EXTENDED SIEGERT THEOREM IN THE RELATIVISTIC INVESTIGATION OF THE DEUTERON PHOTODISINTEGRATION REACTION

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Photodisintegration of the deuteron - motivation:

- breakup reaction, includes effects of the bound state (deuteron), continuum states (np-pair)
- real photon - $q^2 = 0$, investigation of the off-shell behavior of nucleon form factors

Investigations of the deuteron photodisintegration:

- plane-wave relativistic impulse apporiximation (K.Yu. Kazakov, S.Eh. Shirmovsky, Phys.Rev.C63:014002,2001)
- effects of negative energy components in deuteron (K.Yu. Kazakov, D.V. Shulga, Phys.Rev.C65:064002,2002)
- relativistic contribution of the final state interaction (S.G. Bondarenko, V.V. Burov, K.Yu. Kazakov, D.V. Shulga, Phys.Part.Nucl.Lett.1:178-185,2004)
- effects of the two-particle current by using Siegert theorem (S.G. Bondarenko, V.V. Burov, K.Yu. Kazakov, D.V. Shulga, *in preparation*)

Let us consider the charge and current operators as a sum of n-particle operators:

$$\hat{\rho} = \sum_{n\geq 1} \hat{\rho}_{[n]}, \qquad \hat{\mathbf{j}} = \sum_{n\geq 1} \hat{\mathbf{j}}_{[n]},$$

Using the equation of current conservation in a form

$$\boldsymbol{\nabla} \cdot \hat{\mathbf{j}} + i[\hat{H}, \hat{\rho}] = 0,$$

one obtains the following decomposition on the n-particle operators

$$\boldsymbol{\nabla} \cdot \hat{\mathbf{j}}_{[1]} + i\left[\hat{T}_{[1]}, \hat{\rho}_{[1]}\right] \qquad (n=1)$$

$$+\, \boldsymbol{\nabla} \cdot \hat{\mathbf{j}}_{[2]} + i\left[\hat{T}_{[1]}, \hat{\rho}_{[2]}\right] + i\left[\hat{V}_{[2]}, \hat{\rho}_{[1]}\right] \qquad (n=2)$$

$$+\, ...$$

Applying the Siegert *ansatz* for the two-body system

$$\hat{\rho}_{[2]} = 0$$

one obtain

$$\boldsymbol{\nabla} \cdot \left(\hat{\mathbf{j}}_{[1]} + \hat{\mathbf{j}}_{[2]}\right) + i\left[\hat{T}_{[1]}, \hat{\rho}_{[1]}\right] + i\left[\hat{V}_{[2]}, \hat{\rho}_{[1]}\right] = 0$$

After the Fourier transformation and some algebra the equation

$$\boldsymbol{\nabla}\cdot\hat{\mathbf{j}}+i\left[\hat{H},\hat{\rho}_{[1]}\right]=0$$

can be rewritten in a limit $\mathbf{q}\rightarrow 0$ as original Siegert theorem

$$\hat{\mathbf{j}}(\mathbf{q}=0)=i[\hat{H},\hat{\mathbf{D}}]=\dot{\hat{\mathbf{D}}}$$

with electric dipole moment

$$\mathbf{D}=\sum e_i\mathbf{x}_i.$$

The transversal components are not included into consideration.

To take into account the transversal components of the current, one need to use the following expression

$$(1 + \mathbf{q} \cdot \boldsymbol{\nabla}_{\mathbf{q}})\hat{\mathbf{j}}(\mathbf{q}) = -i\boldsymbol{\nabla}_{\mathbf{q}}\dot{\hat{\rho}}(\mathbf{q}) - 2i\mathbf{q} \times \hat{\boldsymbol{\mu}}(\mathbf{q}).$$

After applying some algebra one can obtain for the current operator

$$\hat{\mathbf{j}}(\mathbf{q}) = \hat{\mathbf{j}}_C(\mathbf{q}) + \hat{\mathbf{j}}_M(\mathbf{q}),$$

where the generalized electric dipole and magnetic moments are introduced

$$\hat{\mathbf{j}}_C(\mathbf{q}) = i[\hat{H}, \hat{\mathbf{D}}(\mathbf{q})] \qquad \hat{\mathbf{j}}_M(\mathbf{q}) = -i\mathbf{q} \times \hat{\mathbf{M}}(\mathbf{q})$$

$$\hat{\mathbf{D}}(\mathbf{q}) = -i\int_0^1 \frac{d\lambda}{\lambda}\,\boldsymbol{\nabla}_{\mathbf{q}}\,\hat{\rho}_{(1)}(\lambda\mathbf{q}) \qquad \hat{\mathbf{M}}(\mathbf{q}) = -i\int_0^1 d\lambda\,\boldsymbol{\nabla}_{\mathbf{q}} \times \hat{\mathbf{j}}_{(1)}(\lambda\mathbf{q})$$

This is the extended Siegert theorem.

To find expression for the amplitude of the deuteron photodisintegration

$$\langle \mathbf{P}_f, f | \hat{S} | \mathbf{P}_i, i \rangle = \hat{A}^\mu (P_f - P_i) \langle \mathbf{P}_f, f | \hat{j}^\mu(\mathbf{0}) | \mathbf{P}_i, i \rangle,$$

with

$$\hat{A}^\mu (P_f - P_i) = \int d^4x e^{i(P_f - P_i)\cdot x} \hat{A}^\mu (x)$$

Using Foldy identity for the Fourier transformed expressions

$$\int d^3R \, e^{i\mathbf{KR}} \mathbf{j}(\mathbf{R}) =$$

$$- \int d^3R \int_0^1 d\lambda \, [e^{i\lambda \mathbf{KR}} \mathbf{R} \, (\boldsymbol{\nabla} \cdot \mathbf{j}(\mathbf{R})) + i\lambda e^{i\lambda \mathbf{KR}} \mathbf{K} \times (\mathbf{R} \times \mathbf{j}(\mathbf{R}))],$$

the amplitude becomes

$$\left\langle \mathbf{P}_f, f \middle| \hat{S} \middle| \mathbf{P}_i, i \right\rangle = (2\pi)^4 \delta^{(4)}(P_f - P_i - q) T_{fi}$$

with

$$T_{fi} = -\left\langle 0_\gamma \middle| \hat{\mathbf{E}}(0) \middle| 1_\gamma^q \right\rangle \cdot \mathbf{D}_{fi}(\mathbf{K}) - \left\langle 0_\gamma \middle| \hat{\mathbf{H}}(0) \middle| 1_\gamma^q \right\rangle \times \mathbf{M}_{fi}(\mathbf{K}),$$

and photon matrix elements

$$\left\langle 0_\gamma \middle| \hat{\mathbf{E}}(0) \middle| 1_\gamma^q \right\rangle = \frac{i}{\sqrt{2E_\gamma}} \left(E_\gamma \boldsymbol{\varepsilon} - \mathbf{q}\, \varepsilon_0 \right),$$

$$\left\langle 0_\gamma \middle| \hat{\mathbf{H}}(0) \middle| 1_\gamma^q \right\rangle = \frac{i}{\sqrt{2E_\gamma}}\, \mathbf{q} \times \boldsymbol{\varepsilon}.$$

The generalized electric dipole and magnetic moments are introduced in terms of matrix elements of 1-particle current

$$\hat{\mathbf{D}}(\mathbf{q}) = -i \int\limits_0^1 \frac{d\lambda}{\lambda}\, \boldsymbol{\nabla}_{\mathbf{q}} \left\langle \mathbf{P}_i + \lambda\mathbf{q}, f \middle| \hat{\rho}_{(1)}(0) \middle| \mathbf{P}_i, i \right\rangle,$$

$$\hat{\mathbf{M}}(\mathbf{q}) = -i \int\limits_0^1 d\lambda\, \boldsymbol{\nabla}_{\mathbf{q}} \times \left\langle \mathbf{P}_i + \lambda\mathbf{q}, f \middle| \hat{\mathbf{j}}_{(1)}(0) \middle| \mathbf{P}_i, i \right\rangle.$$

Finally

$$T_{fi} = \frac{-1}{\sqrt{2E_\gamma}} \left[E_\gamma \int\limits_0^1 \frac{d\lambda}{\lambda} \left(\boldsymbol{\varepsilon} \cdot \boldsymbol{\nabla}_{\mathbf{q}}\right) \rho_{(1)}(\lambda\mathbf{q}) + \int\limits_0^1 d\lambda \left(\mathbf{q} \times \boldsymbol{\varepsilon}\right) \cdot \left(\boldsymbol{\nabla}_{\mathbf{q}} \times \mathbf{j}_{(1)}(\lambda\mathbf{q})\right) \right]$$

$$
\begin{aligned}
j_\mu^{(1)}(\boldsymbol{q}) &= \left\langle \mathbf{K}+\lambda\mathbf{q}, f \left| \hat{j}_\mu(0) \right| \mathbf{K}, i \right\rangle = \\
&= Sp\left\{ \bar{\chi}^{(0)}_{Sm_S}(\mathbf{p})\Gamma_\mu^{(1)}\left(q_\lambda\right)\Lambda_{\lambda\mathbf{q}}G^{(1)}\left(\mathcal{L}^{-1}_{\lambda\mathbf{q}}\left(\frac{K-q_\lambda}{2}+p\right)\right)\right. \\
&\qquad \left. \Gamma_{m_d}\left(\mathcal{L}^{-1}_{\lambda\mathbf{q}}\left(p-\frac{q_\lambda}{2}\right);K^{(0)}\right)\Lambda^{-1}_{\lambda\mathbf{q}}\right\} \\
&+(-1)^{I+1}Sp\left\{ \bar{\chi}^{(0)}_{Sm_S}(-\mathbf{p})\Gamma_\mu^{(2)}\left(q_\lambda\right)\Lambda_{\lambda\mathbf{q}}G^{(2)}\left(\mathcal{L}^{-1}_{\lambda\mathbf{q}}\left(\frac{K-q_\lambda}{2}-p\right)\right)\right. \\
&\qquad \left. \Gamma_{m_d}\left(\mathcal{L}^{-1}_{\lambda\mathbf{q}}\left(-p-\frac{q_\lambda}{2}\right);K^{(0)}\right)\Lambda^{-1}_{\lambda\mathbf{q}}\right\}
\end{aligned}
$$

Here $\mathcal{L}^{\pm 1}_{\mathbf{q}}$ corresponds to Lorenz transformation from the center of mass system to the laboratory system:

$$
k_0 = \frac{1}{M_d}\left(E_d k_0' \mp \mathbf{q}\cdot\mathbf{k}'\right) \qquad \mathbf{k} = \mathbf{k}' + \frac{\mathbf{q}}{M_d}\left(\frac{\mathbf{q}\cdot\mathbf{k}'}{M_d+E_d} \mp k_0'\right),
$$

and BS vertex functions for the deuteron are transformed as

$$
\Lambda^{\pm 1} = \sqrt{\frac{E_d+M_d}{2M_d}}\left(1 \mp \frac{\gamma^0\boldsymbol{\gamma}\cdot\mathbf{q}}{E_d+M_d}\right)
$$

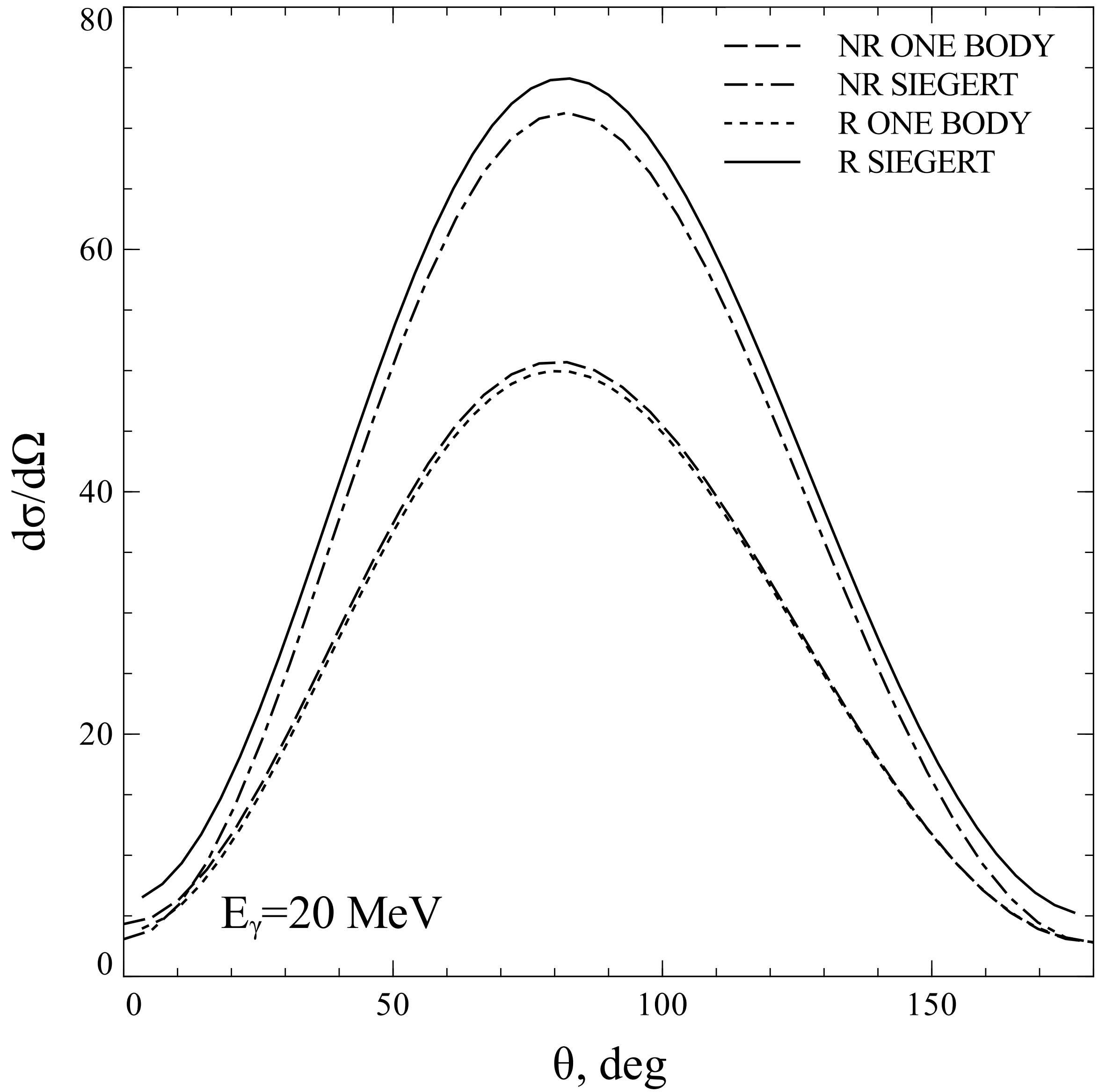
BS amplitude for the np-pair

$$\chi^{(0)}_{Sm_s}(p_f, P_{f(0)}) = \sum_{m_1 m_2} C^{Sm_S}_{\frac{1}{2}m_1 \frac{1}{2}m_2} u^{(1)}_{m_1}(\hat{\mathbf{p}})\, u^{(2)}_{m_2}(-\hat{\mathbf{p}})\,.$$

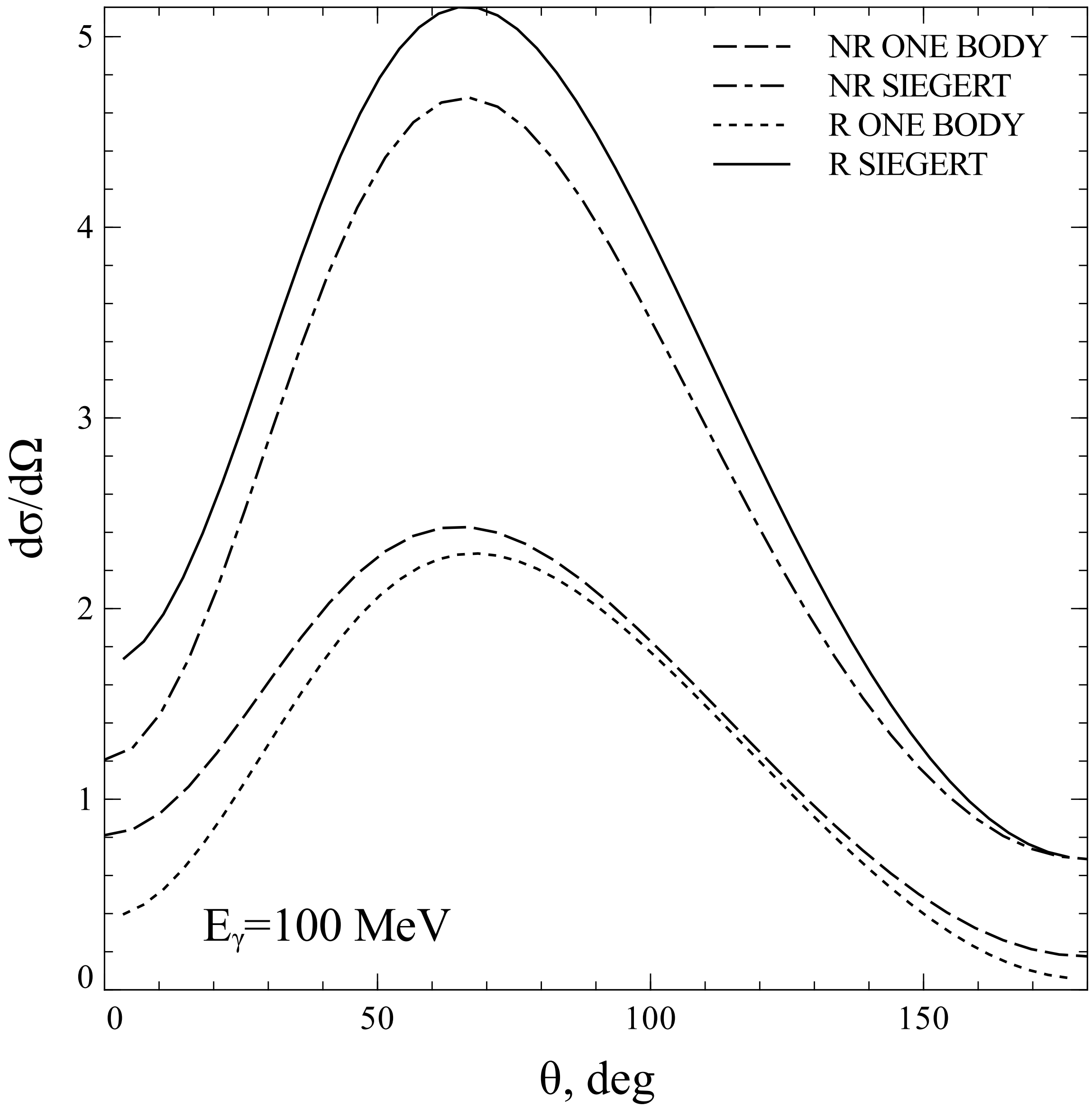
The deuteron BS vertex function $\Gamma_{m_d}(k, K_i)$ calculated by using the Graz II kernel separable kernel.

The γNN electromagnetic vertex is in on-mass-shell form

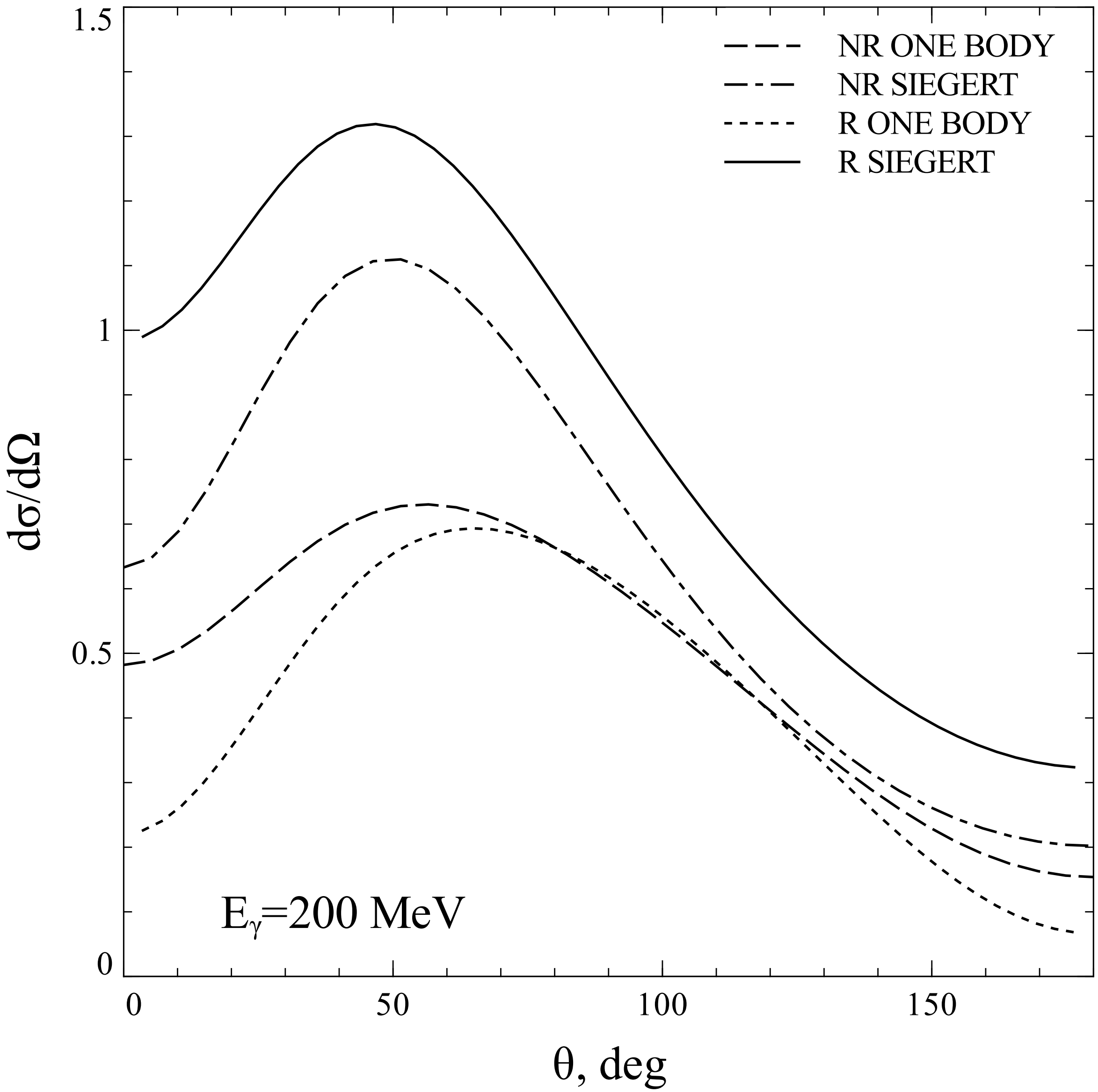
$$\Gamma^{(1,2)}_{\mu} = \gamma^{(1,2)}_{\mu} F^{(1,2)}_{1} - 1/4m(\gamma_\mu \hat{q} - \hat{q}\gamma_\mu)^{(1,2)} F^{(1,2)}_{2}.$$



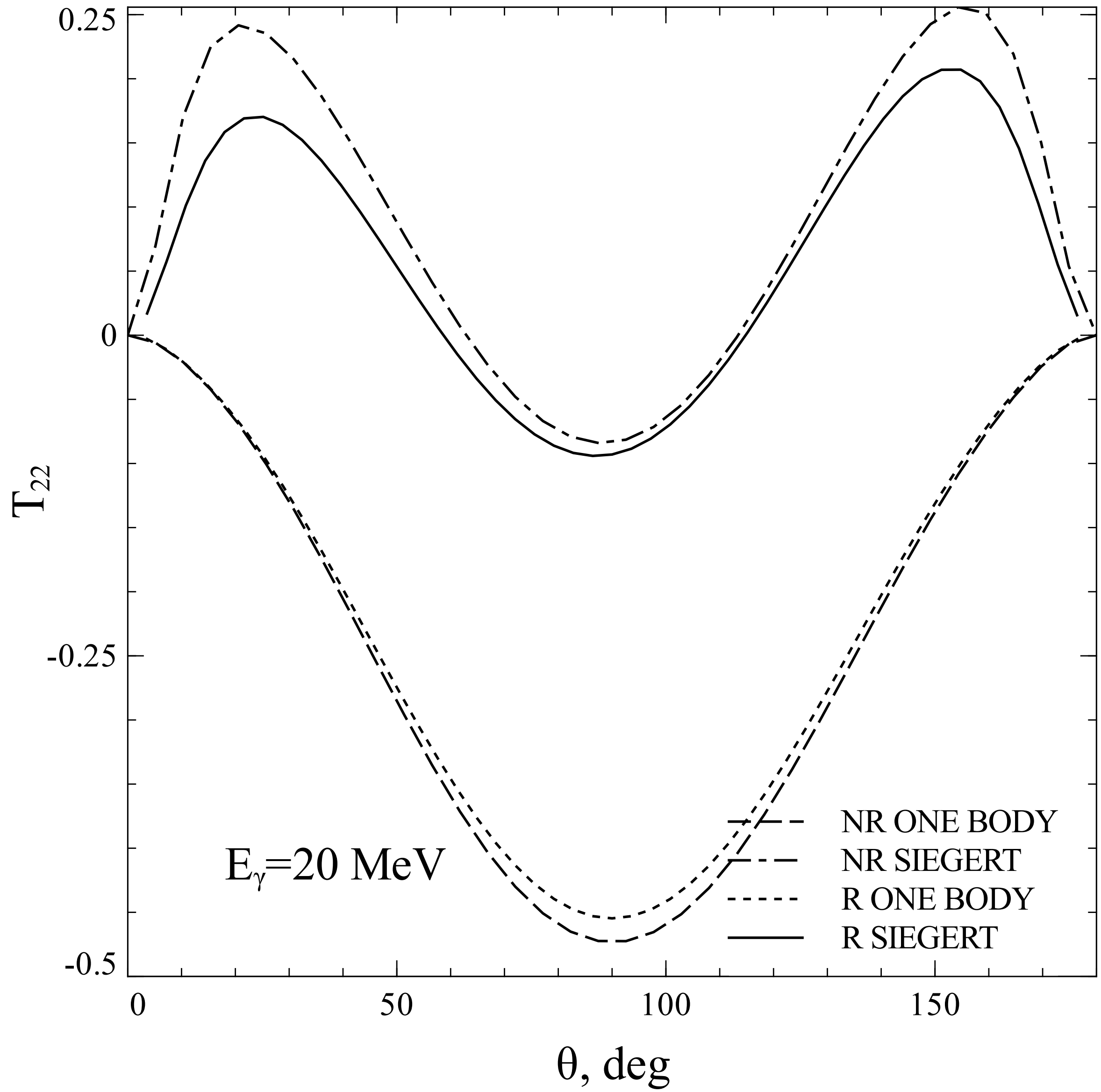
Angular distribution with $E_\gamma = 20$ MeV



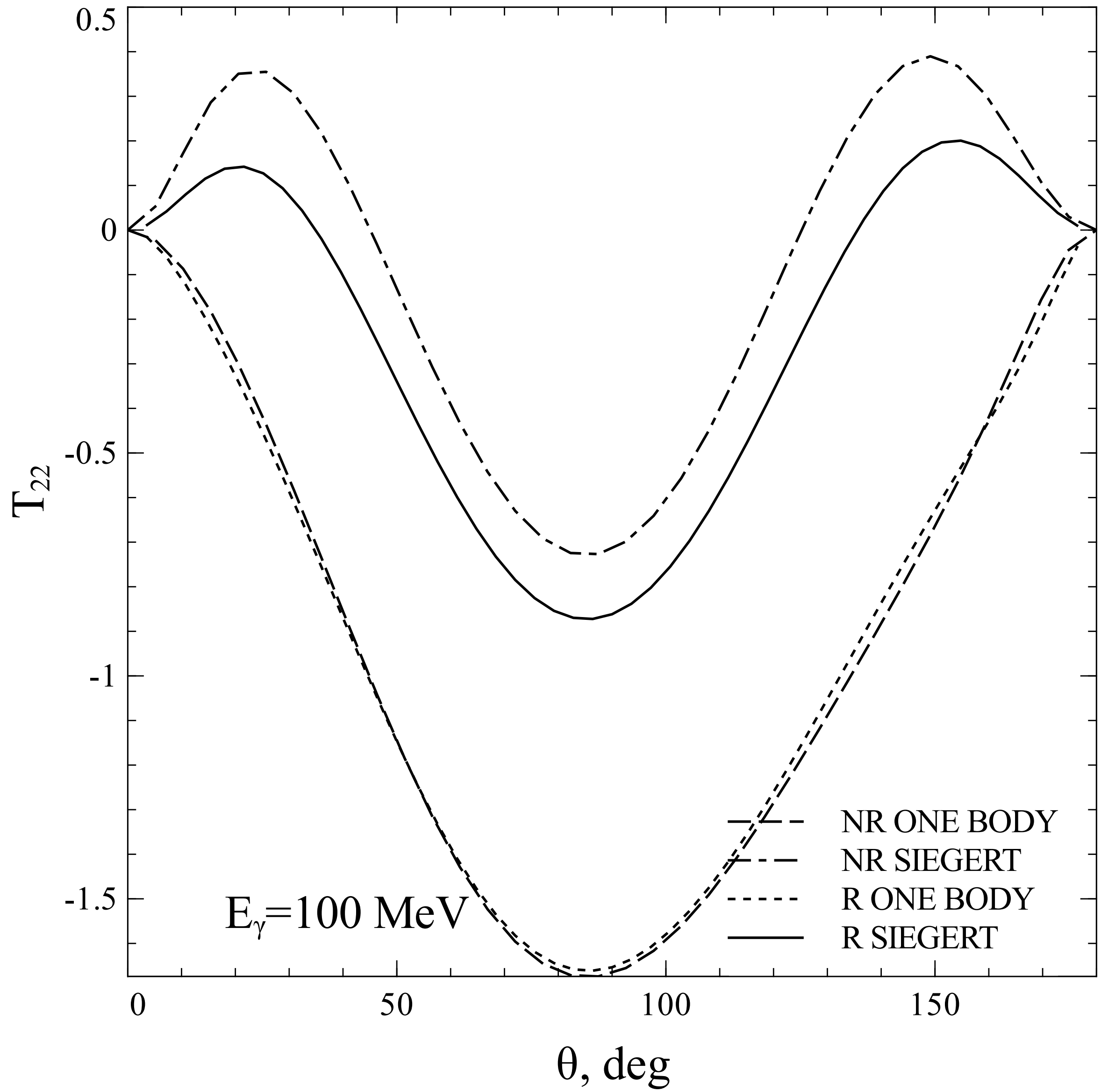
Angular distribution with $E_\gamma = 100$ MeV



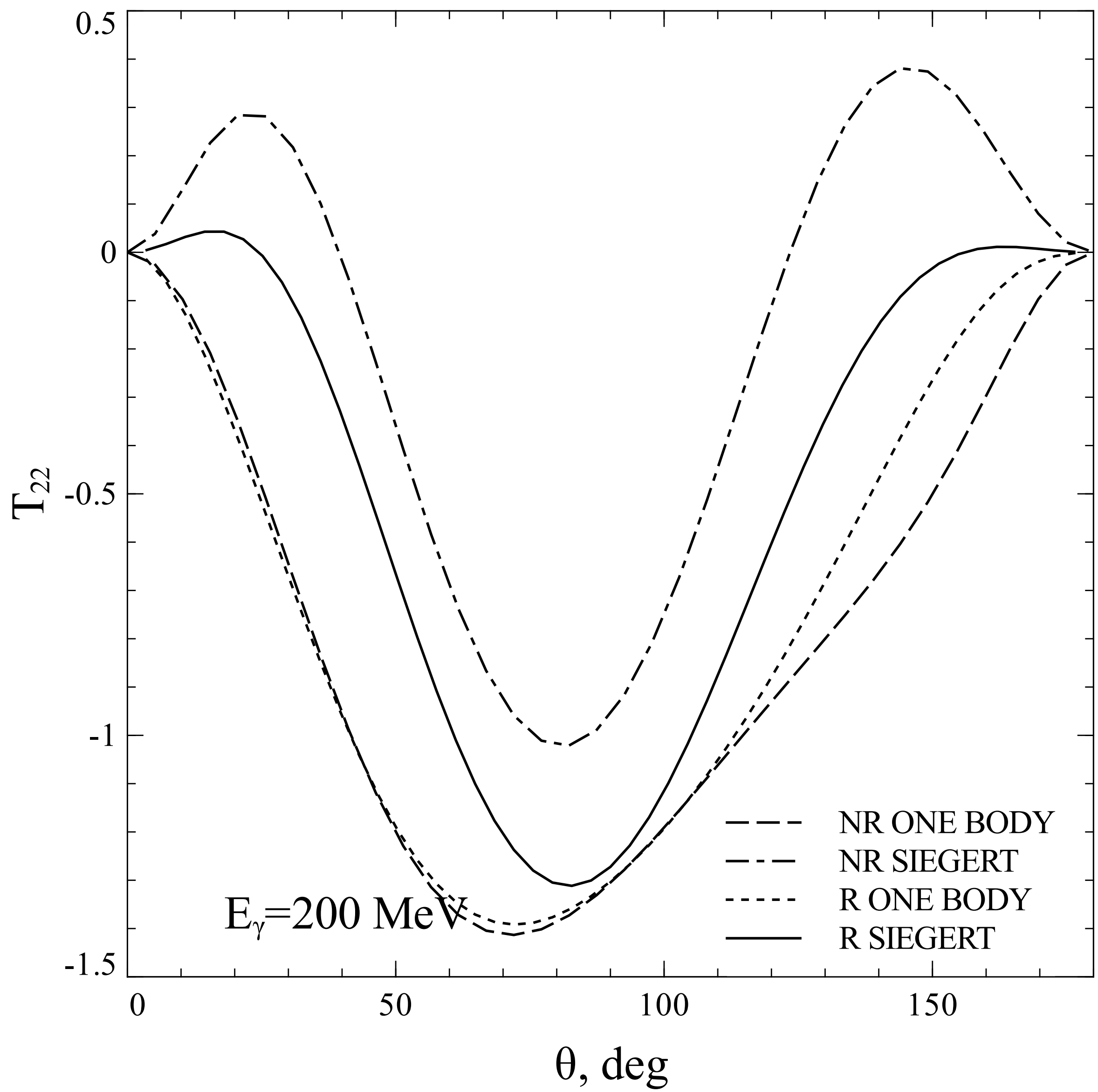
Angular distribution with $E_\gamma = 200$ MeV



Component T_{22} of the deuteron tensor assymetry with $E_\gamma = 20$ MeV



Component T_{22} of the deuteron tensor assymetry with $E_\gamma = 100$ MeV



Component T_{22} of the deuteron tensor assymetry with $E_\gamma = 200$ MeV

Conclusion:

- effects of the two-particle current are investigated for reaction of the deuteron photodisintegration by applying the extended Siegert theorem;
- the contributions are found to be positive and rather large for the cross section and deuteron tensor assymetry.