On extraction of the total photoabsorption cross section on the neutron from data on the deuteron

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- Motivation:

  GRAAL experiment (proton, deuteron)

  $\Rightarrow$ neutron [F15(1680) resonance]

- Some theory:

  on analysis of Armstrong, 1972

  folding (Fermi motion)

  nonadditive corrections (FSI, etc)

- Some results

Motivation

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ELEMENTARY PARTICLES AND FIELDS
Experiment

2010

Total Cross Sections for Photoabsorption on Light Nuclei in the Energy Range 600–1500 MeV

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Abstract—Experimental data of the GRAAL Collaboration on the total cross sections for photoabsorption on deuterium and carbon targets at gamma-ray energies in the range between 600 and 1500 MeV are presented. The experiment was performed in a beam of photons obtained by the method of the Compton backscattering of laser photons at the electron storage ring of the European Synchrotron Radiation Facility (ESRF, Grenoble, France) by using a wide-aperture detector covering a solid angle close to 4π. The total photoabsorption cross sections were determined by two independent methods: by subtracting the empty-target background and by summing partial cross sections for meson photoproduction. The total cross sections for photoabsorption on quasifree protons and neutrons are shown to agree both in magnitude and in shape within a 5% precision of the measurements. In contrast to data previously available in the literature, both cross sections show distinctly the $F_{15}(1680)$ resonance at a photon energy of about 1 GeV.

Bartalini et al, Phys. At. Nucl. 71, 75 (2008)
Rudnev et al, Phys. At. Nucl. 73, 1469 (2010)

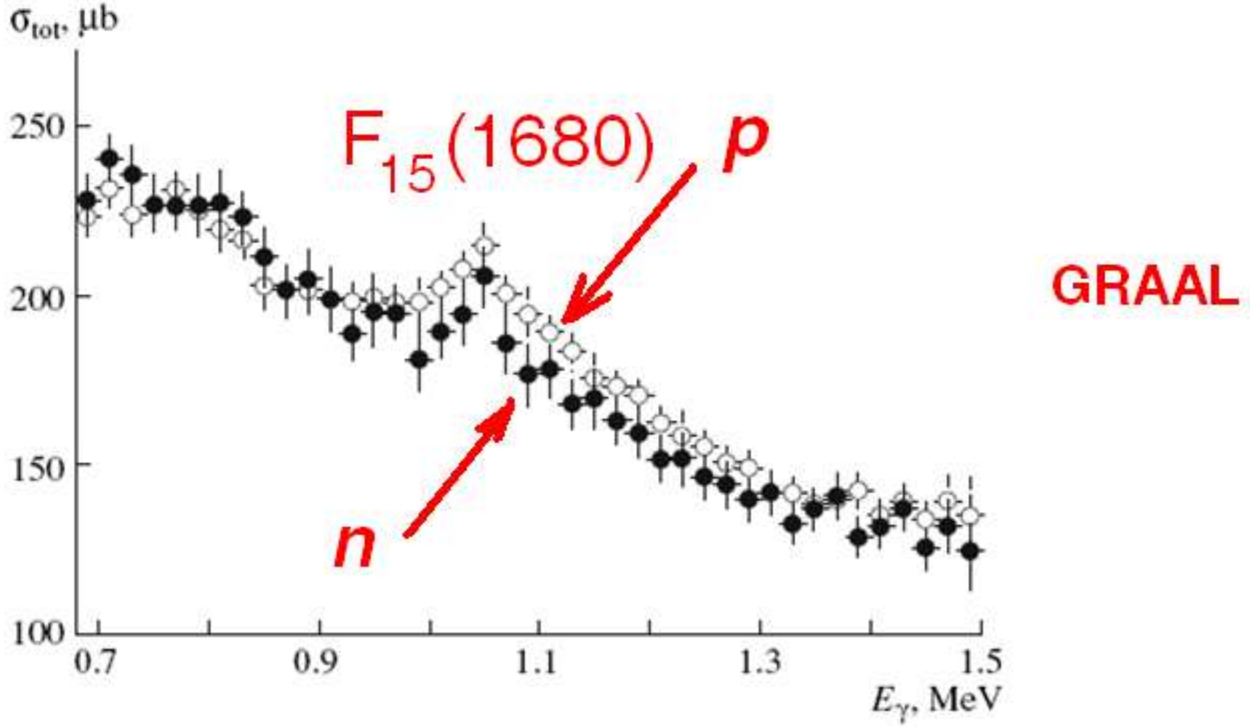
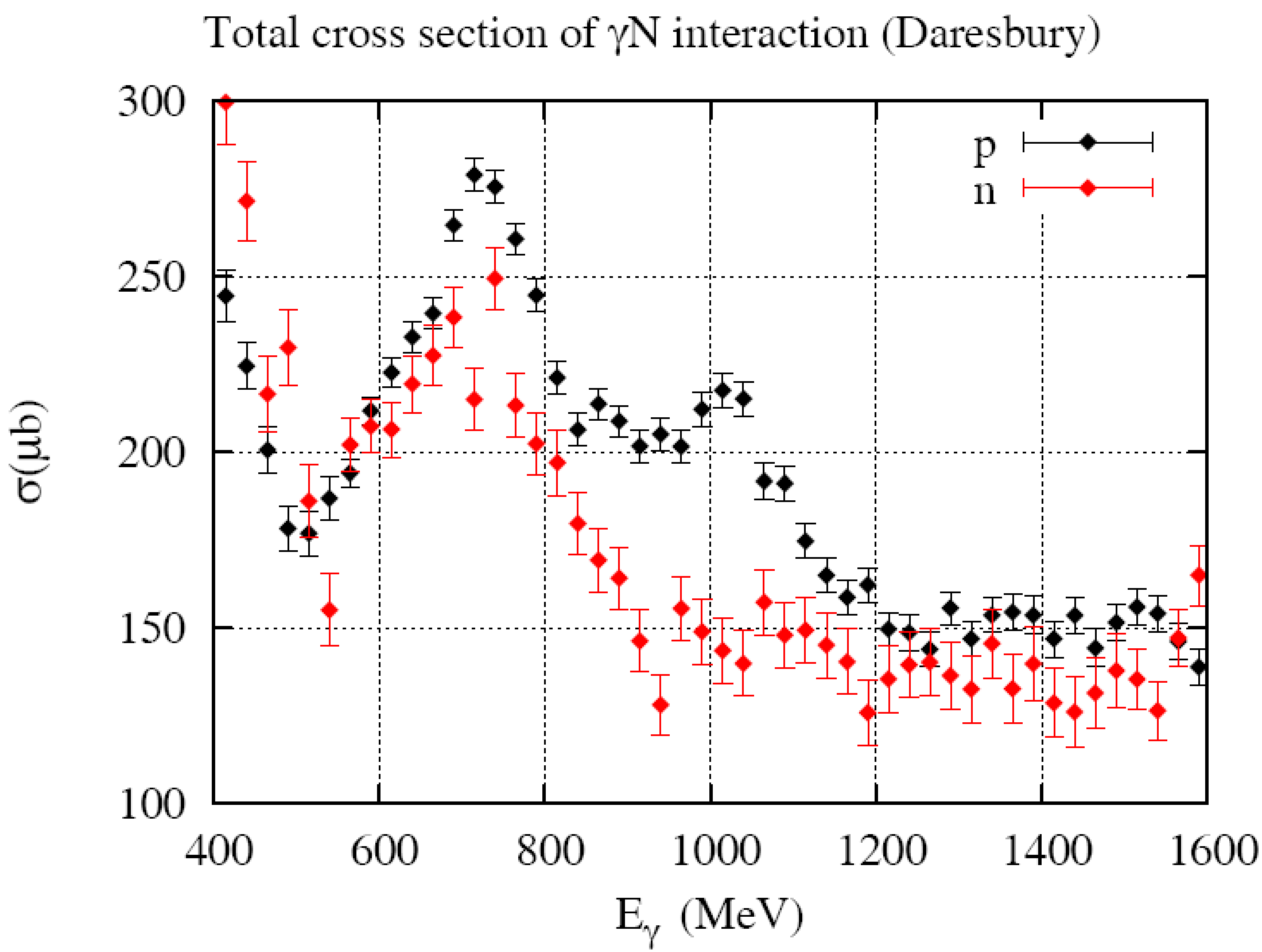


Fig. 2. Total cross sections for photoabsorption on (open circles) a bound proton and (closed circles) a bound neutron that were obtained for a deuteron target by the method of summing partial channels.

Striking feature of these data: the resonance F15(1680) is clearly seen in both the cases, with the proton and the neutron.

Other data tell us that F15(1680) is not easily excited off the neutron. See Armstrong et al (1972) and PDG.

Armstrong et al, Phys Rev D5, 1640 (1972)
Armstrong et al, Nucl Phys B41, 445 (1972)



$N(1680)\ F_{15}$

$I(J^P) = \frac{1}{2}(\frac{5}{2}^+)$

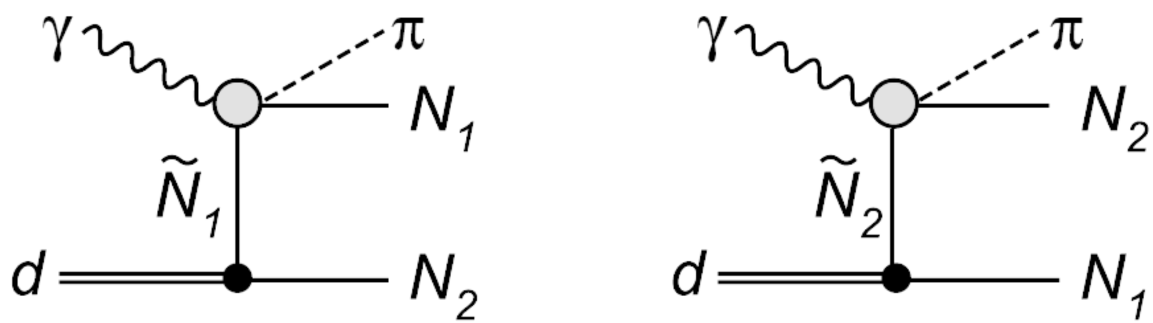
PDG

Breit-Wigner mass = 1680 to 1690 (≈ 1685) MeV
Breit-Wigner full width = 120 to 140 (≈ 130) MeV
$p_{beam} = 1.02$ GeV/c $4\pi\lambda\!\!\!^{-2} = 15.0$ mb
Re(pole position) = 1665 to 1680 (≈ 1675) MeV
−2Im(pole position) = 110 to 135 (≈ 120) MeV

N(1680) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	0.65 to 0.70	571
$N\eta$	(0.0 ±1.0) %	386
$N\pi\pi$	30–40 %	539
$\Delta\pi$	5–15 %	374
$N\rho$	3–15 %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–20 %	–
$p\gamma$	0.21–0.32 %	581
$p\gamma$, helicity=1/2	0.001–0.011 %	581
$p\gamma$, helicity=3/2	0.20–0.32 %	581
$n\gamma$	0.021–0.046 %	581
$n\gamma$, helicity=1/2	0.004–0.029 %	581
$n\gamma$, helicity=3/2	0.01–0.024 %	581

On Fermi motion

As an example, let us consider the reaction $\gamma d \to \pi N N$



The total cross section on the deuteron is

$$\sigma_d^{IA} = \int \frac{d^3\mathbf{p}_s}{(2\pi)^3} |\Psi(\mathbf{p}_s)\ T(\gamma N \to \pi N)|^2$$

The effective photon energy in the $\gamma N \to \pi N$ vertex is

$$\omega^{eff} = \omega\left(1 - \frac{\tilde{p}_z}{M}\right)$$

This is the Döpler shifting.

Let suppose the amplitude $\gamma N \to \pi N$ to be of the resonance form

$$T(\gamma N \to \pi N) = \frac{M_R \Gamma}{W^2 - M_R^2 + i M_R \Gamma}$$

The Hulthen wave function is

$$\Psi(p) = \sqrt{\frac{8\pi\alpha\beta(\alpha+\beta)}{(\alpha-\beta)^2}}\left[\frac{1}{p^2+\alpha^2} - \frac{1}{p^2+\beta^2}\right]$$

Then, the ratio of the deuteron cross section to the nucleon one in the resonance position is

$$f(\omega_R) = \frac{\sigma_d(\omega_R)}{\sigma_N(\omega_R)} = \delta\frac{\alpha+\beta}{(\alpha-\beta)^2}\left[\frac{\beta}{\delta+\alpha} + \frac{\alpha}{\delta+\beta} + \frac{4\alpha\beta}{\alpha^2-\beta^2}\ln\frac{\delta+\beta}{\delta+\alpha}\right]$$

where $\delta = M_R \Gamma / 2\omega_R$.

One can show that

$$0 \le f(\omega_R) \le 1$$

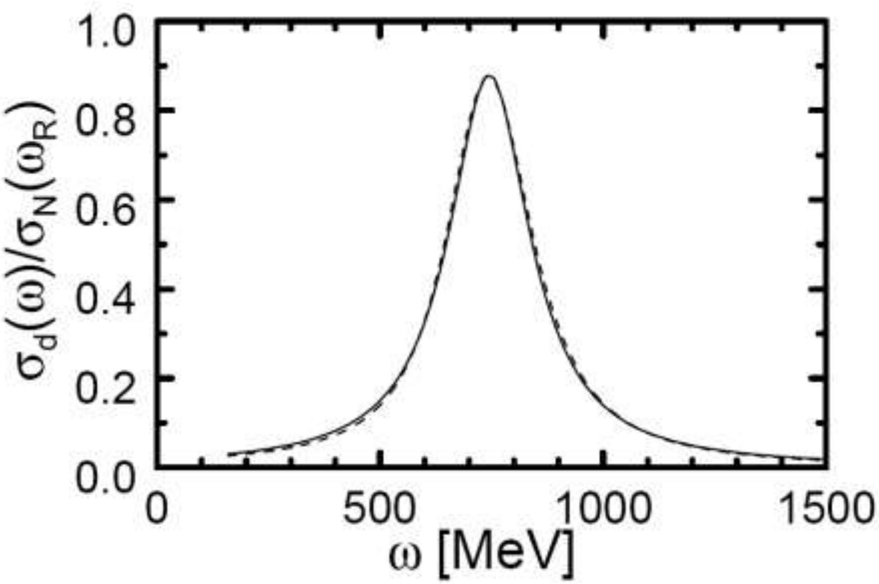
Together with the depression of the peak, the broadening the resonance is expected. The following equality should be valid

$$\int_0^\infty \sigma_d^{IA}(\omega)d\omega = \int_0^\infty \sigma_N(\omega)d\omega$$

One has for the resonance form of σ

$$f(\omega_R)\Gamma'\arctan\left(\frac{M\Gamma}{\kappa\Gamma'}\right) = \Gamma\arctan\left(\frac{M}{\kappa}\right)$$

where $\kappa = M_R\Gamma/2M$. One obtains $\Gamma' = 138$ MeV for $M_R = 1510$ MeV and $\Gamma = 120$ MeV.



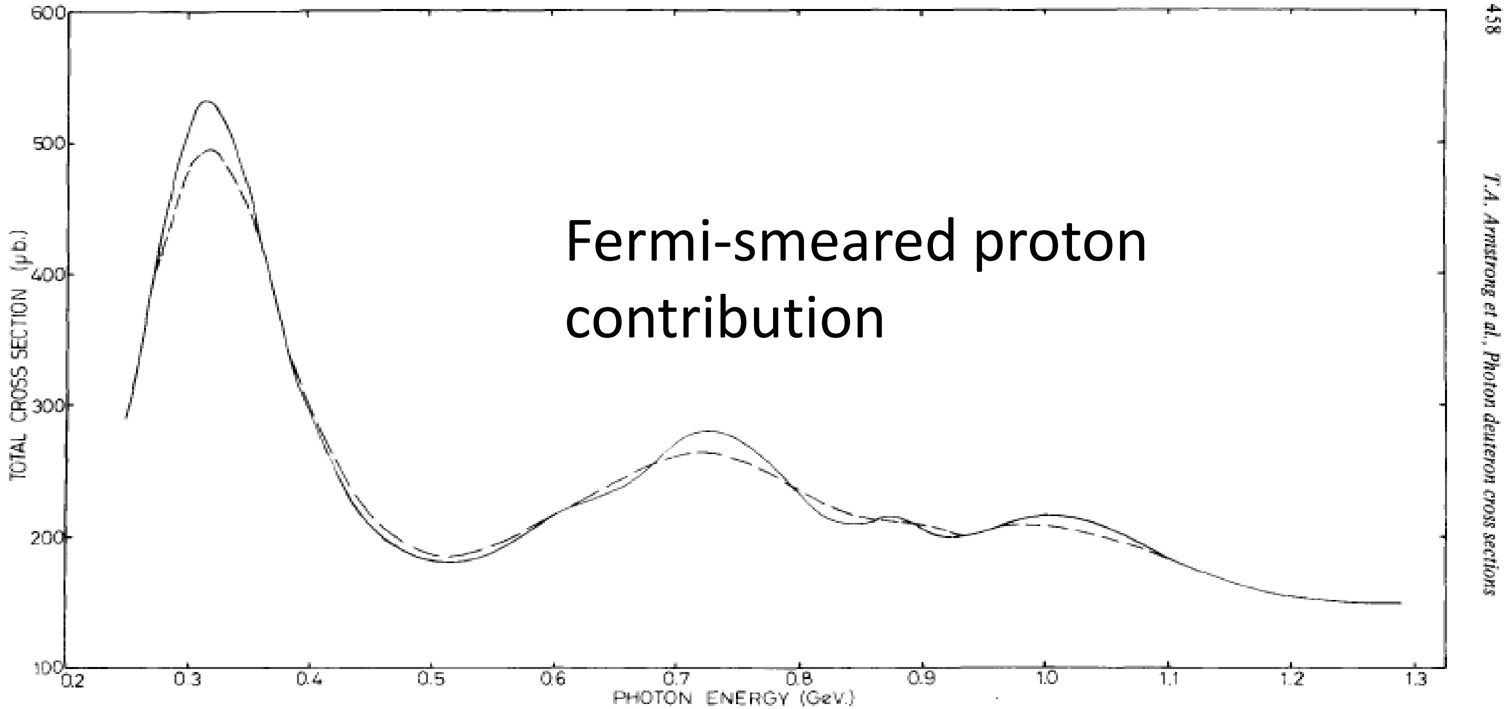


Fig. 6(b). The effects of internal nucleon motion are illustrated by smearing a smooth fit to the proton data (——) into a broadened curve (– – –).

Prescription used: $\sigma_d(\omega) = F_p(\omega)[\sigma_p(\omega) + \sigma_n(\omega)]$

Shortcomings:

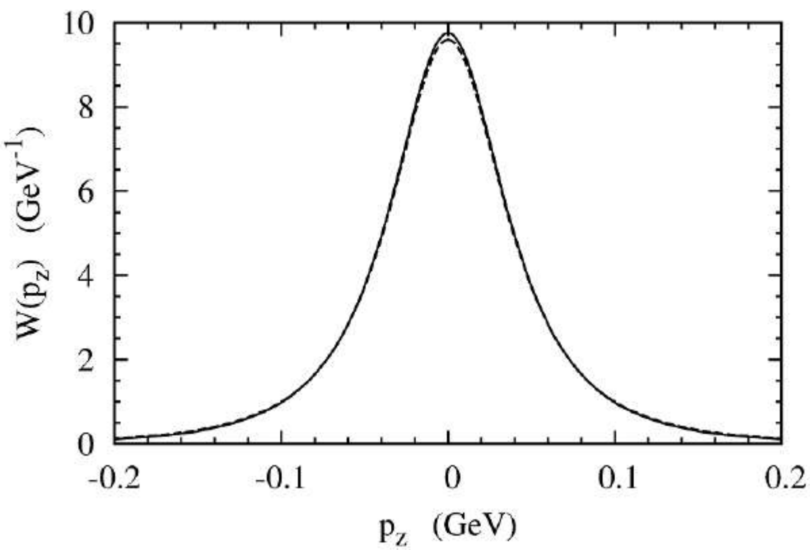
1) actually assumes that shapes of proton and neutron cross sections are the same;
2) inadequate energy bins for neutron;
3) nonadditive corrections are omitted.

Fermi smearing

$$\sigma_d(\omega) = \hat{F}(\omega)[\sigma_p(\omega) + \sigma_n(\omega)] + \Delta\sigma_{pn}(\omega)$$

$$\hat{F}\sigma(\omega) = \int W(p_z)\frac{\omega^{eff}}{\omega}\sigma(\omega^{eff})\,dp_z$$

$$W(p_z) = \int |\psi(p)|^2 \frac{d^2 p_\perp}{(2\pi)^2}$$



Energy resolution

$$\Delta\omega = \frac{\left\langle p_z^2 \right\rangle^{1/2}}{M}\omega \approx 0.057\omega$$

We assume that both $\sigma_p(\omega)$ and $\sigma_n(\omega)$ can be approximated as a sum of a few Breit-Wigner resonances of unknown amplitudes (however with fixed masses and widths taken from PDG) plus a smooth background (a sum of a few powers of W = the total energy, with unknown coefficients):

$$\sigma(\omega) = \sum_i X_i f_i(\omega) \qquad X_i = \text{unknown}, \quad f_i(\omega) = \text{known}$$

All X_i are found from a fit to $\sigma_d(\omega)$. This also gives the wanted cross section $\sigma_{p+n}(\omega)$.

Nonadditive corrections $\Delta\sigma_{pn}(\omega)$

The term $\Delta\sigma_{pn}(E_\gamma)$ in Eq. (3) takes into account various effects violating additivity of the photoabsorption cross sections on individual nucleons.

Among them:

- interference of diagrams for the proton and neutron leading to identical final states;
- The Fermi statistics of the emitted nucleons (antisymmetrization) leading to the so-called Pauli-blocking;
- interaction between emitted particles including the interaction of unbound nucleons, binding of the nucleons and the formation of a deuteron in the final state, interaction of pions (and in principle other particles), produced on the same nucleon, with the second nucleon in the deuteron;

FSI

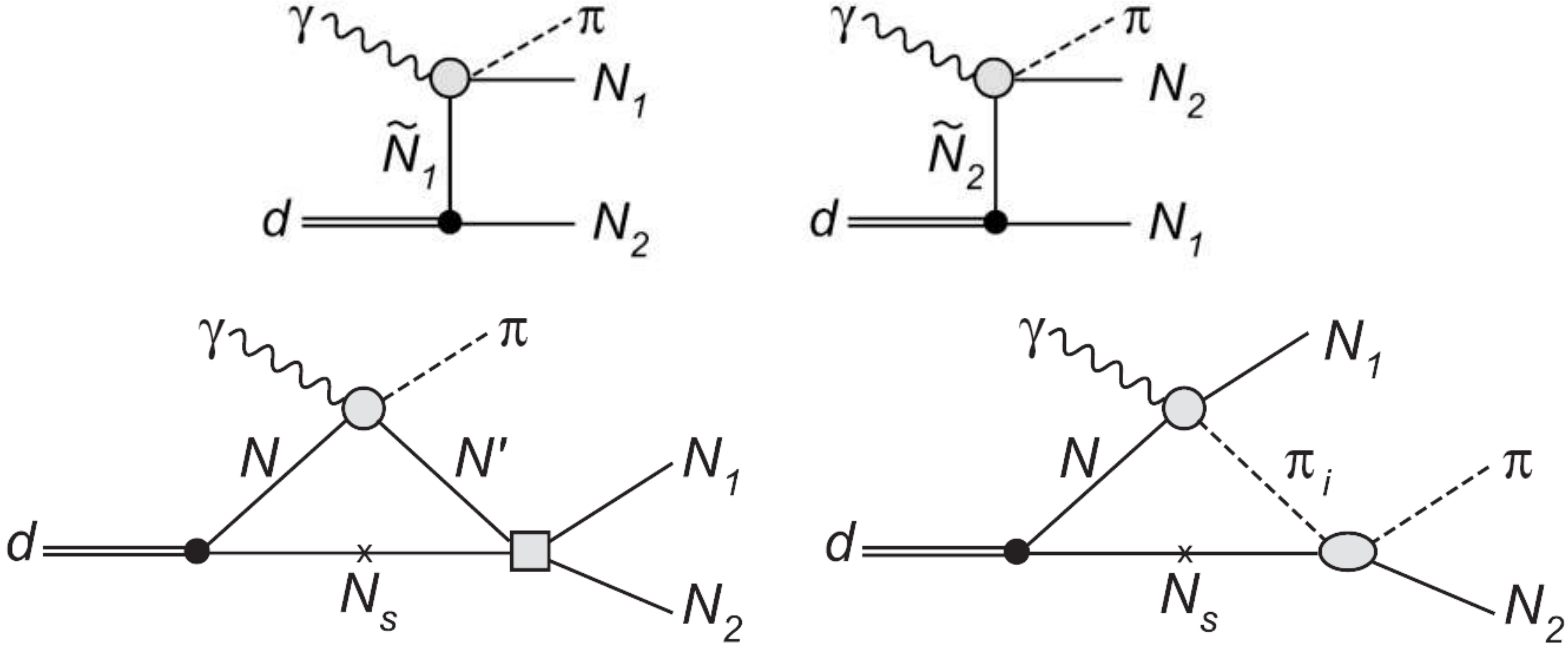
- absorption of the pion (the presence of processes such as photodisintegration of the deuteron - without the presence of pions in the final state).

Estimates of $\Delta\sigma_{pn}(\omega)$

The case of $\gamma d \to \pi NN$:

Interference of diagrams of IA

NN and πN FSI interaction



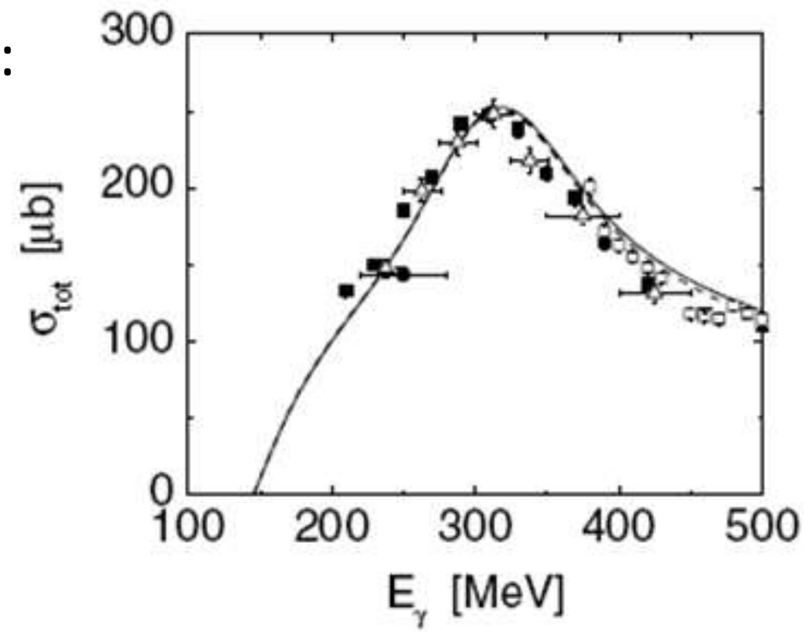
An extension (to higher energies) of the model developed for the $\Delta(1232)$ energy region in:

M. L. et al. Phys Rev C74, 014014 (2006)

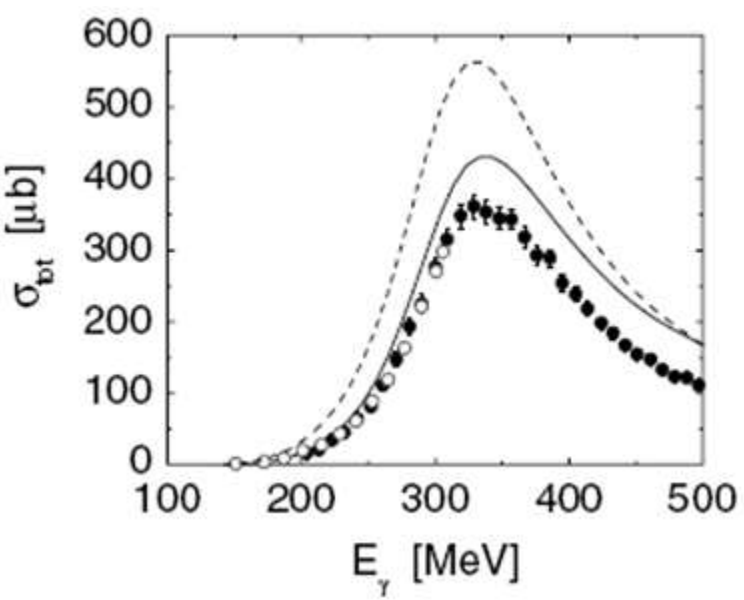
M. L. Phys Rev C82, 044002 (2010)

(``elementary'' $\gamma N \rightarrow \pi N$ amplitudes plus NN and πN FSI).

This approach works well for $\gamma d \rightarrow \pi^- pp$:



But for $\gamma d \rightarrow \pi^0 pn$ agreement is only qualitative:

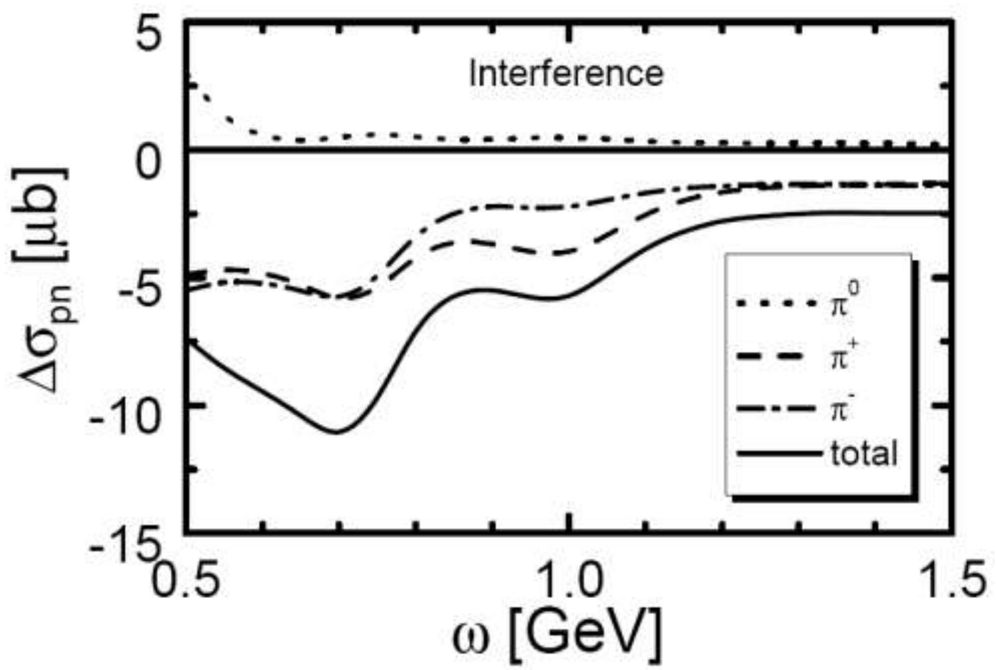


Reason of this failure is unknown: in calculations of other authors there is a similar discrepancy…

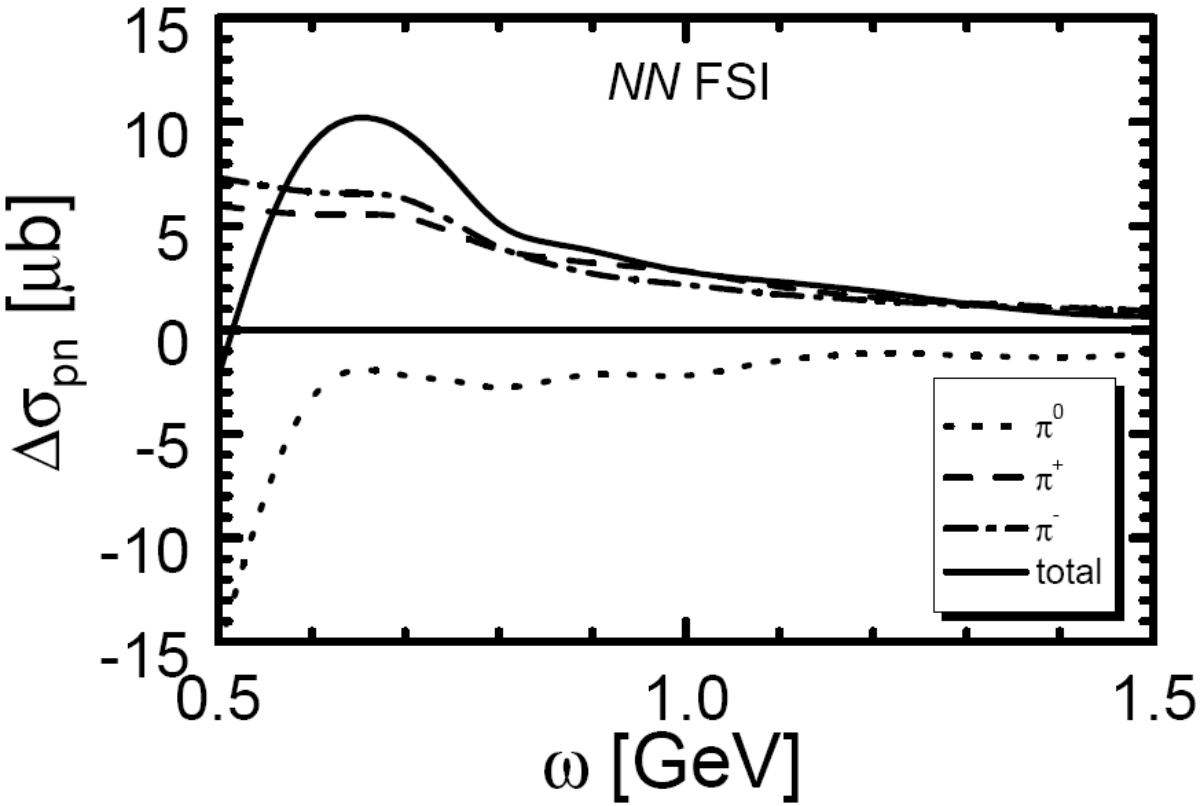
For calculations at GRAAL energies, ``elementary'' amplitudes of $\gamma N \to \pi N$, $\pi N \to \pi N$ and $NN \to NN$ have been taken from SAID (with a proper off-shell extrapolation).

Some results for $\Delta\sigma_{pn}(\omega)$:

1) Interference contributions to $\gamma d \to \pi NN$, IA



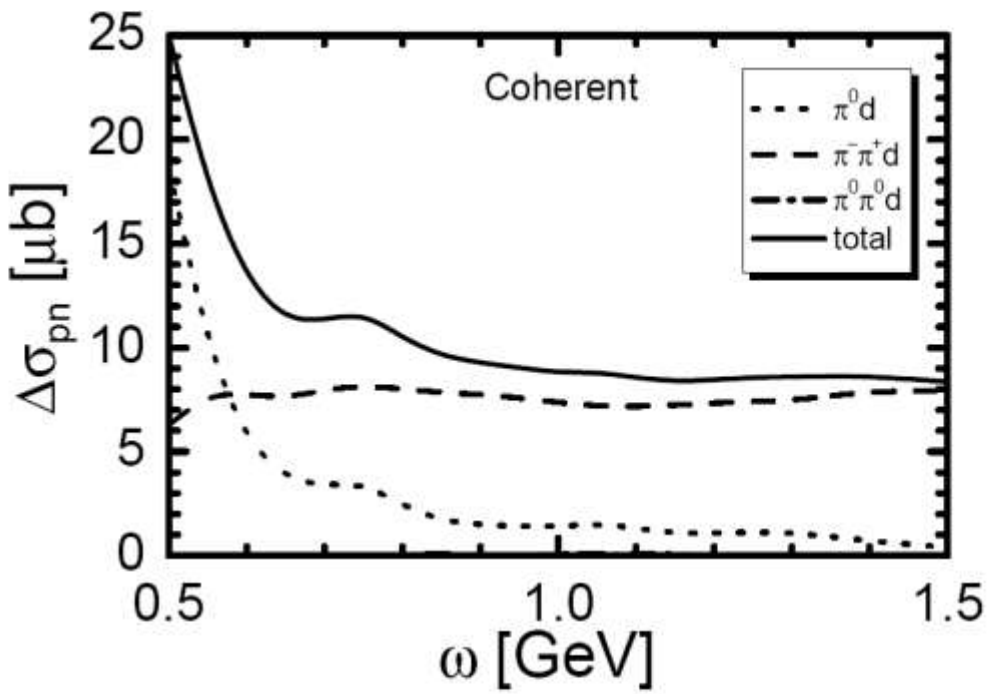
2) $\gamma d \to \pi NN$: NN interaction in the final state



3) $\gamma d \to \pi NN$: πN interaction in the final state is negligible for GRAAL energies, $\Delta\sigma_{pn}(E_\gamma) \leq 1$ μb.

4) Related contribution of NN FSI that leads to a bound state (deuteron): coherent photoproduction of π^0 (found in IA).

5) Also shown coherent contribution due to double-pion photoproduction $\gamma d \rightarrow \pi^+\pi^- d$ (borrowed from Fix and Arenhoevel, Eur Phys J A25, 115 (2005)).



Note that NN FSI effects in $\gamma d \rightarrow \pi^0 pn$ and $\gamma d \rightarrow \pi^0 d$ have a tendency to compensate each other. The same is valid for $\gamma d \rightarrow \pi^+\pi^- pn$ and $\gamma d \rightarrow \pi^+\pi^- d$.

6) Contribution to $\Delta\sigma_{pn}(\omega)$ from incoherent double pion photoproduction was found using results by Fix and Arenhoevel, Eur Phys J A25, 115 (2005).

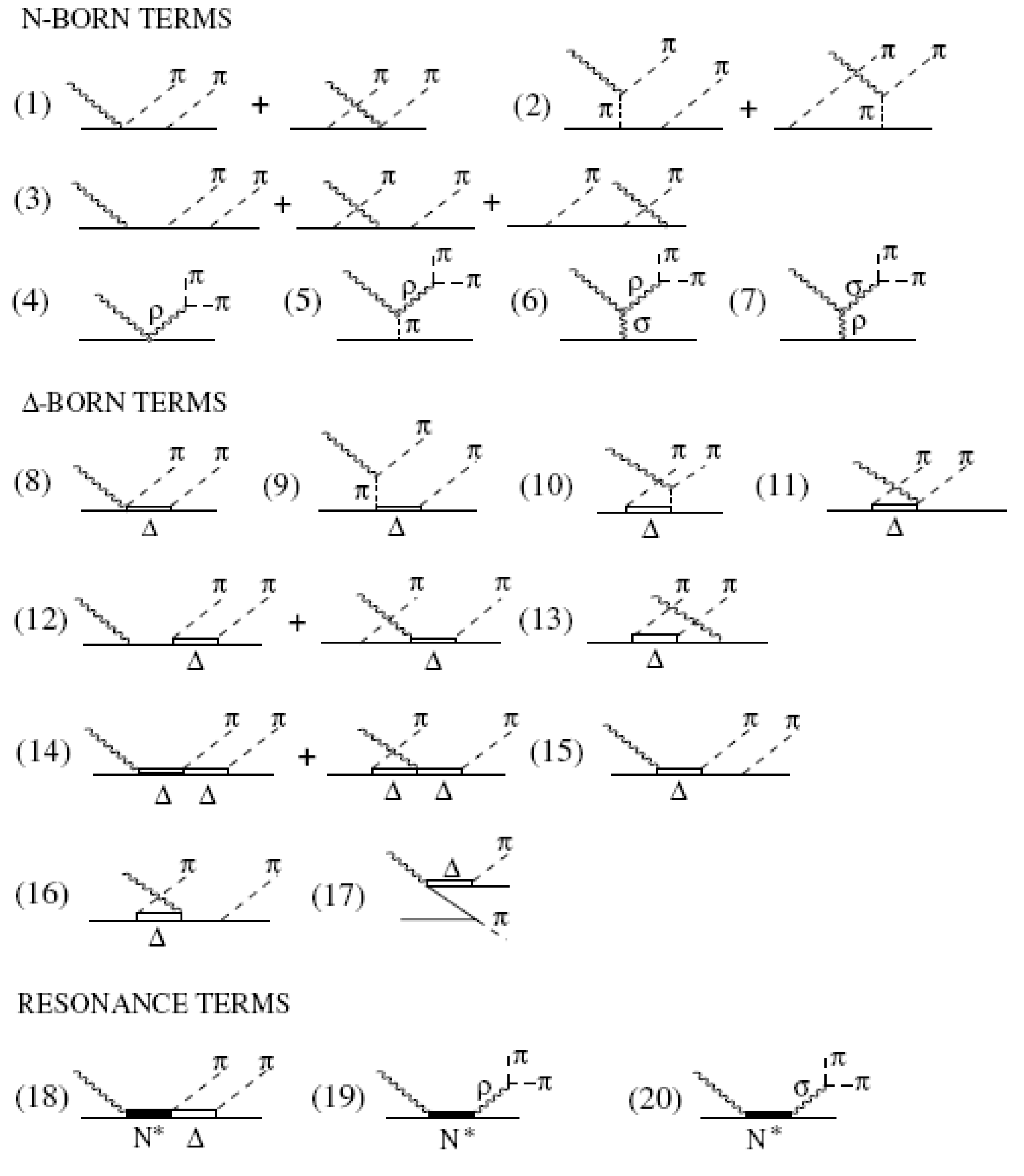
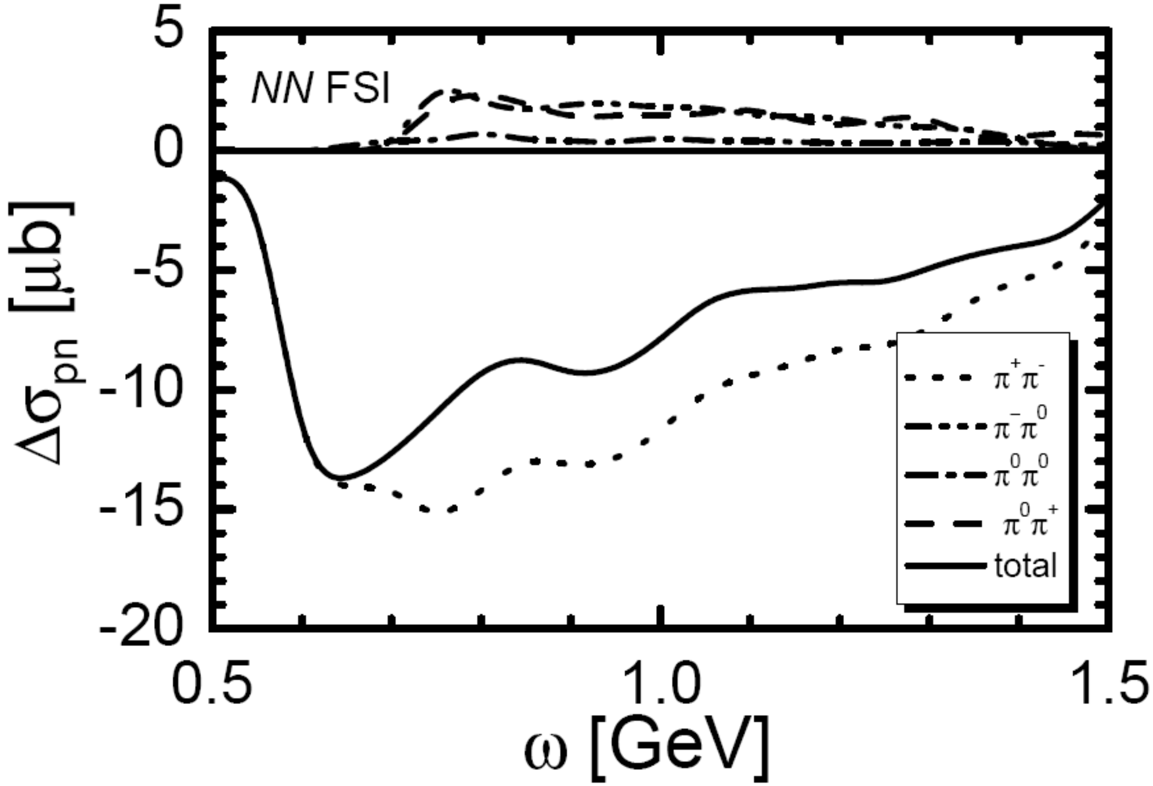


Fig. 1. Diagrams for the reaction $\gamma N \to \pi\pi N$ used in the present work.

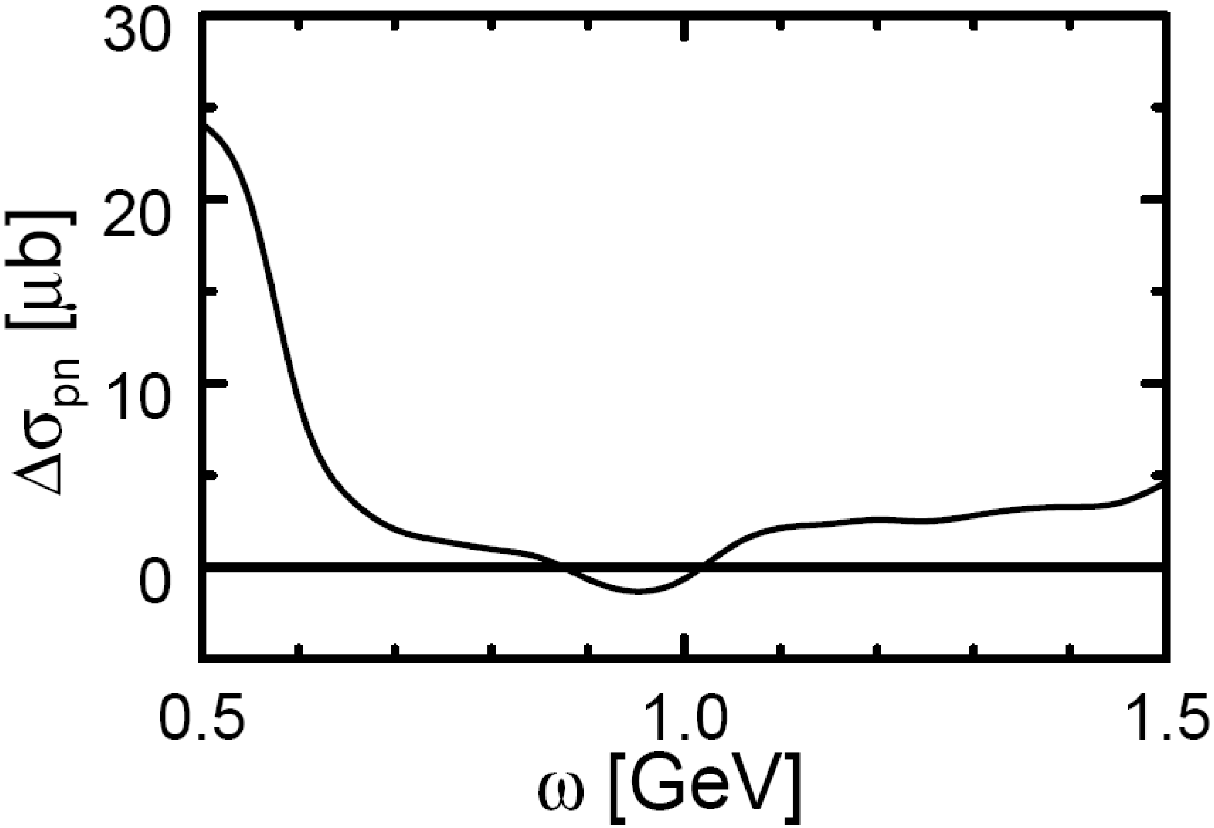
7) Contribution to $\Delta\sigma_{pn}(\omega)$ from NN FSI in $\gamma d \to \pi\pi NN$



8) $\sigma(\gamma d \to pn)$ is also part of $\Delta\sigma_{pn}(\omega)$. It is negligible at GRAAL energies.

9) reactions of η-meson production ($\gamma d \to \eta pn$ and $\gamma d \to \eta d$) give also very small contribution to the nonadditive part $\Delta\sigma_{pn}(\omega)$.

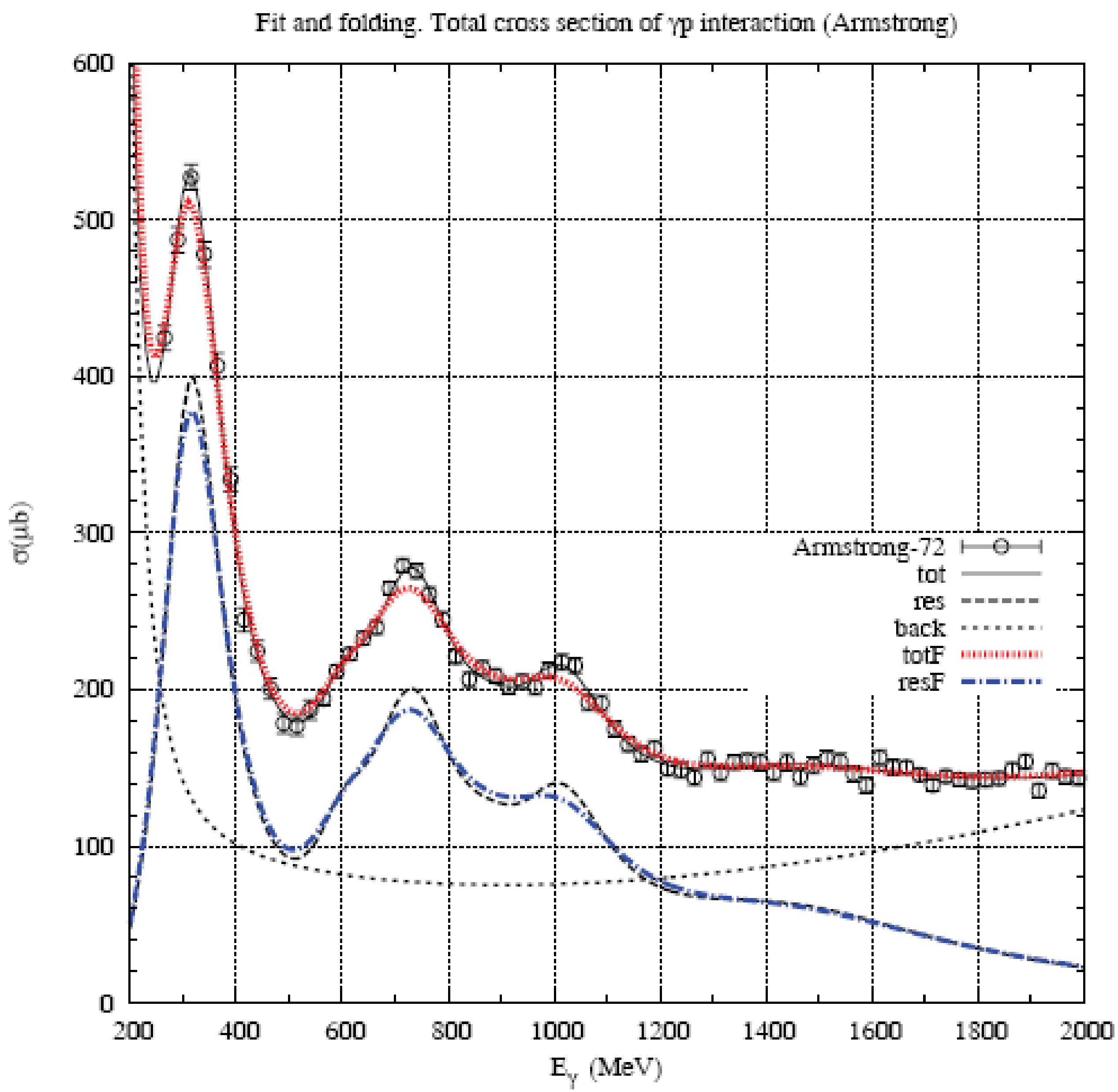
Unexpectedly, these pieces all together give a rather small net effect for $\Delta\sigma_{pn}(\omega)$ at GRAAL energies:



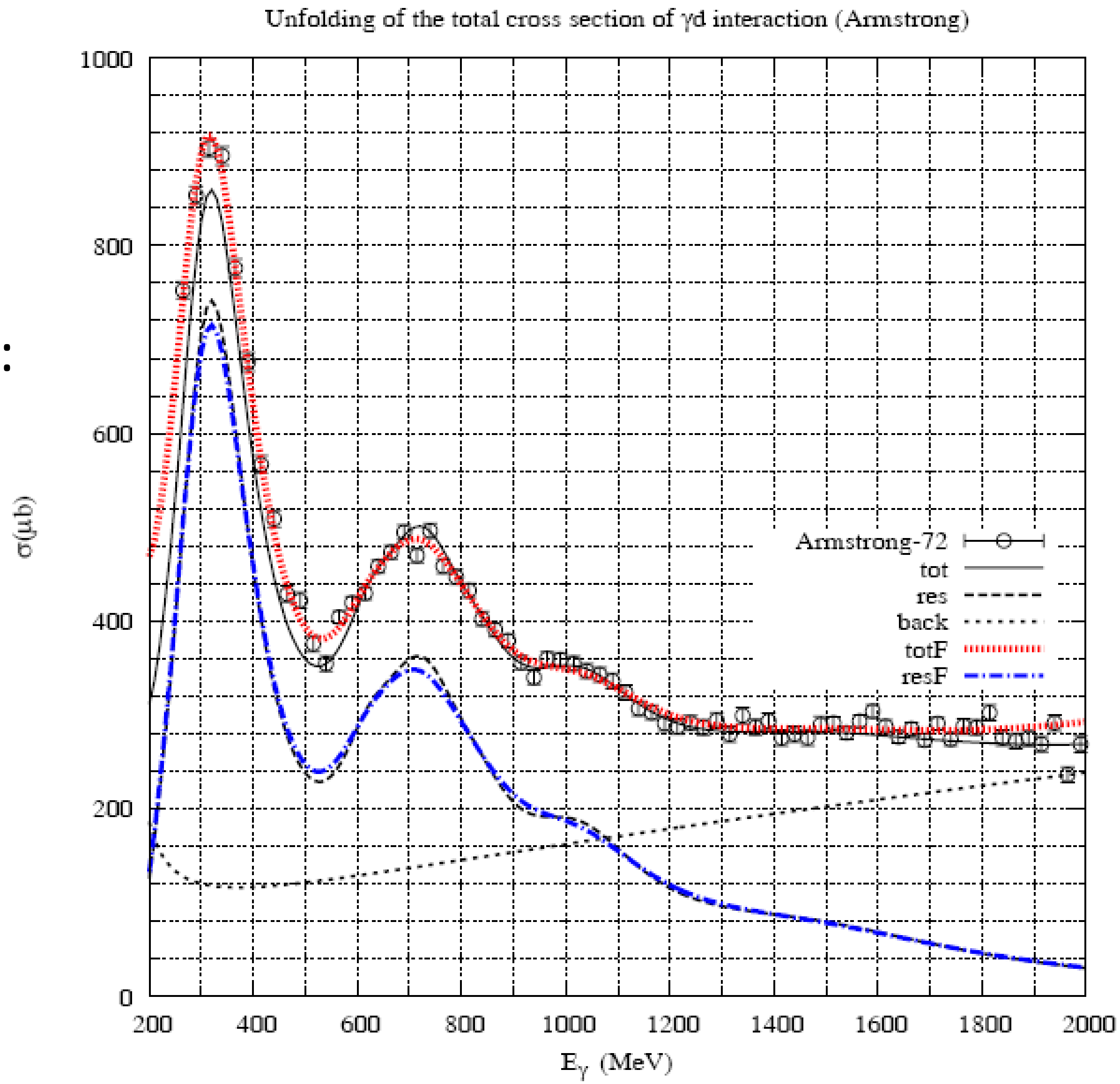
More essential values arise in partial channels (this may be important for extraction of neutron cross sections in partial channels).

How all this works for the Armstrong data

proton:

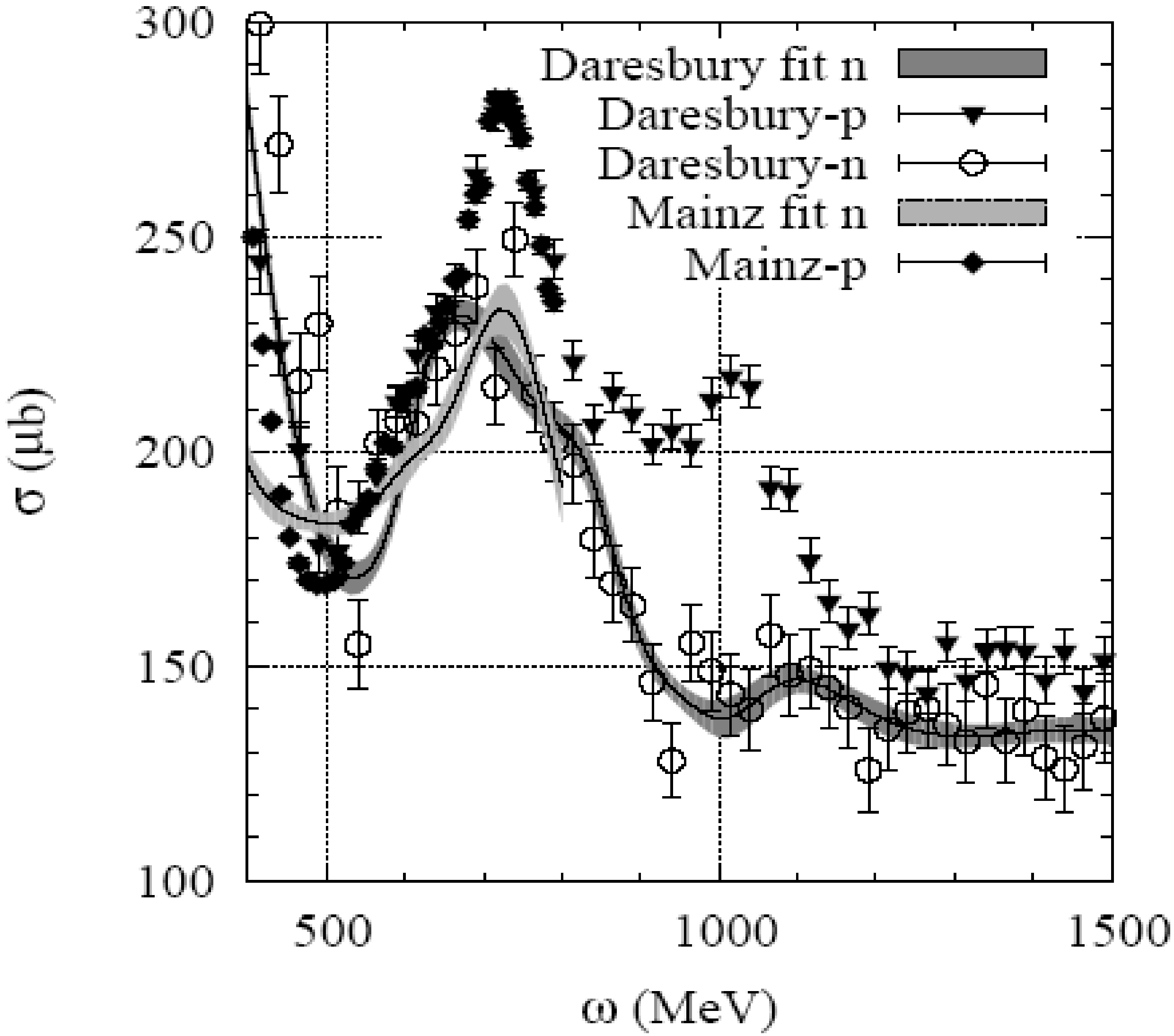


deuteron:



Unfolding of the total cross section of γd interaction (Armstrong)
1000
800
600
400
200
0
σ(μb)
200
400
600
800
1000
1200
1400
1600
1800
2000
Eγ (MeV)
Armstrong-72
tot
res
back
totF
resF

Mainz and Daresbury data together



Conclusions

Improved procedure of extracting the total photoabsorption cross section off the neutron from data on the deuteron is presented.

It involves a more correct treatment of folding/unfolding the Fermi smearing of nucleon contributions.

Also nonadditive corrections are evaluated at medium (preasymptotic) energies where VMD does not yet work.

We hope that the obtained results will be useful for analysis of GRAAL (and future) results.

Thank you for your attention