DOUBLE PHOTOPRODUCTION OF NEUTRAL PIONS ON LIGHT NUCLEI

Egorov Mikhail

Tomsk Polytechnic University

16th September 2014

Dubna. JINR. 2014

Content

Photopruduction

nuclear reactions under electromagnetic radiation attack

Properties:

- Rescattering photons in all nuclear volume up to $E_\gamma \approx 2$ GeV
- Impulse approximation ($\lambda_\gamma << \langle r_{N-N} \rangle$, $\tau_{interact.} << \tau_{relax}$)
- Smallness of electromagnetic coupling constant $\longrightarrow$ Born approximation.

Models

The study of nucleon resonances is a very important tool for evaluating modern hadron models. Photoproduction of neutral pions plays a sizeable role for the study of resonances contributions since background components like as meson pole terms or Kroll-Rudermann terms are strongly suppressed due to the weak coupling of the photon to neutral mesons.

for searching a missing in (γ, π^0)-reaction resonances[1]

there are following models

1. L.Y. Murphy, J.-M. Laget, DAPNIA/SPhN-96-10 (1996) (relativized isobar model with vector meson exchange)
2. A. Gomez Tejedor, E.Oset. Nucl. Phys. A 600 (1996)
3. A. Fix, H. Arenhövel. Eur. Phys. J. A 25 (2005) (non relativistic isobar model with meson exchange)

[1] Interesting review of the problem V.D.Burkert, T.-S.Lee//Int.J.of Mod.Phys.E13(2004)1035

Models

Model with the inclusion of simulations

1. O. Buss [*et al.*]. Phys. Rept. 512 (2012) (GiBUU "Transport Model" simulations)
2. A.V. Sarantsev [*et al.*] hep-ph 0707.3591v4 (2007) (Bonn-Gatchina - partial wave analyze)

Dynamical coupled channel model (DCC -model)

- P. Mühlich, L. Alvarez-Ruso, O. Buss, U. Mosel // Phys. Lett. B. -2004, -T. 595, 216-222p.
- A. Matsuyama, T. Sato, T.-S. H. Lee // Phys.Rept. -2007, -T.439, 193-253 p.
- H. Kamano , S.X. Nakamura, T.-S. H. Lee, T. Sato // Phys. Rev. C. -2013, -T.88, 035209

Problems

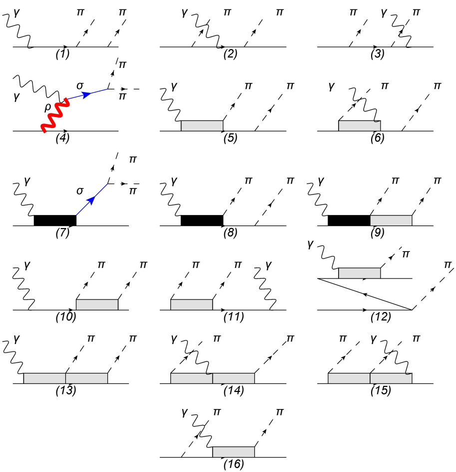
however! to describe one reaction there are almost different reaction imaginations in different models

$\Rightarrow$ there wasn't systematical study of $(\gamma, 2\pi^0)$ reactions on a number of nuclei.

$$\gamma A \rightarrow A\pi^0\pi^0 \tag{1}$$

$\Rightarrow$ As we has seen these reactions are in strong dependence on the amplitude details. $\Rightarrow$ Let us illustrate how it depends on parameters (masses,widths, couplings...).

diagrams of tree level
(1-4) –N-Borns terms; (5-6,10-16) –$P_{33}(1232)$-Born terms; (7-9) – resonances red solid–ρ-meson, blue solids – σ-meson, black boxes – resonances.



Model

Diagrams(**7-9**) include $L_{2T,2J}$(mass) :
$P_{11}(1440)$,$D_{13}(1520)$,$D_{33}(1700)$,$D_{15}(1675)$
,$F_{15}(1680)$,$S_{31}(1630)$, $D_{13}(1700)^{\star\star\star}$,$S_{11}(1650)$,
$F_{35}(1905)$,$P_{13}(1720)$,$P_{33}(1600)^{\star\star\star}$
in boxes additional to *Fix and Arenhövel*[2] model terms (**a.c.**).

For partial decay widths are being defined we'll use averaged ones on PDG compilation.

Latter thing will be helpfull on what extend model depends on its parameters.

[2] A. Fix, H. Arenhövel. Double pion photoproduction on nucleon and deuteron / Fix A., Arenhövel H. // Eur. Phys. J. -2005. -A **25**, -115 p.

Model

Isotopic structure of the $(\gamma, 2\pi^0)$ process

$$< I_f|\hat{T}|I_i >= \sqrt{(2t_i+1)(2\tau_f+1)}(-1)^{T+\tau_f+t_i+\bar{t}} \\ (B^{[\bar{t}]})_0 C^{\tau_i m}_{\tau_f m\, \bar{t} 0} \begin{pmatrix} t_f & T & \tau_f \\ \tau_i & \bar{t} & t_i \end{pmatrix} \tag{2}$$

tensor $(B^{[\bar{t}]}) = A', B'$ in accordance with isospin transfered is $\bar{t} = 0, 1$. $< I_f|, |I_i >$ - wave functions in iso-space; t_i, t_f- active nucleon isospin, τ_i, τ_f -isospin of initial and final nuclei.

Deuteron $\Rightarrow \bar{t} = 0 \Rightarrow$ outlooks as isovector filter.

Model

Coupling constants, used in model, $f_{\pi NN}$- found in the framework of relativized isobar model where $f^2_{\pi NN}/4\pi = 0.08$. Meson-baryon constants in modulus

N^*	$f_{\pi NN^*}$	$f_{\pi \Delta N^*}$	$f_{\rho NN^*}$
N	1.0	2.08	5
$\Delta(1232)P_{33}$	2.1	3.8	–
$\Delta(1600)P_{33}$	0.48	1.97	17.5(p)
$N(1520)D_{13}$	0.29	0.7(s)/0.7(d)	2.7
$N(1700)D_{13}$	0.08	1.75(s)/0.09(d)	1.8
$N(1680)F_{15}$	0.07	0.4(p)/0.1(f)	6.0(p)/22.4(f)
$N(1440)P_{11}$	1.1	3.4	23.7
$\Delta(1700)D_{33}$	0.1	1.9(s)/0.3(d)	3.4(s)/21.1(d)
$N(1650)S_{11}$	1.5	0.4	1.65
$N(1535)S_{11}$	1.2	0.37	1.27(s)
$\Delta(1905)F_{35}$	0.02	0.5(p)/0.04(f)	7.5(p)
$\Delta(1910)P_{31}$	0.34(p)	0.8	–
$N(1720)P_{13}$	0.26(p)	1.3(p)	19.5(p)
$N(1675)D_{15}$	0.16	0.6(d)/0.05(g)	5.8
$\Delta(1620)S_{31}$	0.8	0.8	2.7

Model

..continue

N^*	$f_{\sigma NN^*}$	g^M	g^E
N	10.02	$-0.06/1.85$	
$\Delta(1232)P_{33}$	-	-1.81	-0.067
$\Delta(1600)P_{33}$	-	-0.086	0.09
$N(1520)D_{13}$	1.86	0.58/0.85	-0.027/0.22
$N(1700)D_{13}$	-	0.07/0.08	-0.012/-0.007
$N(1680)F_{15}$	1.6	0.53/1.45	0.20/0.24
$N(1440)P_{11}$	5.4	0.07/0.36	
$\Delta(1700)D_{33}$	-	-0.50	0.24
$N(1650)S_{11}$	0.9		-0.05/ -0.087
$N(1535)S_{11}$	1.0		-0.05/-0.16
$\Delta(1905)F_{35}$	-	-0.60	-0.087
$\Delta(1910)P_{31}$	-	-0.016	
$N(1720)P_{13}$	-	-0.06/-0.030	-0.025/0.020
$N(1675)D_{15}$	36.4(f)	-0.22/0.43	-0.03/-0.05
$\Delta(1620)S_{31}$	-		-0.07

Rescattering

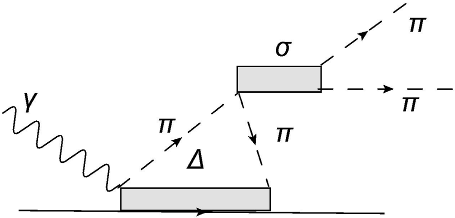
In double π^0 production this effect should plays a sizeable role. How to estimate it? $\Rightarrow$ 2π-molecule or σ-meson model.

1. L. Roca, E.Oset, M.J. Vicente Vacas. Phys. Lett.B **541** (2002) 77-86; L. Roca, E. Oset, M.J. Vicente Vacas. Nucl. Phys. A**721** (2003) 719p.
   $\Rightarrow$ a visible shift to lower masses region in $d\sigma/d\omega_{\pi\pi}$ distribution
2. E. Oset, H. Toki, M. Mizobe, T. Tyr Takahashi. Prog. of Theoretical Phys. V **103** N2 (2000) 351
   $\Rightarrow$ contribution of $\pi\pi$ - rescattering is sizable in $E_\gamma \approx 600$ MeV region.

As it is a pole in $\pi\pi$
rescattering amplitude, there is an additional fitted parameter.

Rescattering

In the model under consideration we are computed the following diagram



Another terms are small enough.

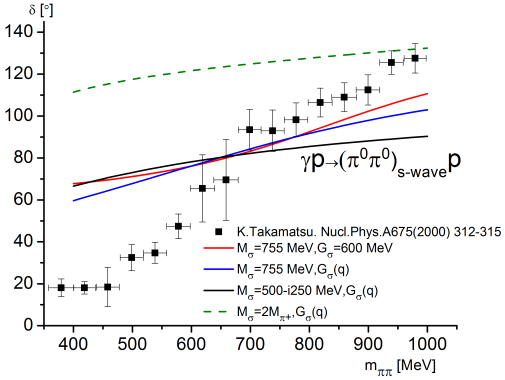
$$\int \frac{1}{(2\omega_\pi)} \frac{1}{(2\pi)^3} t_{\gamma p \to \pi^+\pi^- p} \frac{1}{\frac{q^2}{2\mu} - \frac{\xi^2}{2\mu} + i\epsilon} t_{\pi^+\pi^- \to 2\pi^0} I_{\sigma\pi\pi} d^3\vec{\xi}$$

$$+(\pi^+ \leftrightarrow \pi^-),$$

$$t_{\pi^+\pi^- \to 2\pi^0} = -\frac{H^\dagger_{\sigma\pi\pi} H_{\sigma\pi\pi}}{\omega^2_{\pi\pi} - m^2_\sigma + i\Gamma_\sigma m_\sigma} \frac{1}{2\omega_{\pi\pi}} \qquad (3)$$

Rescattering

propagation of two pions $\frac{1}{\omega_{\pi\pi}^2 - m_\sigma(m_\sigma - i\Gamma_\sigma(q))}$; Exploration of another one see for example in *M.Egorov, A.Fix*[3]



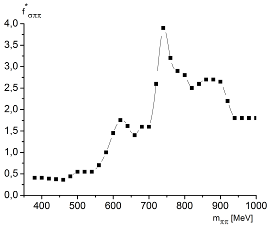
[3]Role of the $\pi\pi$ interaction in pairwise π^0 photoproduction on proton// Russian Phys.J.-2011, T.54.-N4.-58p.

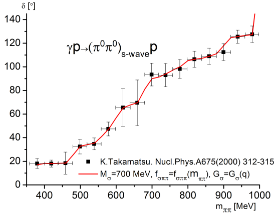
Rescattering

In s-wave rescattering

$$\Gamma_\sigma(q) = \frac{f^2_{\sigma\pi\pi}}{2\pi} q^*, \ where \ q^* = \sqrt{\omega^2_{\pi\pi}/4 - m^2_\pi} \qquad (4)$$

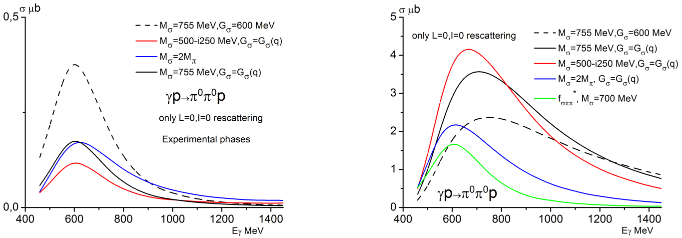
Let use $f^*_{\sigma\pi\pi}$ for phase shifts to achieve





Rescattering

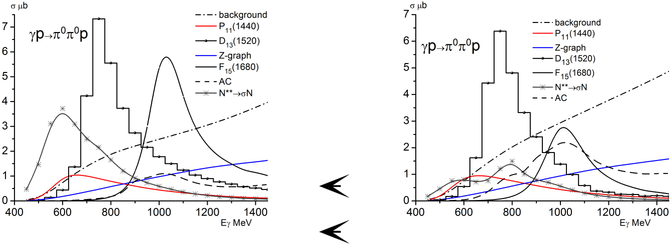
there are two situations in one of them we use experimental phase shifts alone for to $\pi\pi$ amplitude evaluation (left pannel), and theoreticaly predicted phase shifts (right pannel)



green solid curve on the right pannel indicates $\pi\pi$ rescattering effects with new $f^*_{\sigma\pi\pi}$ "constant".

Cross sections

Spectra of sizeable nucleon excitations. Right pannel: parameters of *Fix and Arenhövel*[4] *model*; left pannel: present calculations

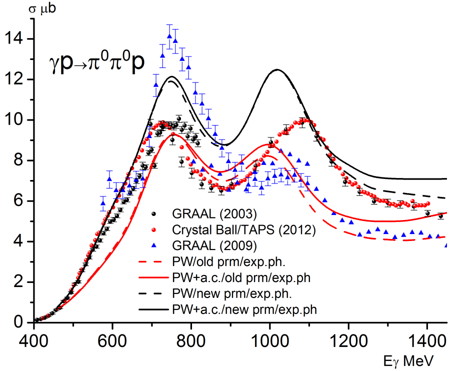


Differences is in $D_{13}(1530)$, $F_{15}(1680)$ and in $N^{**} \to \sigma N$ channel.

[4]A. Fix, H. Arenhövel. Double pion photoproduction on nucleon and deuteron / Fix A., Arenhövel H. // Eur. Phys. J. -2005. -A **25**, -115 p.

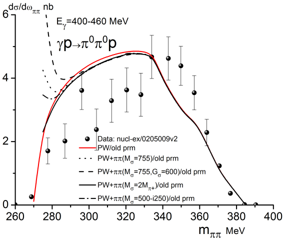
Cross sections

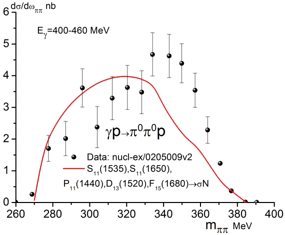
It is the situation where without all other interactions in final state only changes in coupling constants may solve the "missing" resonance problem



Cross sections

Pure rescattering mechanism is of small magnitude in comparison with decay $N^{**} \rightarrow \sigma N$

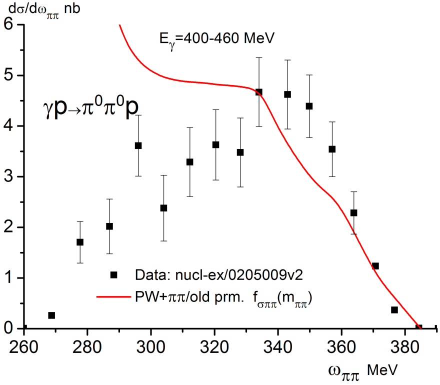




We are in incompetent statement to evaluate σ properties,but we may see visible role of some "unkown" mesonic resonance with the σ properties.

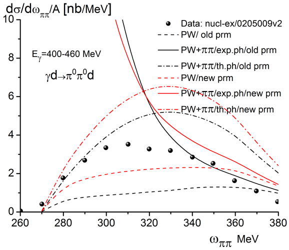
Cross sections

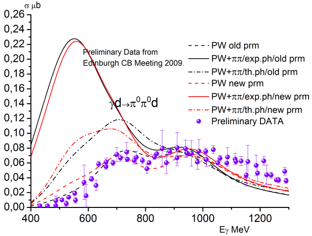
Due to unkown s-wave phase shifts we can not reproduce cross sections in small masses region.



Cross sections

Looking forward to deuteron (and $A > 2$ nuclei) case

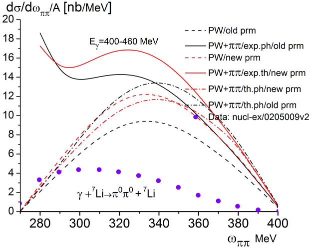


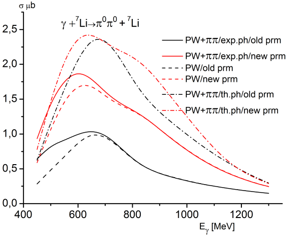


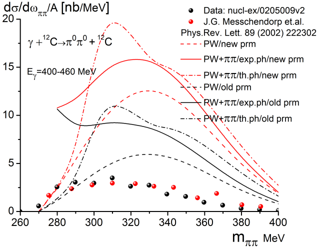
According to the total cross section deuteron data role of $\pi\pi$ rescattering should be out of visibility, i.e. dissagreement on left pannel is of different nature.

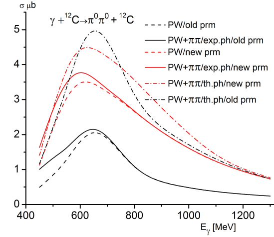
Cross sections

following with A increase









Cross sections

Intermediate summary

- present isobar model depends on parameters meaning
- rescattering of $\pi\pi$ subsystem is less important as it predicted by some authors
- from the $N^{**} \to \sigma N$ point of view role of σ is sizeable in $\frac{ds}{d\omega_{\pi\pi}}$
- in $A > 2$ case, cross section of $A(\gamma, 2\pi^0)A$ process also depends on target isospin.
- role of two ingredients: final πN interaction and intermediate meaning of the parameters should be also separated.

DWIA

It is the interaction of produced particles with final nucleus that makes visible change in cross section's form $\Rightarrow$ multiple rescattering $\Rightarrow$ insuperable efforts $\Rightarrow$ potential models: (simplicity, good agreement with experiment.)

- Attenuation factor (K. Brueckner, K. Serber, K.Watson. 84, N2 (1951) 258; S.Fernbach, R.Serber, T. Taylor. 75, N9 (1949) 1352) related with scattering length λ and with its classical trajectory $x(\vec{r})$ in nuclear volume V

$$f = \frac{A}{V}\int \exp\left(-\frac{x(\vec{r})}{2\lambda}\right) dV$$
$$= \frac{3A}{2x}\left(1 - \frac{2}{x^2}\left(1 - (1+x)\exp(-x)\right)\right), where\, x = \frac{R}{\lambda} \quad (5)$$

Nuclear density $\rho = \frac{A}{V}$. Would it be so simple enough?

DWIA

for d, use f_1 was evaluated with density destribution: $\rho = \frac{A}{V}$ and f_2 with $\rho_s = \frac{4}{\pi^{3/2} r_0^3} \exp - \left(\frac{r^2}{2r_0^2} \right)$ in ^7Li we use f_3 and f_4 for s and p shell;

$W^{J.M.Laget.Nucl.Phys.A194(1972)81-102}$

$T_\pi(MeV)$	$-W(MeV)$	f_1	f_2	f_3	$f_4(s/p)$
300	48	.532	.735	.51	.34/.79
280	54	.526	.707	.47	.33/.77
260	63	.516	.667	.42	.32/.75
240	71	.508	.634	.38	.30/.73
220	77	.502	.608	.35	.29/.71
200	78	**.500**	**.602**	**.34**	**.29/.70**
180	71	.506	.624	.37	.30/.72
160	56	.520	.683	.44	.32/.75
140	43	.533	.739	.52	.34/.79
120	30	.546	.804	.62	.36/.83
100	20	.557	.858	.71	.39/.86
80	12	.566	.907	.81	.40/.88
60	7	.572	.940	.87	.41/.90
40	4	.576	.961	.91	.42/.91
20	2	.578	.974	.94	.43/.92

Results

- additional resonance's contributions to the present model can not dramatically change cross distributions in comparison with coupling changes in visible resonances
- rescattering mechanism fall out if we are going to reproduce $\pi\pi$ s-wave phase shifts with propagator proportional to $\frac{1}{\omega_{\pi\pi}^2 - m_\sigma(m_\sigma - i\Gamma_\sigma)}$
- cross section in $A(\gamma, 2\pi^0)A$ process depends on target isospin
- final state interaction under the distort wave impulse approximation strongly depends on the nuclear model i.e its direct application in double pion production is doubtful enough.

Conclusion

- The next step in $(\gamma, 2\pi^0)$ process understanding is in an extraction of 1/2,3/2-isospin components in intermediate states
- The work is supported by Dynasty foundation, TPU grant LRU-FTI-123-2014

Model

In non relativistic regime T-matrix is defined as

$$T = K + i\vec{\sigma} \cdot \vec{L} \quad (6)$$

K-non spin-flip part and $\vec{L}$ -spin flip part. $\hat{\sigma}$(Wigner-Eckart
normalized as:

$$\begin{aligned} \langle j'm'|\sigma^{[J]}_{j'j,M}|jm\rangle &= C^{j'm'}_{jmJM}, \text{if } j' \neq j \\ \langle jm|\sigma^{[J]}_{jj,M}|jm\rangle &= 2\sqrt{j(j+1)}C^{jm}_{jmJM} \end{aligned} \quad (7)$$

A_λ in position $W = M_R$ *Fix and Arenhövel*, $\Gamma_{N^* \to \pi N, \Delta\pi, \rho N, \sigma N}$.

Cross sections