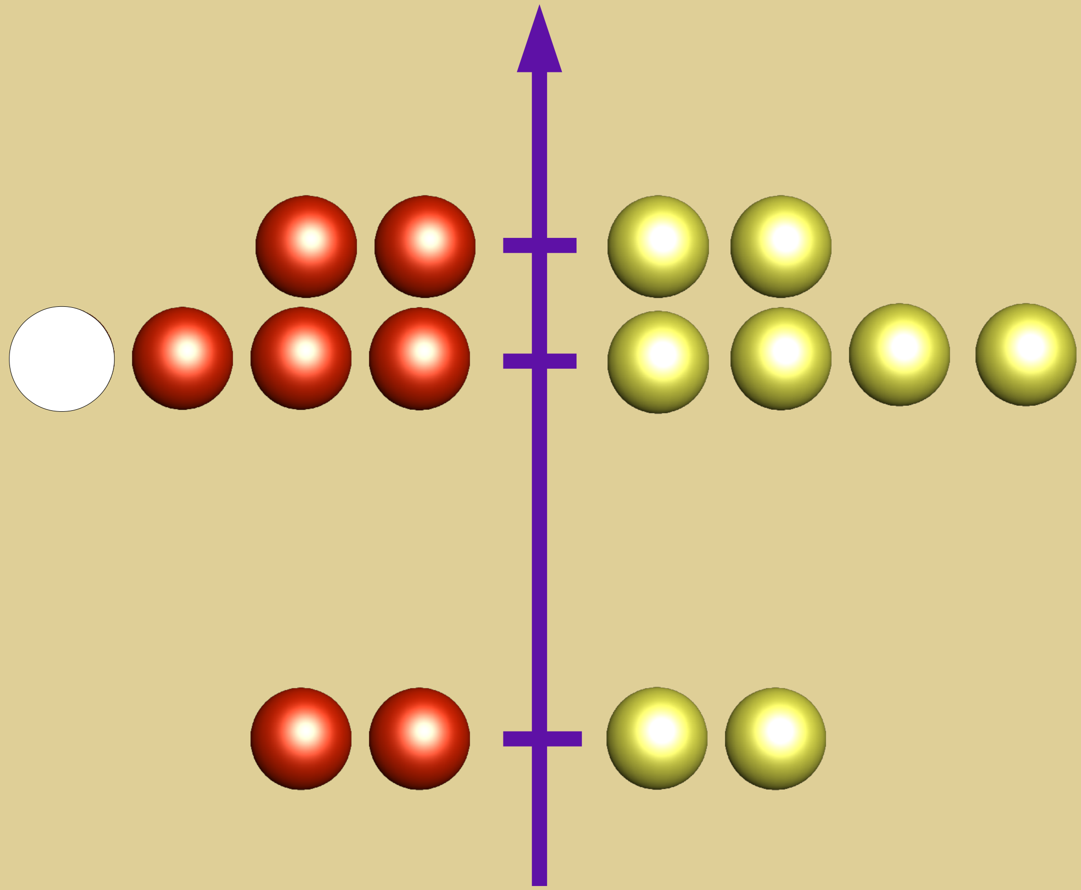


p1/2 knockout



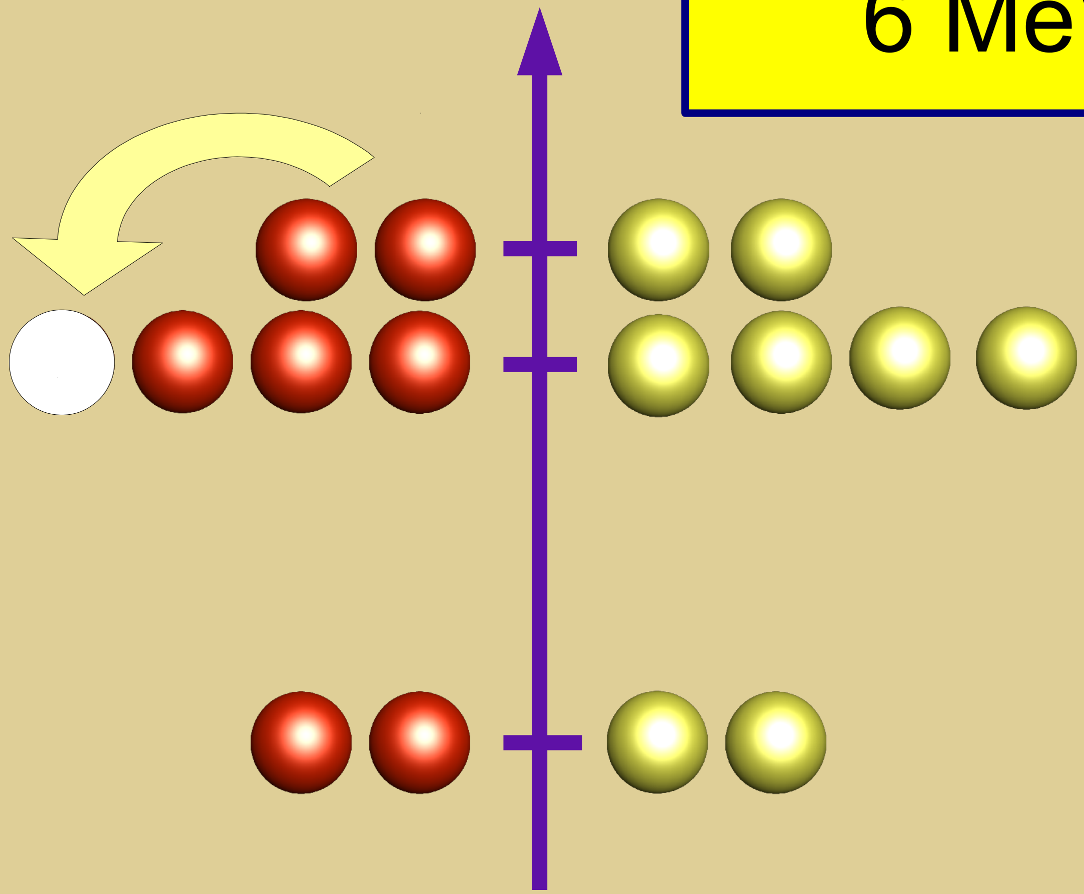
No γ emission

p3/2 knockout

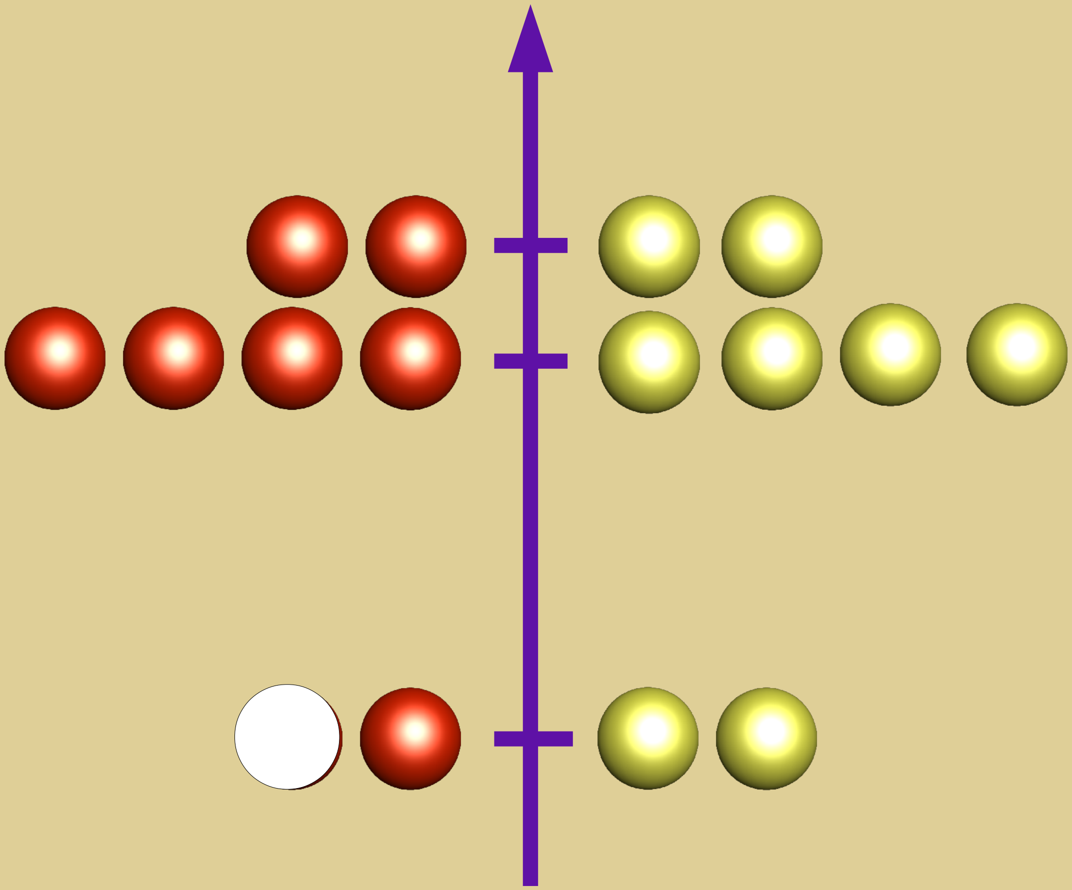


p3/2 knockout

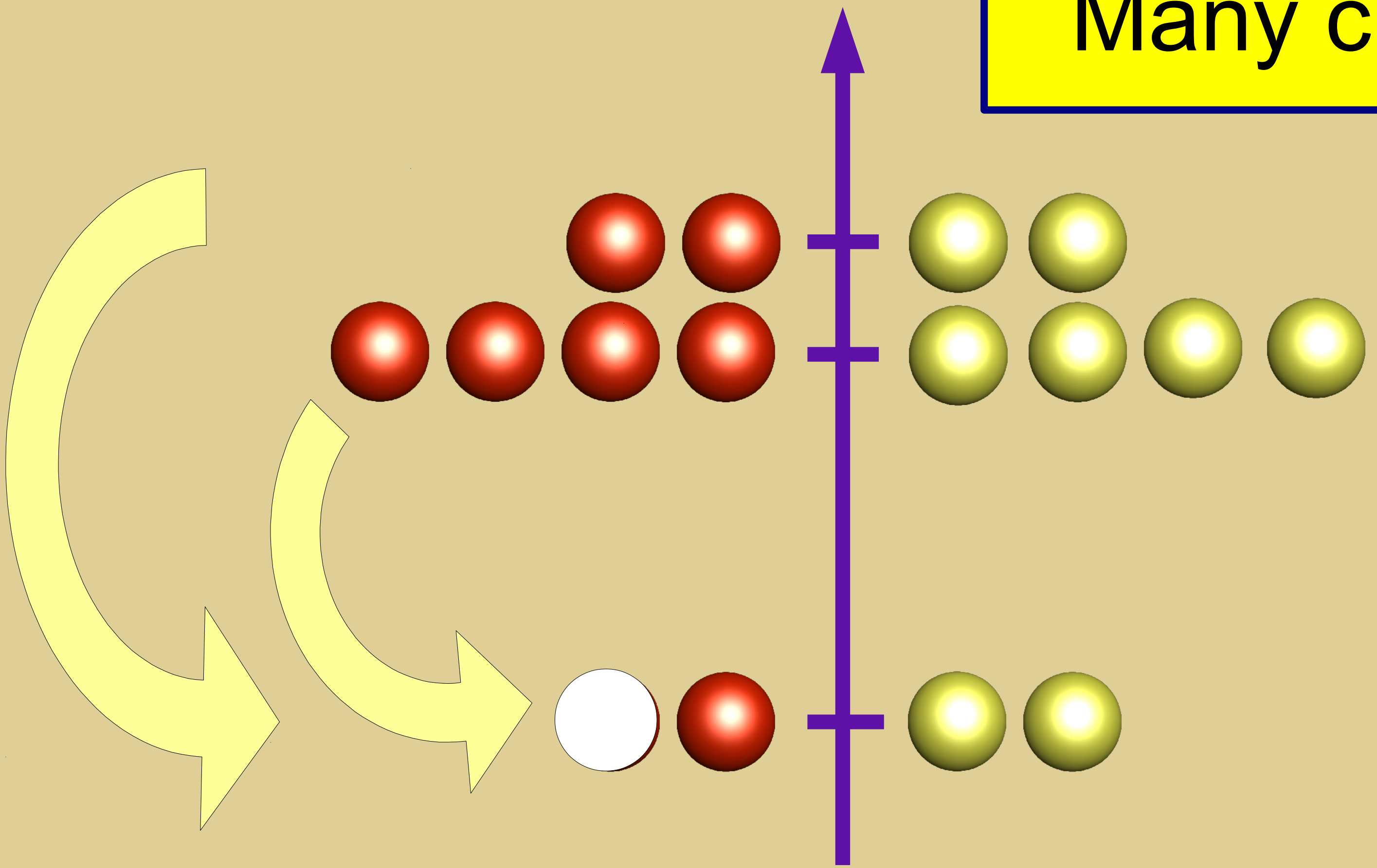
6 MeV as γ



s1/2 knockout



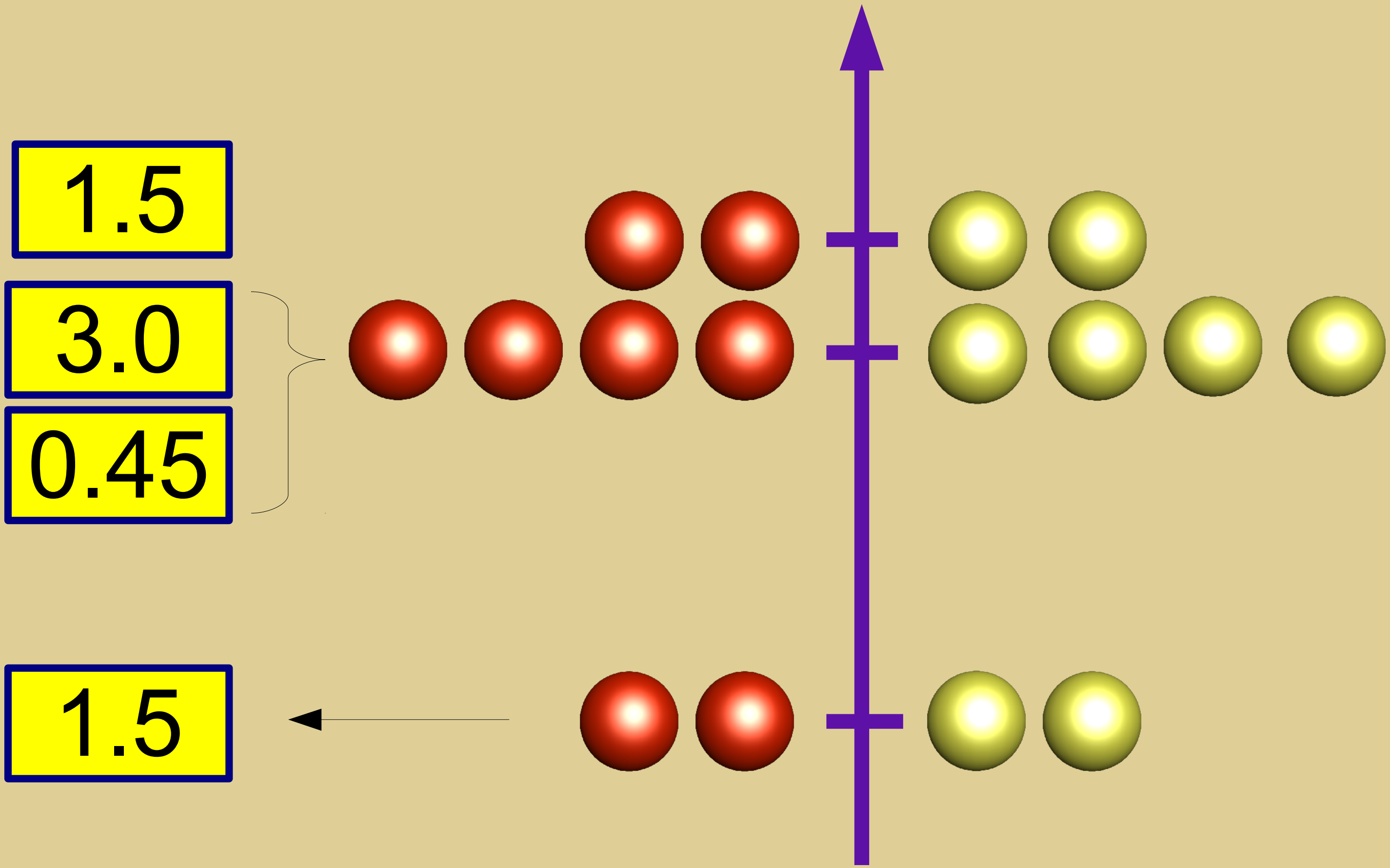
s1/2 knockout



Many channels

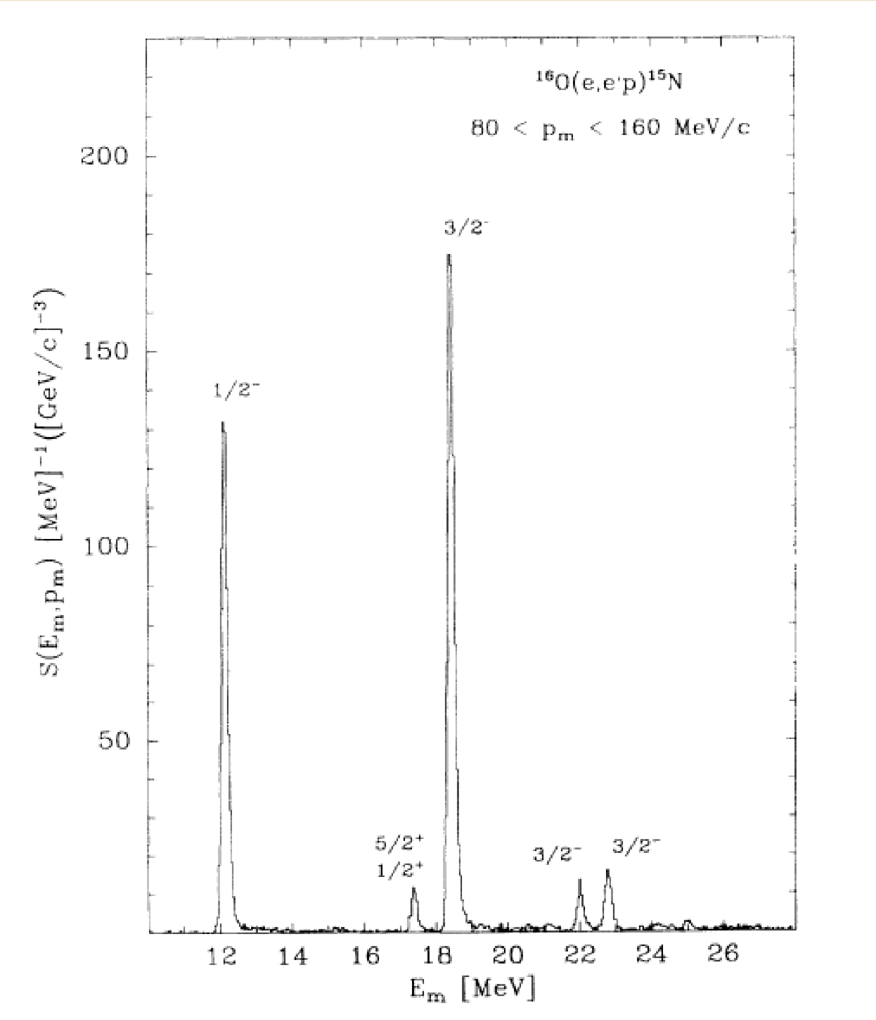
Branching ratio for $E\gamma$ > 4 MeV is ~12%,
Ejiri, PRC 48, 1442 (1993)

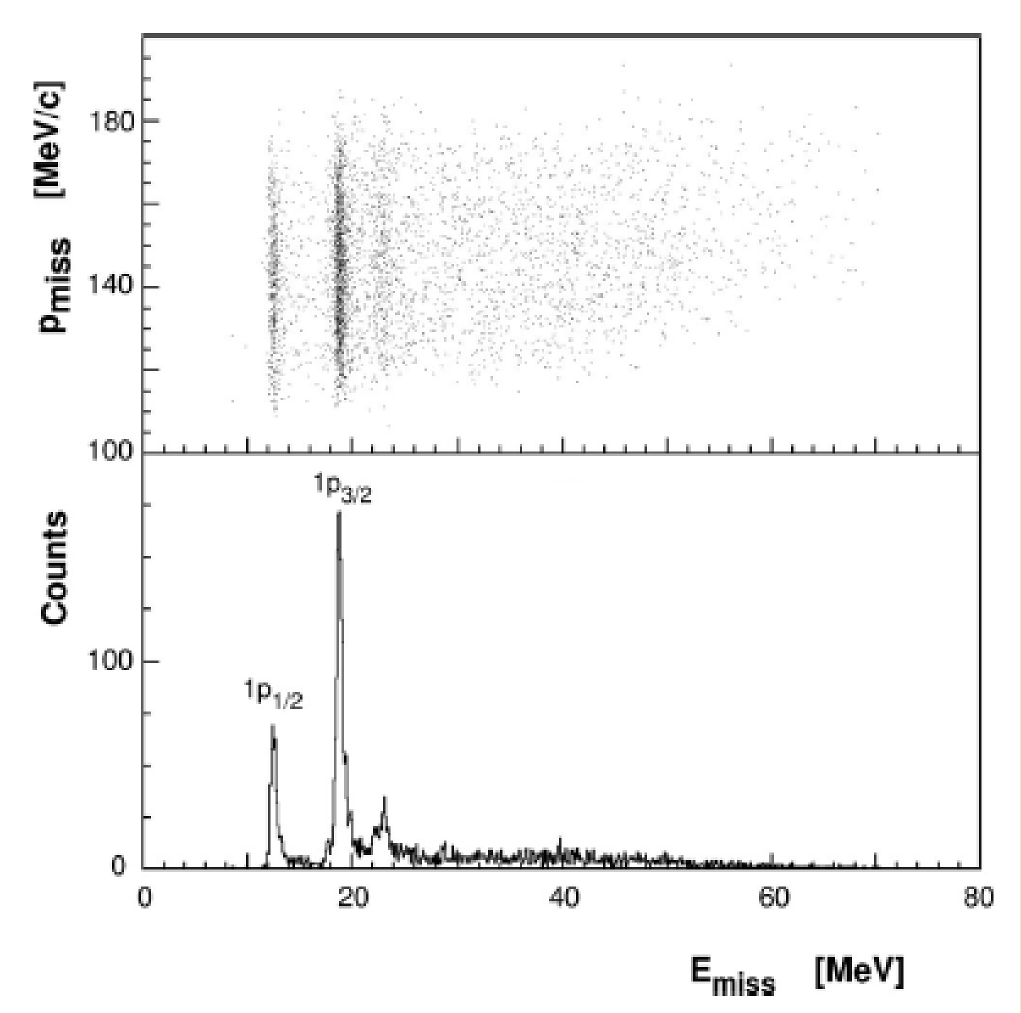
Spectroscopic strengths from the (e,e'p) Saclay data



M. Bernheim *et al.*, NP A375, 381 (1982)

Finite widths





M. Leuschner *et al.*,
PRC 49, 955 (1994)

K.G. Fissum *et al.*,
PRC 70, 034606 (2004)

Cross section for γ emission accompanying NC event

It is a product of

- NC cross section for the knockout from each shell
- branching ratios for deexcitation by γ emission

$$B(p_{\frac{1}{2}}) = 0\%, \quad B(p_{\frac{3}{2}}) = 100\%, \quad B(s_{\frac{1}{2}}) \approx 15\% \text{ for } E_\gamma > 6 \text{ MeV}$$

F. Ajzenberg-Selove, NP A523, 1 (1991);
H. Ejiri, PRC 48, 1442 (1993);
K. Kobayashi et al., arXiv:nucl-ex/0604006

Cross section for γ emission accompanying NC event

- The cross sections for each shell and for the whole nucleus are calculated using the spectral function obtained by Omar Benhar.

- Accuracy of the spectral function, accounting for nucleon-nucleon correlations, has been shown against (e,e'p) data.

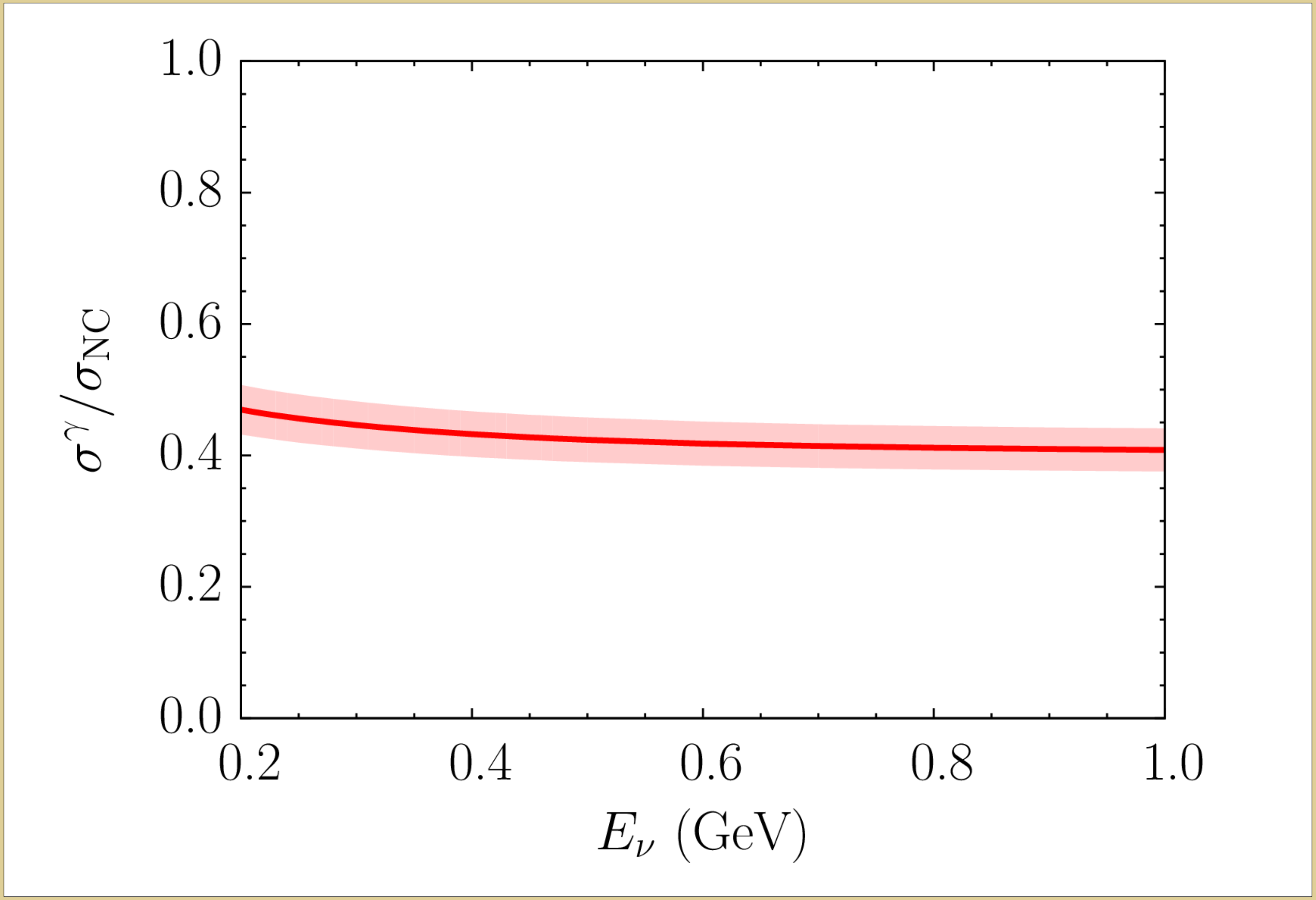
Cross section for γ emission accompanying NC event

Our estimate is that

- ~7-MeV photons (from the s1/2 knockout) follow **$\lesssim$3.5%** NC events

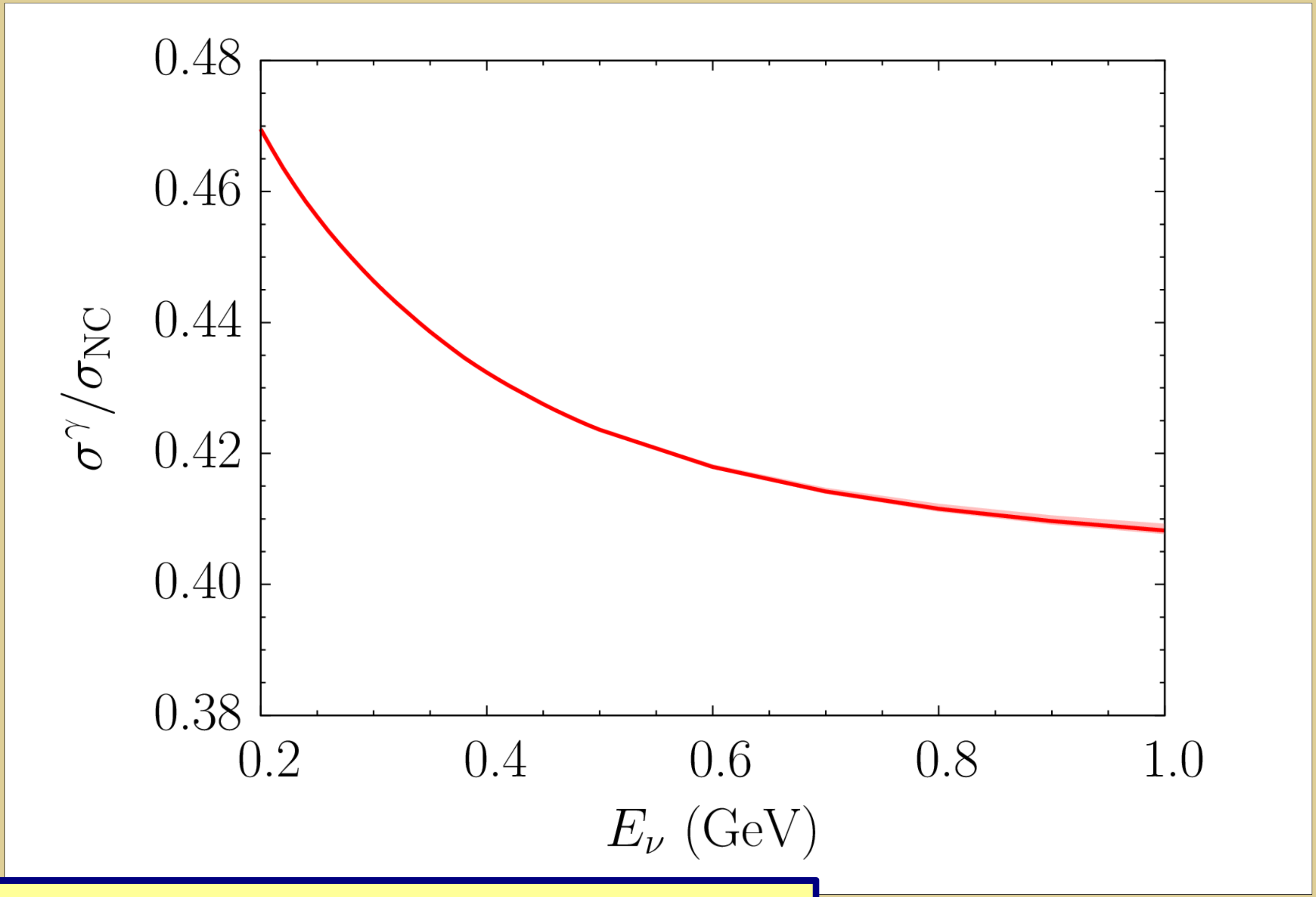
- 6-MeV photons (from the p3/2 knockout) follow **~40%** NC events

6-MeV γ production vs. NC



Ratio weakly dependent on *E*

6-MeV γ production vs. NC



Ratio largely independent of M_A.
Band for M_A 1.03 – 1.39 GeV

What features of oxygen are essential?

1. Large contribution to the cross section from a narrow level deexciting into photons

2. Deexcitation with $E\gamma > 5$ MeV providing clear signal

3. Available spectral function

Summary

❶ **Deexcitation into photons of $E\gamma > 5$ MeV following the NC interaction may provide a useful signature for water Cherenkov detectors**

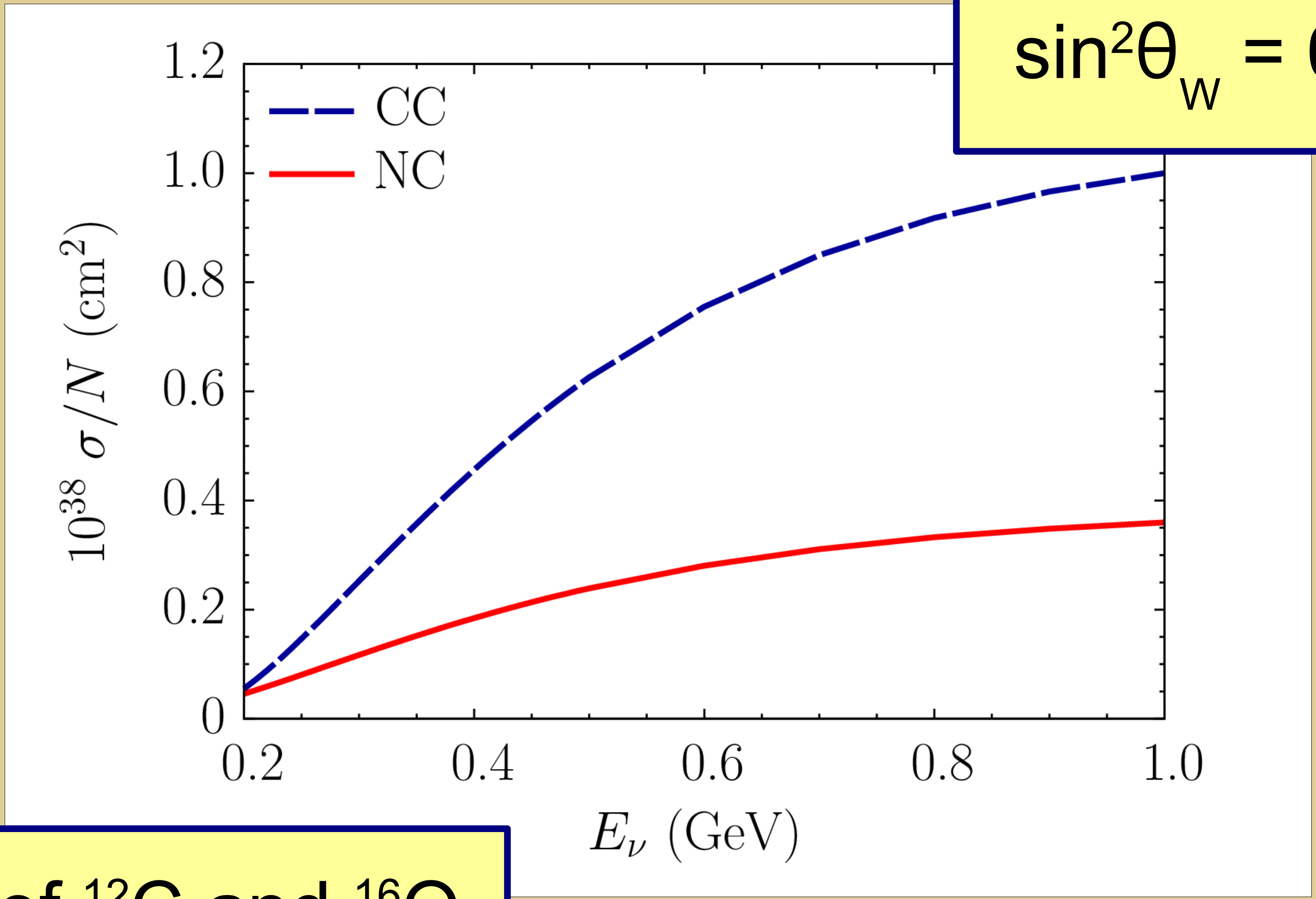
❷ **The ratio $\sigma(\gamma)/\sigma(\mathrm{NC})$ is largely independent of the axial mass value**

❸ **In the important for T2K region $E \lesssim 1$ GeV, the ratio is ~40% for the 6-MeV γ's from p3/2 knockout. The $E\gamma > 6$ MeV photons from s1/2 hole are just 2-3%.**

Back-up slides

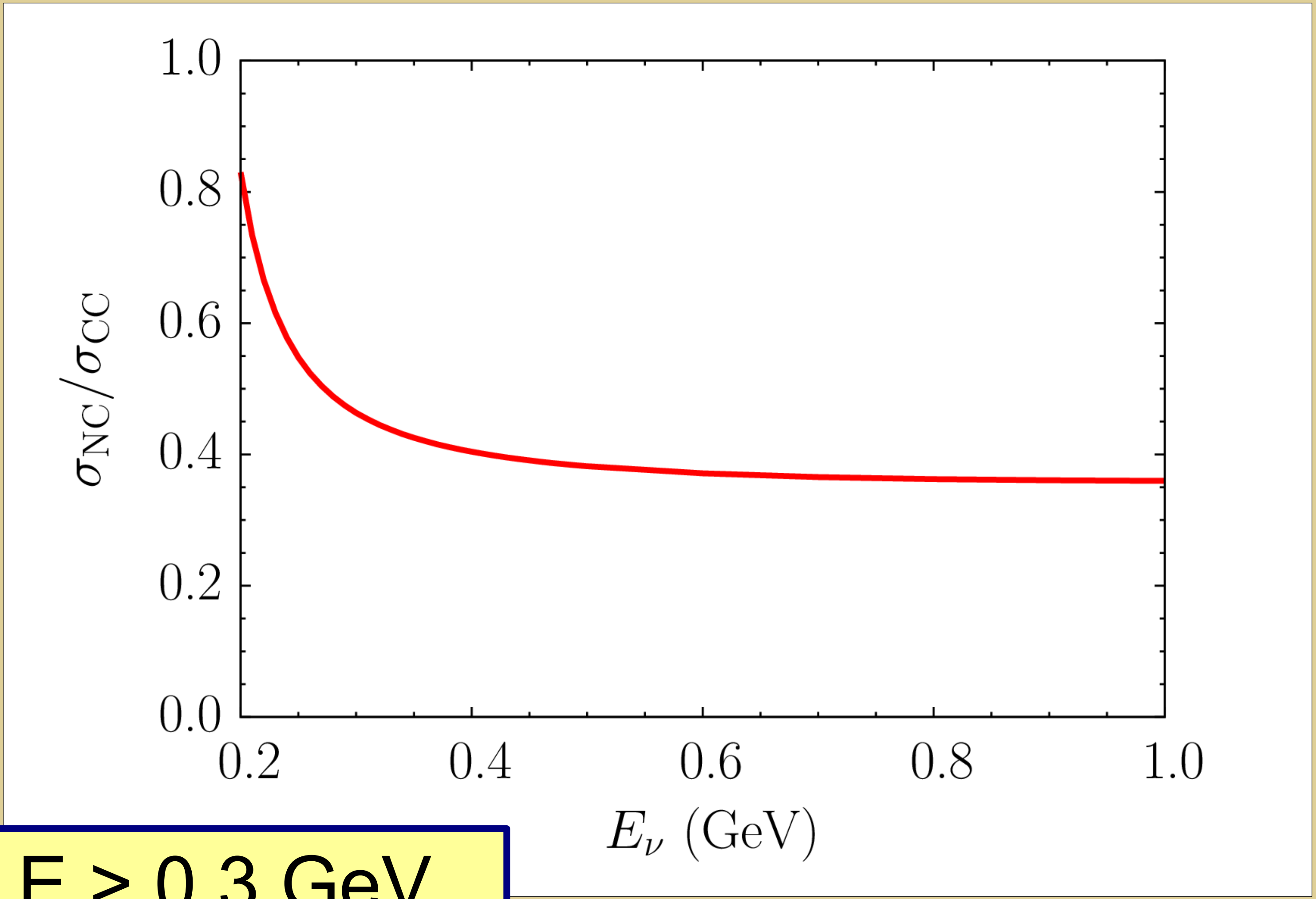
NC vs. CC for symmetric nuclei

$\sin^2\theta_W = 0.231$



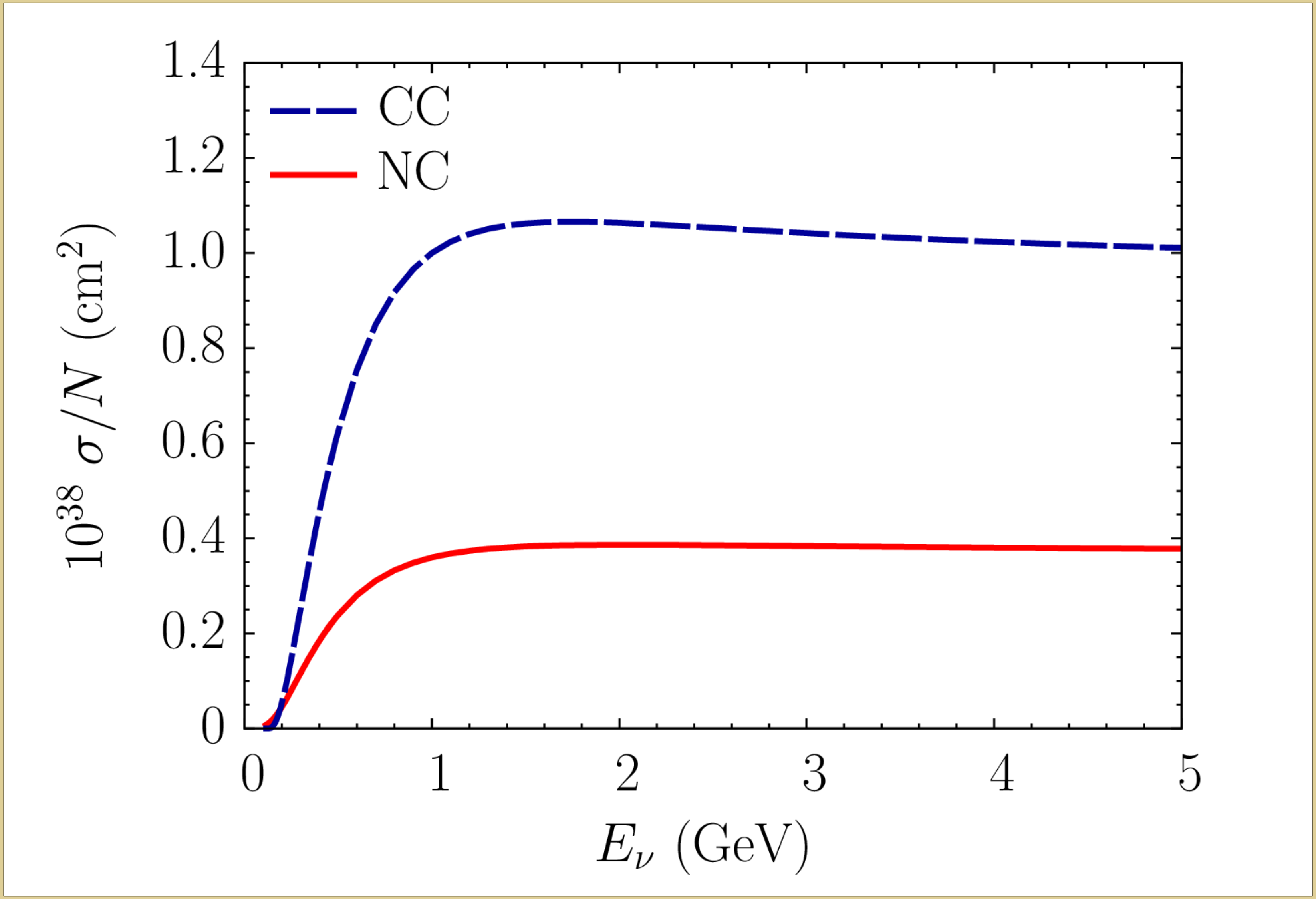
σ/N of ^{12}C and ^{16}O agree to 2.5%

NC vs. CC for symmetric nuclei

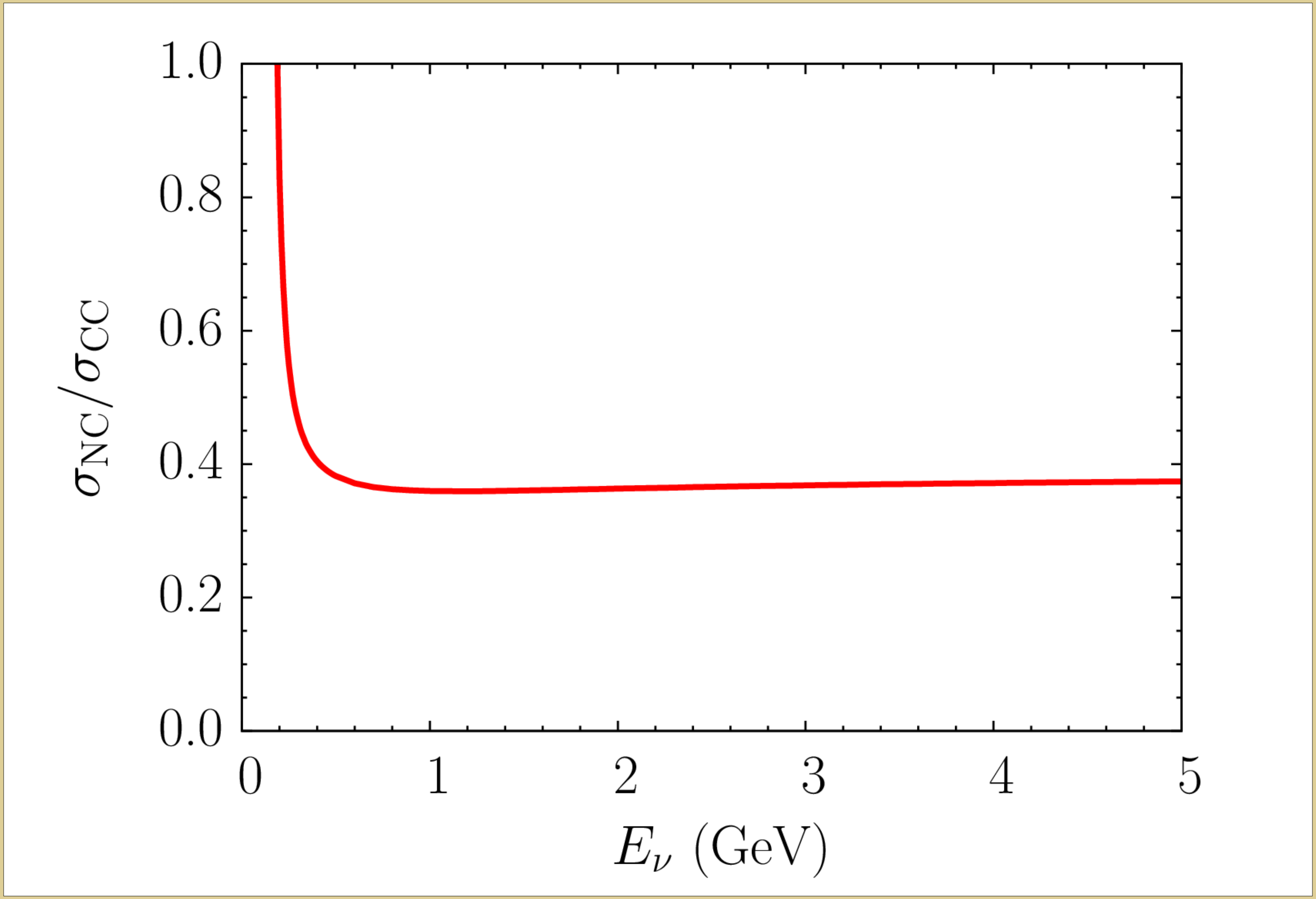


For E > 0.3 GeV
$\sigma_{NC} \approx 0.37\ \sigma_{CC}$

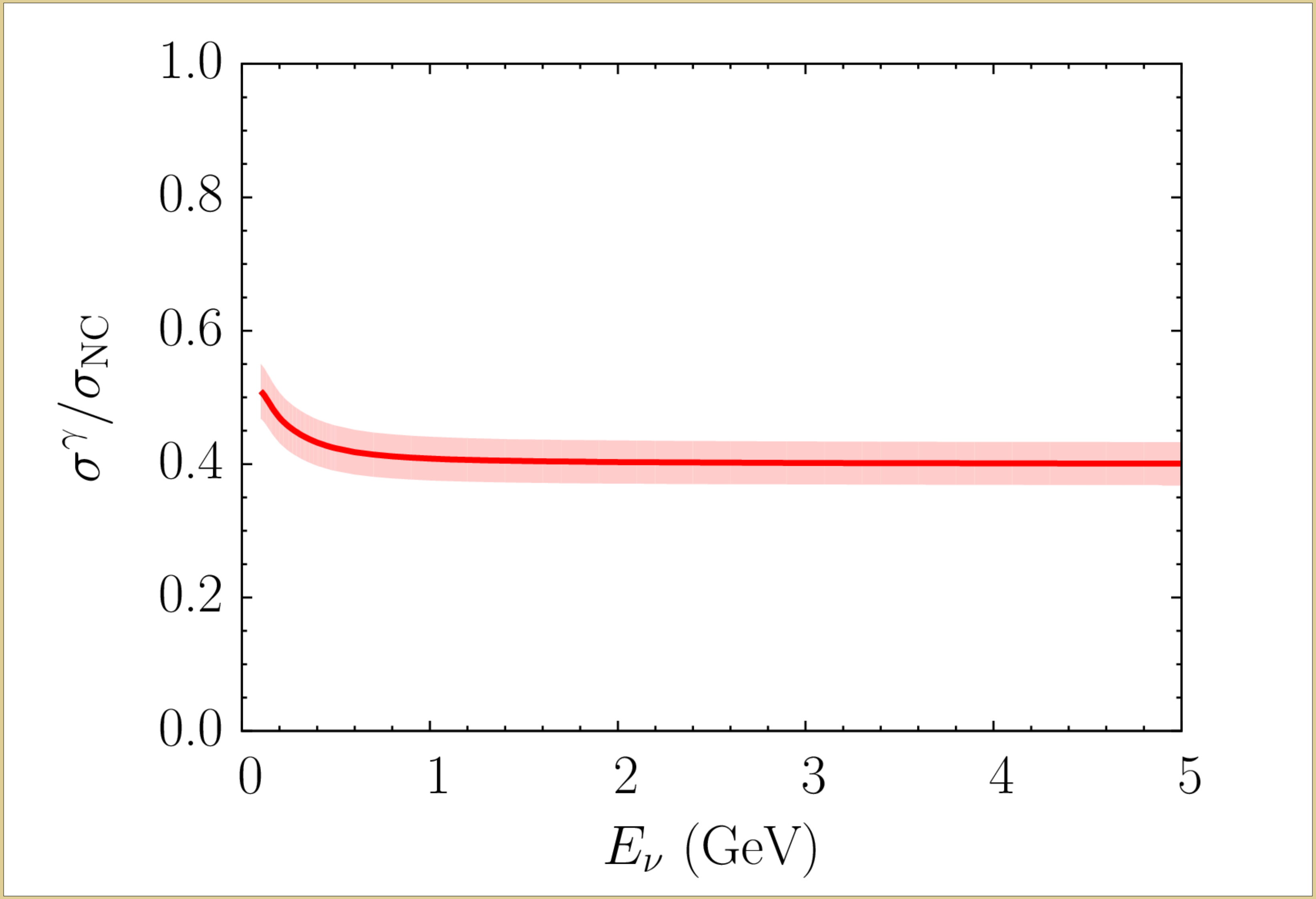
NC vs. CC for symmetric nuclei



NC vs. CC for symmetric nuclei



6-MeV γ production x-section vs. NC x-section



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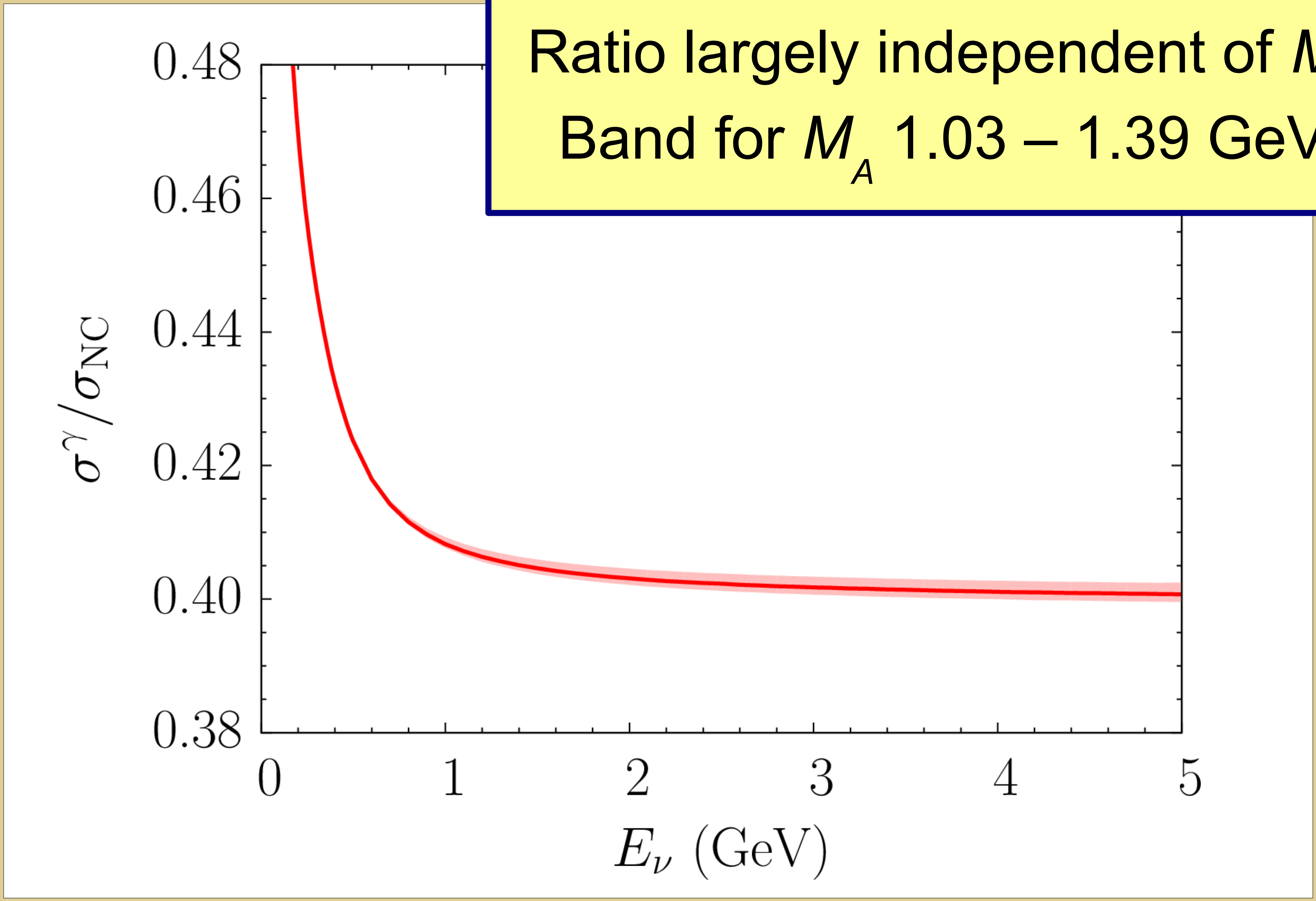

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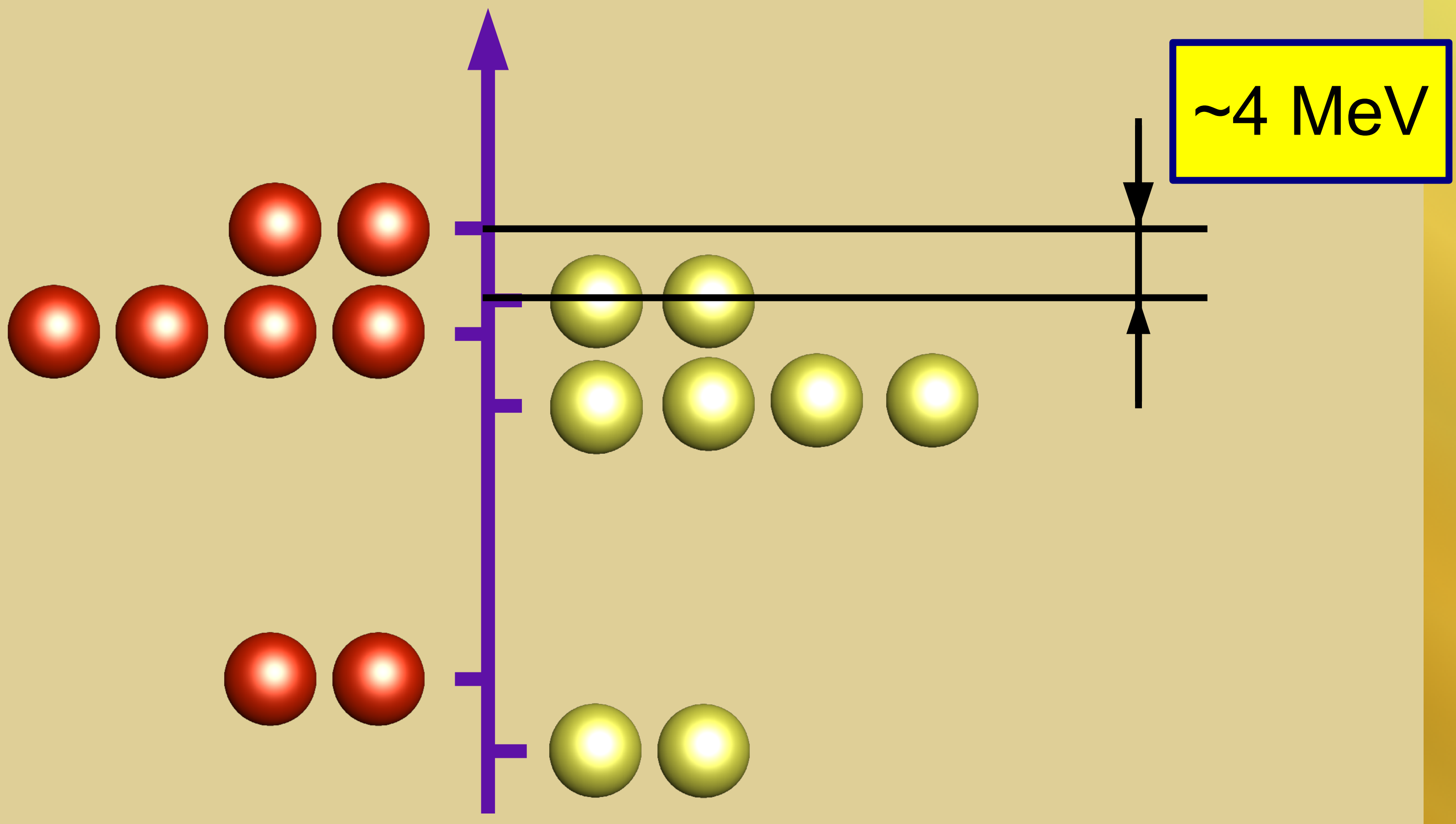
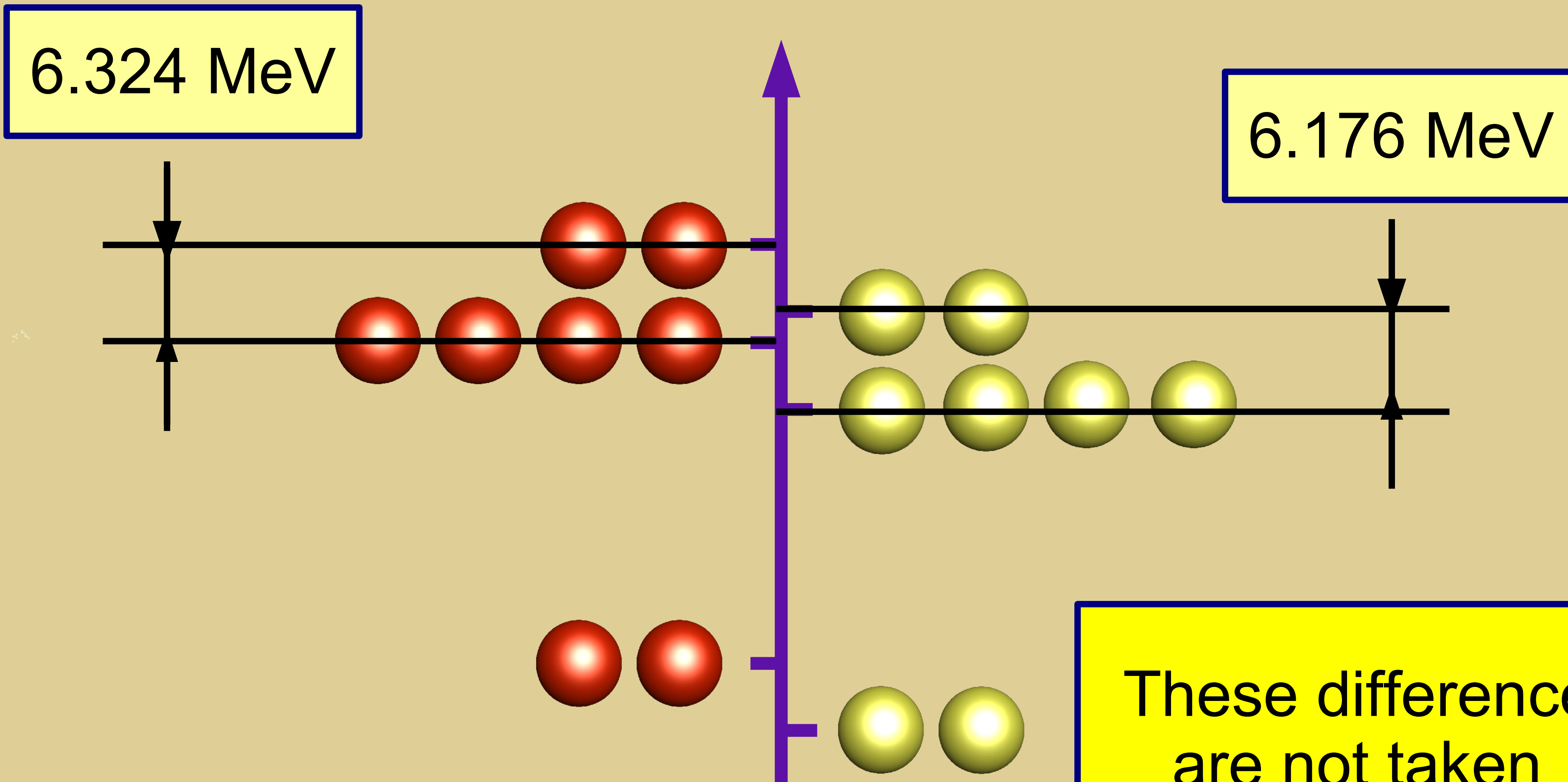


Structure of the oxygen nucleus



These differences are not taken into account