Isovector giant dipole and quadrupole resonances, and Direct+Semidirect photonucleon reactions.

M. H. Urin

(MEPhI, KVI)

Plan

1. Aims
2. Methods
3. Results
4. Summary

Collaborators:

M.L. Gorelik (MEPhI)
I.V. Safonov (MEPhI)
B.A. Tulupov (INR RAN)

1. Aims

- In the main, we attempt to describe in a semimicroscopic way the partial DSD and SD photonucleon reactions in the vicinity of the IVGDR and IVGQR in medium- and heavy-mass spherical nuclei.

- Up to now only the phenomenological DSD model is used. The SD (γp)-reactions via $\mathrm{IVGDR}_{>}$ (the specific double GR) aren't described.

- To reach the main aim, we check abilities of the approach and specify model parameters by description of photoabsorption in the vicinity of the IVGDR.
  Then the gross properties of the IVGDR multiplet, of the IVGQR and, that is most important, the DSD and SD photonucleon reactions are described without use of adjustable parameters.

- Schematic representation of the IVGDR multiplet (separate page)

- The operators $V(x)=\sum_a V(x_a)$ generating the excitations:

$$V_L^{(i)}(x)=V_L(r)Y_{LM}(\vec{n})\tau^{(i)}\ , \qquad \tau^{(i)}=\left\{\tau^{(+)},\tau^{(3)},\tau^{(-)}\right\}$$

- DSD (γn)-, ($n\gamma$)-, (γp)-reactions via $IVGDR_<$.

  Specific SD (γp)-reactions via $IVGDR_>$.

  Asymmetry (relatively 90º) of the (γn)-reaction differential cross section is due to interference of the amplitudes of the DSD(1^-)- and SD(2^+)-reactions in the vicinity of the IVGQR.

2. Methods

◆ Semimicroscopic approach is based on the continuum-RPA method and a phenomenological treatment of the spreading effect.

◆ Input quantities:

(i) a phenomenological mean field and the momentum-independent Landau-Migdal *p*-*h* interaction bound by some selfconsistency conditions (for the problems under consideration the isospin selfconsistency is most important), the mean-field and interaction parameters are found from independent data;

(ii) the energy- and radial-dependent smearing parameter directly introduced into the CRPA eqs. (in spirit of the optical model for the nucleon-nucleus scattering);

(iii) the "velocity" parameter, used to take effectively into account contribution of the isovector momentum-dependent forces in formation of the isovector (nonspin-flip) GRs.

2. Methods (continuation)

◆ Quantities calculated in the CRPA for a given probing operator $V(x)$ (very schematically):

(i) strength function:

$$S_V(\omega)=-\frac{1}{\pi}\mathrm{Im}\left(\left(V(x)A(x,x',\omega)V^{eff}(x,\omega)\right)\right)=-\frac{1}{\pi}\mathrm{Im}$$

free *p-h* propogator effective operator

$$V^{eff}(x,\omega)=V(x)+F\left(A(x,x',\omega)V^{eff}(x',\omega)\right)\rightarrow$$

p-h interaction

(ii) transition density:

$\rho(x,\omega)$ is defined by $S_V(\omega)=\left|\left(V(x)\rho(x,\omega)\right)\right|^2$;

(iii) DSD-reaction amplitude:

$M_c(\omega)$: $\left(\Psi_{cont}(x)V^{eff}(x,\omega)\Psi_{bound}(x)\right)\rightarrow$

set of the reaction-channel quantum numbers

$\sum_c\left|M_c(\omega)\right|^2=S_V(\omega)$ - the unitary condition;

(iv) energy-averaged quantities with taking the spreading effect into account:

$$\bar{S}(\omega)=S(\omega+iI/2), \qquad \bar{\rho}(x,\omega)=\rho(x,\omega+iI/2),$$
$$\bar{M}_c(\omega)=M_c(\omega+iI/2).$$

(v) effective accounting for contribution of isovector momentum-dependent forces by scaling transformation:

$$\tilde{S}(\omega)=\frac{1}{1+k_L}\bar{S}\left(\frac{\omega}{1+k_L}\right)$$

transformation changes *EWSR*, but doesn't change *NEWSR* (see below)

Within the approach all observables are calculated with the use of the properly modified CRPA eqs.

2. Methods (continuation)

◆ Probing operators and sum rules (in the abcence of m.-d. forces):

$$L=1 \qquad V_1^{(i)}(x)=rY_{1M}\tau^{(i)}\ ; \qquad \tau^{(i)}=\left\{\tau^{(+)},\tau^{(3)},\tau^{(-)}\right\}.$$

$$VT_3=0 \qquad EWSR_1^{(3)}=\int\omega S_1^{(3)}(\omega)d\omega=\frac{3}{8\pi}\frac{\mathrm{h}^2}{m}A.$$

Overtone (isovector partner of the ISGDR):

$$V_{1,\mathrm{ov}}^{(3)}(x)=r(r^2-\eta)Y_{1M}\tau^{(3)}\ ; \qquad \eta\rightarrow\left(V_{1,\mathrm{ov}}^{(3)}(x)\rho_1^{(3)}(x,\omega_{\mathrm{m}})\right)=0.$$

$$EWSR_{1,\mathrm{ov}}^{(3)}=\frac{1}{8\pi}\frac{\mathrm{h}^2}{m}A\left\{11\left\langle r^4\right\rangle-10\eta\left\langle r^2\right\rangle+3\eta^2\right\}$$

$$\Delta T_3=\pm1$$

$$NEWSR_1=\int S_1^{(-)}(\omega)d\omega-\int S_1^{(+)}(\omega)d\omega=\int r^4n^{(-)}(r)dr$$

$$EWSR_1=\int\omega S_1^{(-)}(\omega)d\omega+\int\omega S_1^{(+)}(\omega)d\omega=EWSR_1^{(3)}+\int r^4n^{(-)}(r)U_C(r)dr$$

$$L=2, \quad \Delta T_3=0$$

$$V_2^{(3)}(x)=r^2Y_{2M}\tau^{(3)}, \qquad EWSR_2^{(3)}=\frac{5}{4\pi}\frac{\mathrm{h}^2}{m}\left\langle r^2\right\rangle.$$

◆ <u>Isospin splitting of the IVGDR</u>$^{(3)}$ in not too-heavy nuclei

$T_{>} = T + 1$

"$\left| IVGDR_{>}^{(3)} \right\rangle = \frac{1}{2T+2} \mathrm{T}^{(-)} \left| IVGDR_{1}^{(+)} \right\rangle$",

$S_{>}^{(3)}(\omega) = \frac{4}{2T+2} S_{1}^{(+)}(\omega - \Delta_{C});$

Pauli blocking Coulomb displacement energy

$EWSR_{>}^{(3)} = \int \omega S_{>}^{(3)}(\omega) d\omega \equiv y_{>} \cdot EWSR_{1}^{(3)}$

$T_{<} = T \qquad \left(y_{>} << 1 \right)$

$EWSR_{<}^{(3)} = \left(1 - y_{>}\right) EWSR_{1}^{(3)} \rightarrow \; S_{<}^{(3)}(\omega); \; \left(1 - y_{>}\right) S_{1}^{(3)}(\omega)$

◆ <u>Isovector momentum-dependent forces</u> lead to:

$EWSR_{L}^{(3)} \rightarrow EWSR_{L}^{(3)} = \left(1 + k_{L}\right) EWSR_{L}^{(3)};$ scaling

NEWSR is independent of the forces. transformation

Below the properly modified quantities are only considered.

◆ Cross sections of simplest photonuclear reactions

(i) E1-photoabsorption

$$V^{(E1)}=-\frac{1}{2}V_1^{(3)};\ B=\frac{16\pi^3}{3}\frac{e^2}{\hbar c}$$

$$\sigma_a^{<}=B\omega S^{(E1)}(\omega)\left(1-y_{>}\right);\ \sigma_a^{>}=\frac{B\omega}{N-Z+2}S_1^{(+)}(\omega-\Delta_C)$$

$\sigma_a(\omega)$ Ђ $\sigma_a^{\exp}\rightarrow I,k_1$ are adjusted.

(ii) DSD (γ*n*)- and (*n*γ)-reactions via the IVGDR$_<$

(bound by the detailed balance principle)

$$\frac{d\sigma_\mu^{<}(\omega,\theta)}{d\Omega}=\frac{1}{4\pi}\sigma_\mu^{<}(\omega)\left(1+a_2(\omega)P_2(\cos\theta)\right);$$

$$\left[M_{c(\mu)}^{(E1)},M_{c'(\mu)}^{(E1)}\right]$$

$$\sigma_\mu^{<}(\omega)=B\omega\sum_c\left|M_{c(\mu)}^{(E1)}(\omega)\right|^2\left(1-y_{>}\right)$$

(iii) SD (γ*p*)-reaction via IVGDR$_>$ (specific double GR)

$$\sigma_\mu^{>}(\omega)=B\omega\sum_c\left|M_{c(\mu)}^{(E1)}(\omega)\right|^2;\ M_{c(\mu)}^{(E1)}(\omega)\rightarrow$$

$$\frac{V^{(+)eff}(\omega-\Delta_C)}{\sqrt{N-Z+2}},\quad \mathrm{v}_{IAS}^{tr}=\frac{1}{\sqrt{N-Z+2}}\mathrm{v}$$

symmetry potential

(iv) Asymmetry (relative 90°) of the (γ*n*)- and (*n*γ)-reaction differential cross sections in the vicinity of the IVGQR[3]

$$V^{(E1)} \rightarrow M_c^{(E1)}(\omega) \rightarrow (DSD);$$

$$V^{(E2)}(x) = \frac{1-\tau^{(3)}}{2} r^2 Y_{2\mathrm{M}} \rightarrow M_c^{(E2)}(\omega) \rightarrow (SD)$$

$$\frac{d\sigma_\mu(\omega,\theta)}{d\Omega} = \sum_{L,L'=1,2;N=0-4} A_N^{LL'}(\omega) P_N(\cos\theta)$$

$$\left[M_{c(\mu)}^{(E1)}(\omega), M_{c'(\mu)}^{(E2)}(\omega) \right]$$

terms with $N = 1,3$ are due to interference of $M^{(E1)}, M^{(E2)}$

$$\alpha_{E_x}(\omega,\theta_1) = \frac{\sum_{\mu\in E_x} \frac{d\sigma_\mu^{[-]}}{d\Omega}}{\sum_{\mu\in E_x} \frac{d\sigma_\mu^{[+]}}{d\Omega}}; \qquad \theta_1 = 55^{\mathrm{o}},\ \mathrm{P}_2(\theta_1) = \mathrm{P}_2(\pi\text{-}\theta_1);\ 0$$

$$d\sigma_\mu^{[\mathrm{m}]} = d\sigma_\mu(\theta_1)\,\mathrm{m}\,d\sigma_\mu(\pi-\theta_1)$$

3. Results (^{48}Ca, ^{90}Zr, ^{140}Ce, ^{208}Pb)

- $E1$-photoabsorption

  $\sigma_a(\omega)$ (Fig. 1)

  In the following → no new parameters.

- Gross properties of the IVGDR multiplet

(i) IVGDR$^{(3)}$: $\rho_1^{(3)}(r,\omega_{\rm m})$ (Fig. 2)

(ii) IVGDR$^{(3)}$2 (^{208}Pb): $\omega S_{1,\rm ov}^{(3)}(\omega)$, $\rho_{1,\rm ov}^{(3)}(r,\omega_{\rm m})$ (Figs. 3,4)

(iii) IVGDR$^{(\rm m)}$ (^{90}Zr): $S_1^{(\rm m)}(\omega)$ (Fig. 5)

$\omega_{\rm m}^{(\rm m)}$ Ђ $\omega_{\rm m,exp}^{(\rm m)}$ (Table 1)

(iv) IVGDR$_{>}^{(3)}$

$\sigma_a^{>,<}(\omega)$ (^{90}Zr, Fig. 6); $\omega_{\rm m}^{>}$ (Table 1)

Isolated $T_{>}$ 1^{-}-resonances (Table 2)

(iv) IVGQR$^{(3)}$ (^{208}Pb): $S_2^{(3)}(\omega)$; $\rho_2^{(3)}(r,\omega_{\rm m})$ (Figs. 7,8)

- DSD photoneutron reactions in the vicinity of the IVGDR$^{(3)}$

  ^{208}Pb(γn_μ)-reaction cross sections (calculated) (Fig. 9)

  $(n\,\gamma_\mu)$, $\dfrac{d\sigma_\mu(\varepsilon_n,\theta=90°)}{d\Omega}$ (Figs. 10,11)

- DSD(via $\mathrm{IVGDR}_{<}^{(3)}$) + SD(via $\mathrm{IVGDR}_{>}^{(3)}$) (γp_0)-reaction

  ^{90}Zr(γp_0) (Fig. 12)

- Asymmetry of the ^{208}Pb(γn)-reaction and ^{208}Pb($n\,\gamma_0$)-reaction differential cross sections in the vicinity of the $\mathrm{IVGQR}^{(3)}$

  $\alpha_{E_x}(\omega,55°)$ $E_x < 2$ MeV (Fig. 13a) target ^{nat}Pb

  $E_x < 4$ MeV (Fig. 13b)

  $\alpha_{n\gamma_0}(\omega,55°)$ (Fig. 14)

4. Summary

We realized the main aim of the presented work: semimicroscopic description of

(i) the DSD phootneutron reactions, accompanied by excitation of the $IVGDR_{<}$;

(ii) the direct proton decay of the $IVGDR_{>}$ components;

(iii) the asymmetry (relative 90°) of the of the (γn)- and ($n\gamma$)-reaction differential cross sections in the vicinity of the $IVGQR^{(3)}$.

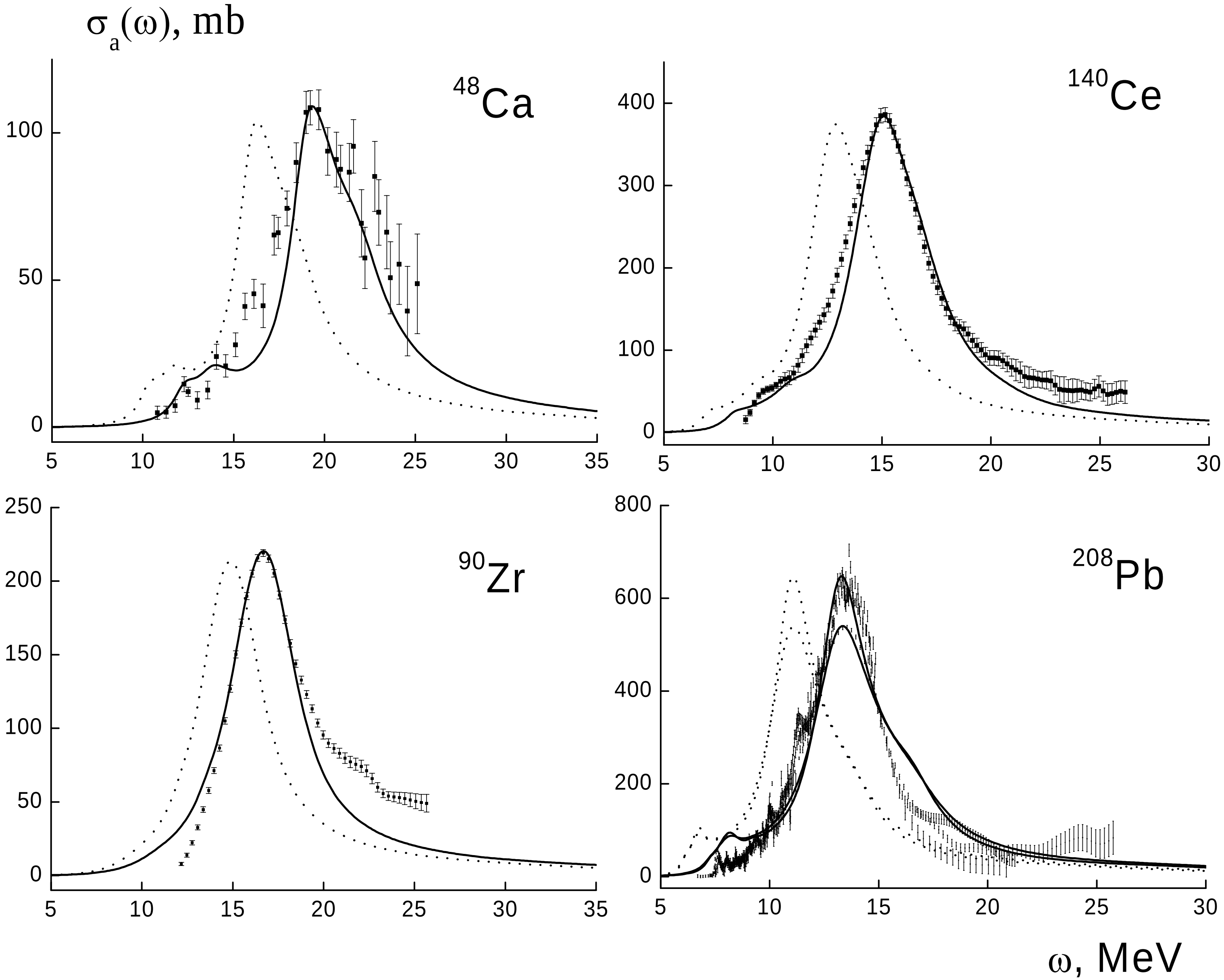
Abilities of the approach in description od the main properties of the IVGDR multiplet (including the IVGDR2) and the IVGQR have been also checked.

Table 1. Calculated and experimental energies (in MeV) of the $IVGDR^{(\pm)}$, $IVGDR^{(3)}_{>}$. Total neutron branching ratios for the $IVGDR^{(3)}$.

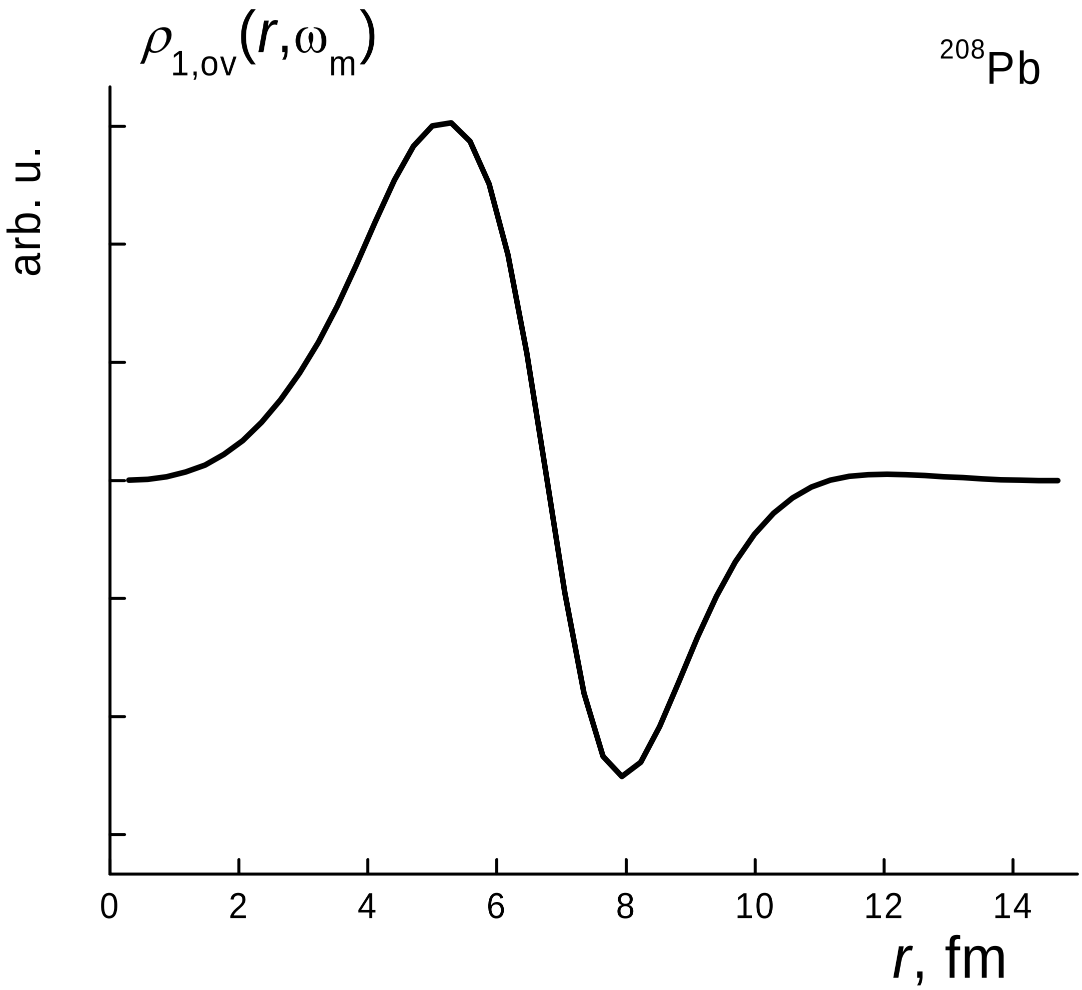
	$\omega^{(-)}_{m,<}$		$\omega^{(+)}_{m}$		$\omega^{(3)}_{m,>}$		b^{tot}_{n}, %
	calc.	exp.	calc.	exp.	calc.	exp.	calc.
^{48}Ca	21.3	-	18.5	-	26.3	25.8	21.4
^{90}Zr	25.15	25.4(0.5)	7.55	10.4(1.8)	20.1	21.2	4.1
^{140}Ce	24.4	(25.3)	no prominent				9.9
^{208}Pb	26.1	26.6(0.5)	giant resonance				8.4

Table 2. Parameters of the $T_{>}$ 1^{-}-resonance, studied via the (*e,e'p*)- reaction (Richter *et al*., 1997)

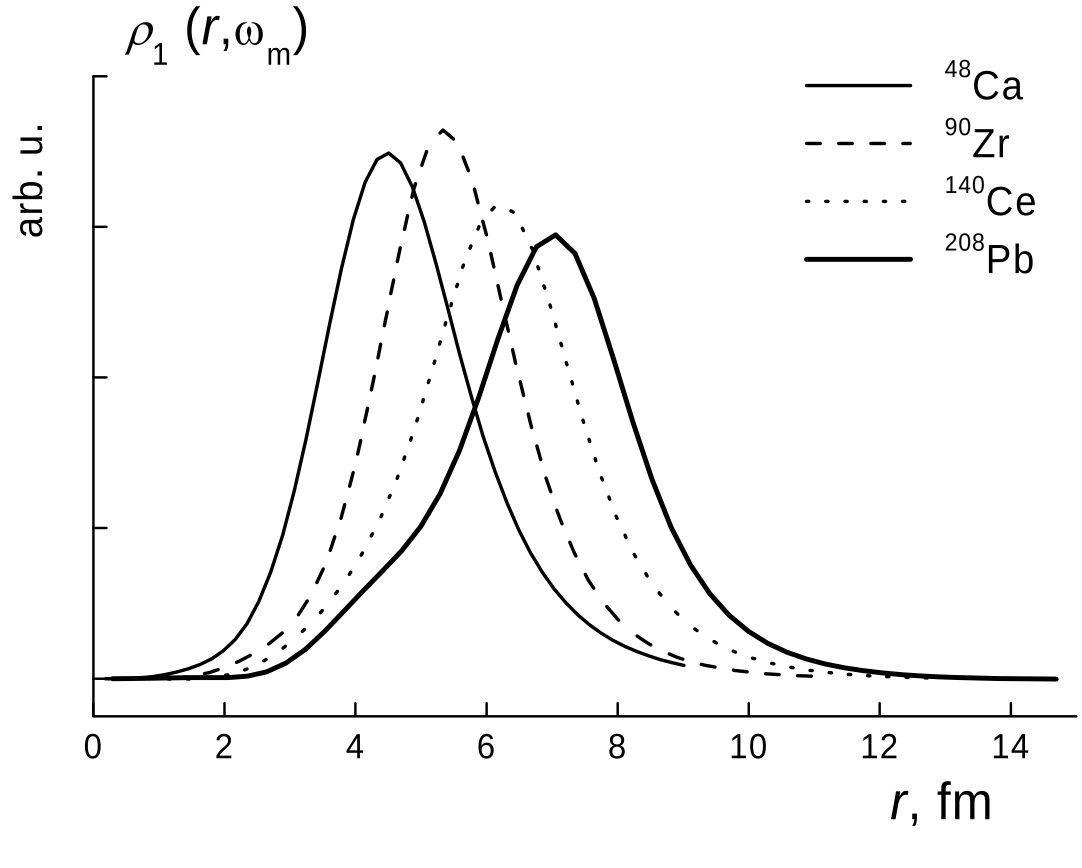
ω_r, MeV		Γ_{γ_0}, eV		Γ_{p_0}, keV		Γ_{p_0}, keV	
calc.	exp.	calc.	calc.	calc.	exp.	exp.	exp.
16.0	16.28	170	108(35)	55	54(18)	25	20(5)
16.5	-	160	-	7	-	150	-
17.0	-	318	-	14	-	70	-



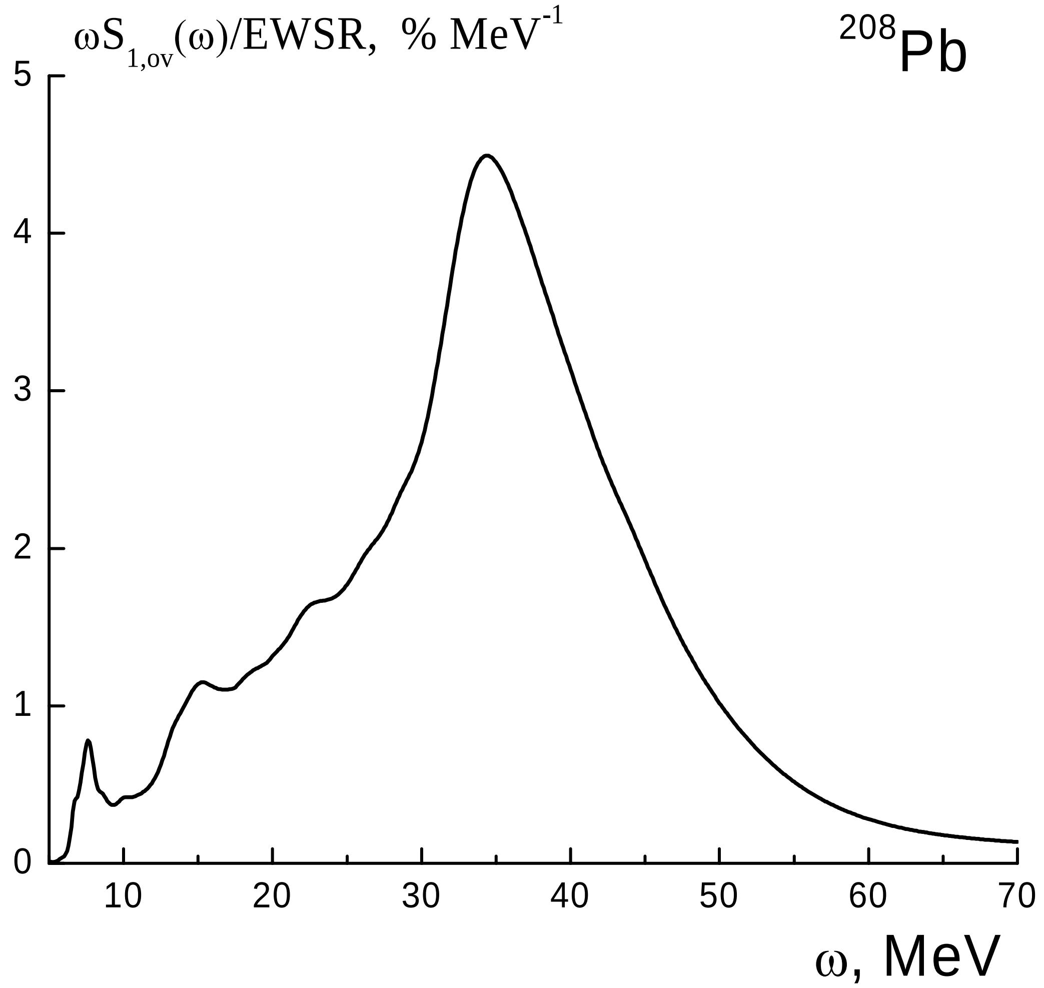
σ_a(ω), mb
48Ca
140Ce
90Zr
208Pb
ω, MeV



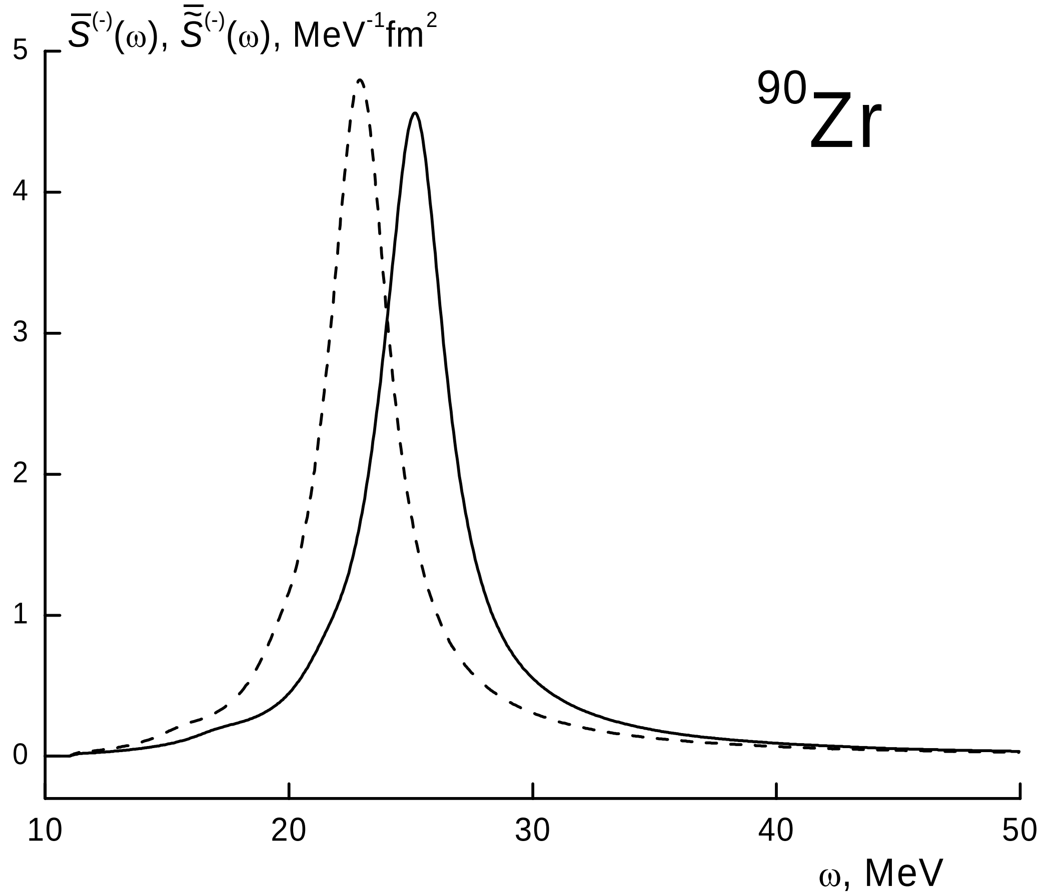
ρ1,ov(r,ωm)
208Pb
arb. u.
0
2
4
6
8
10
12
14
r, fm



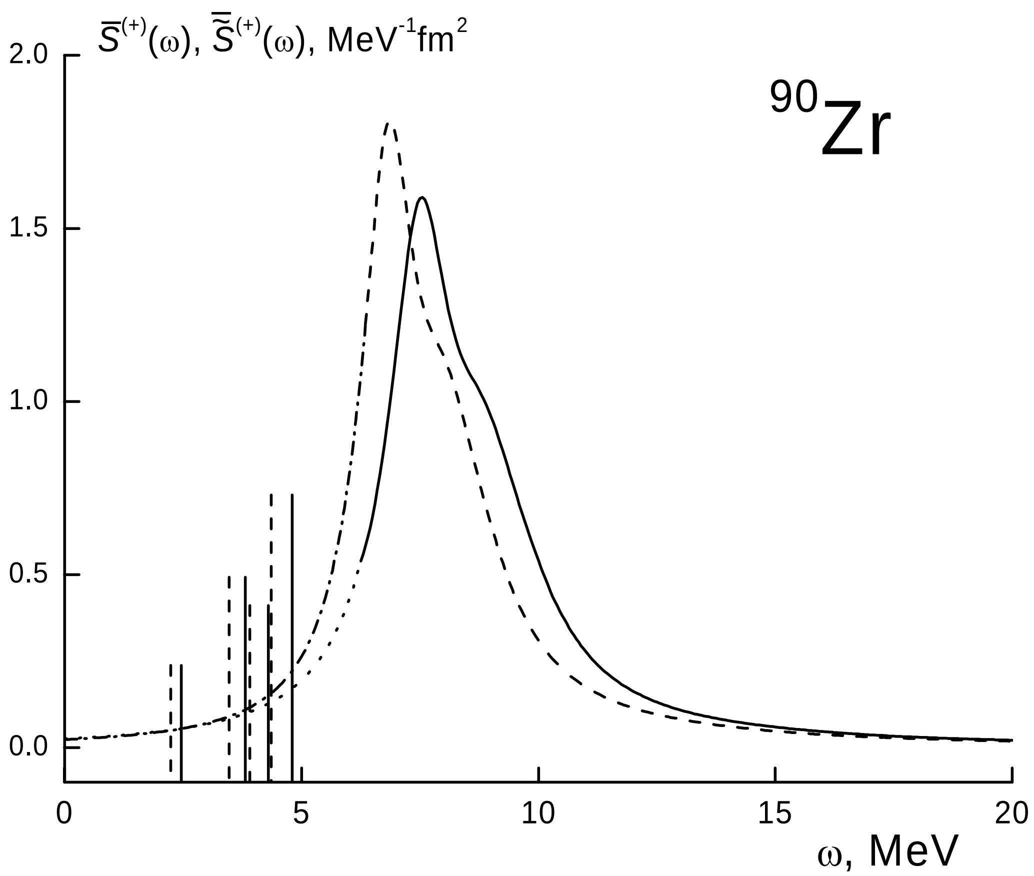
ρ1 (r,ωm)
arb. u.
48Ca
90Zr
140Ce
208Pb
0
2
4
6
8
10
12
14
r, fm



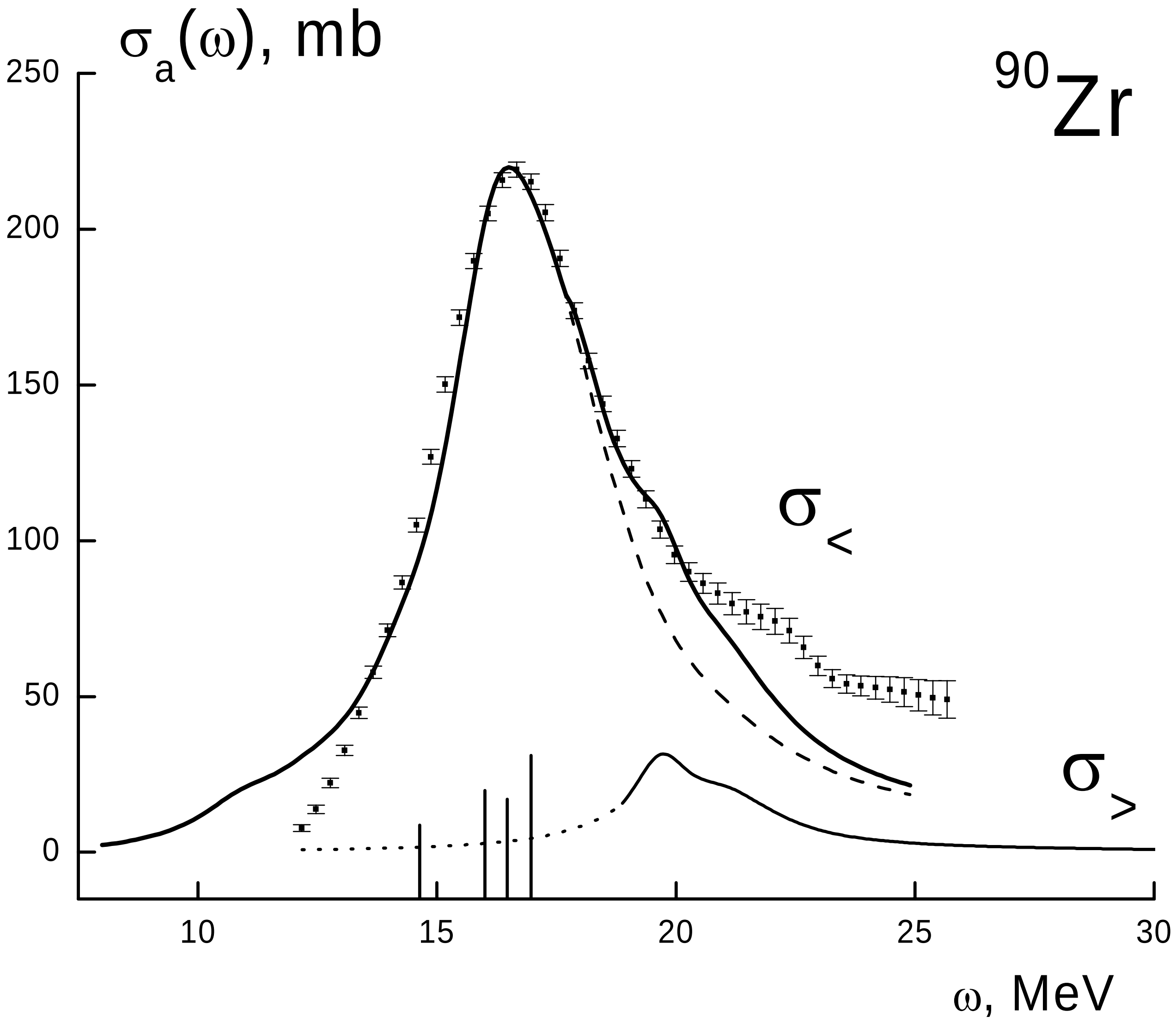
ωS1,ov(ω)/EWSR, % MeV-1
208Pb
5
4
3
2
1
0
10
20
30
40
50
60
70
ω, MeV



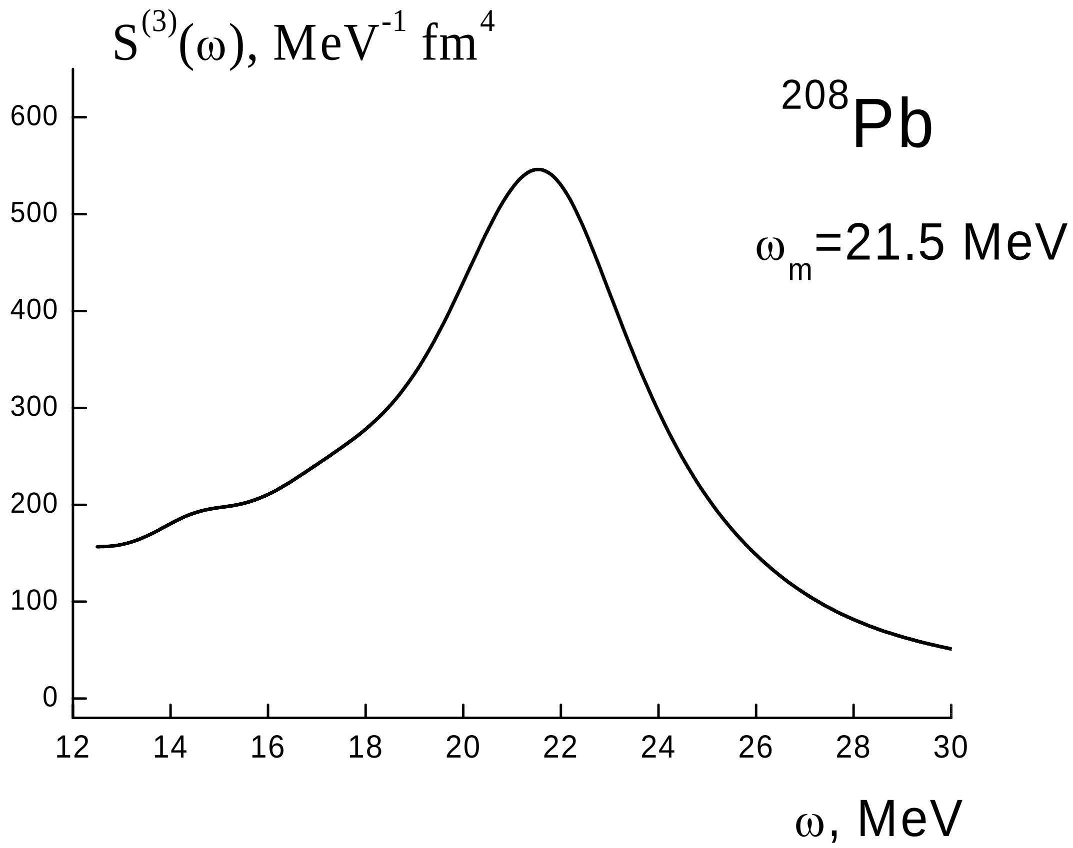
$\bar{S}^{(-)}(\omega)$, $\bar{\bar{S}}^{(-)}(\omega)$, MeV^{-1}fm^2
^{90}Zr
0
1
2
3
4
5
10
20
30
40
50
ω, MeV



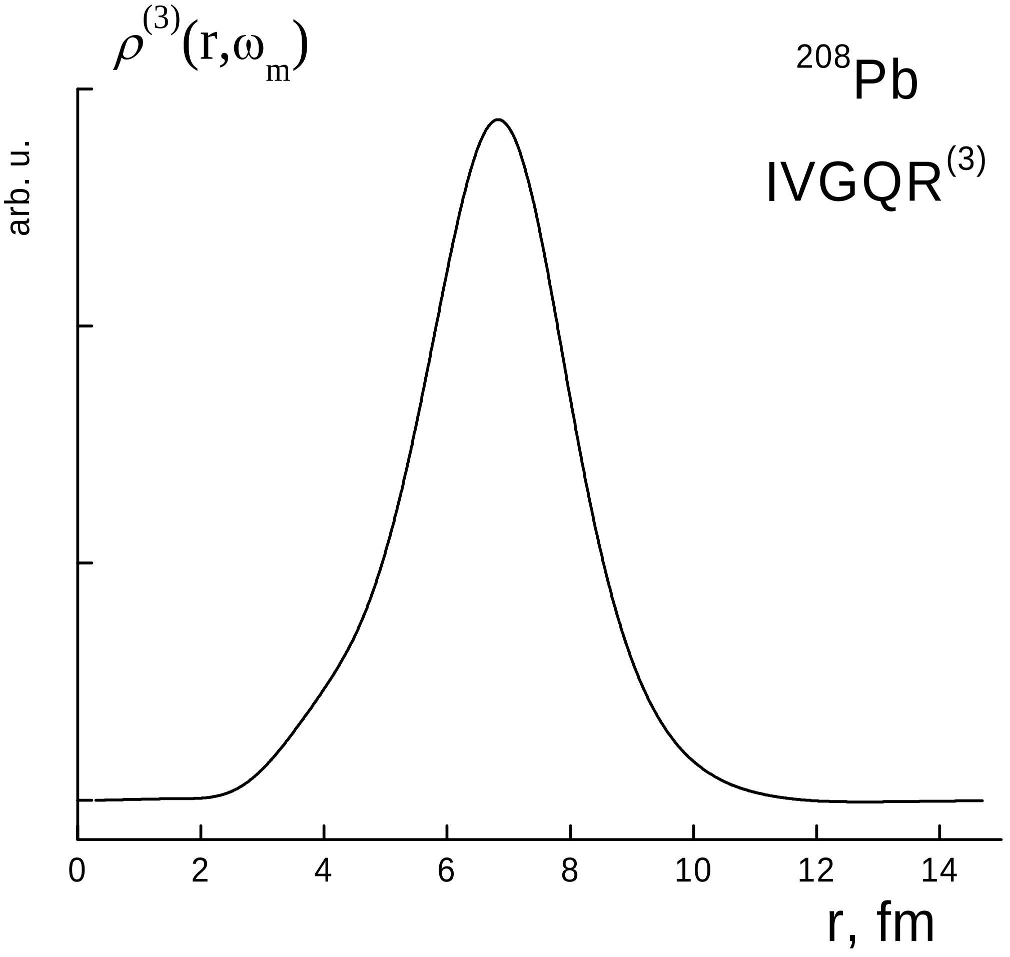
$\bar{S}^{(+)}(\omega)$, $\bar{\bar{S}}^{(+)}(\omega)$, MeV^{-1}fm^2
^{90}Zr
0.0
0.5
1.0
1.5
2.0
0
5
10
15
20
ω, MeV



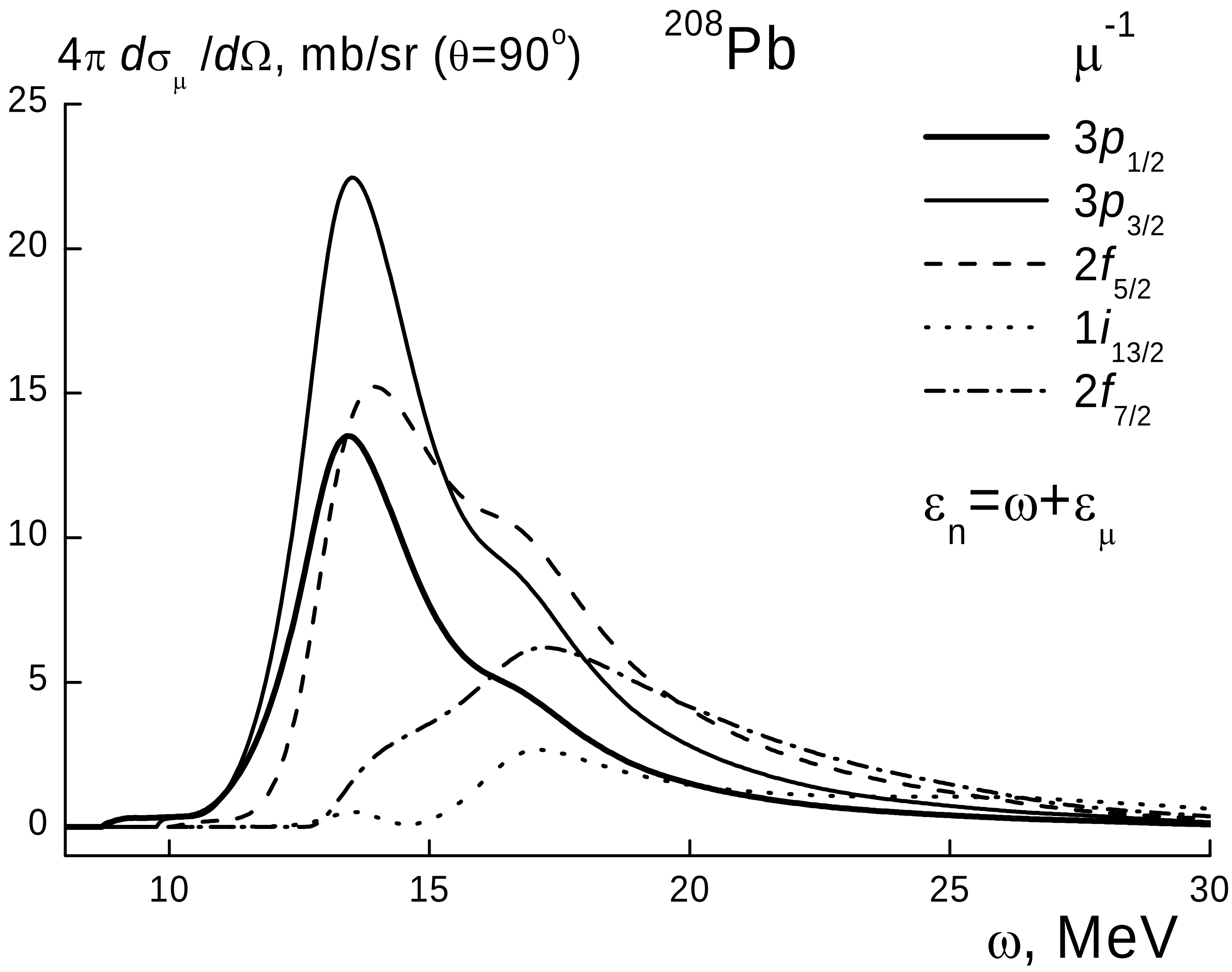
$\sigma_a(\omega)$, mb
^{90}Zr
250
200
150
100
50
0
$\sigma_<$
$\sigma_>$
10
15
20
25
30
ω, MeV



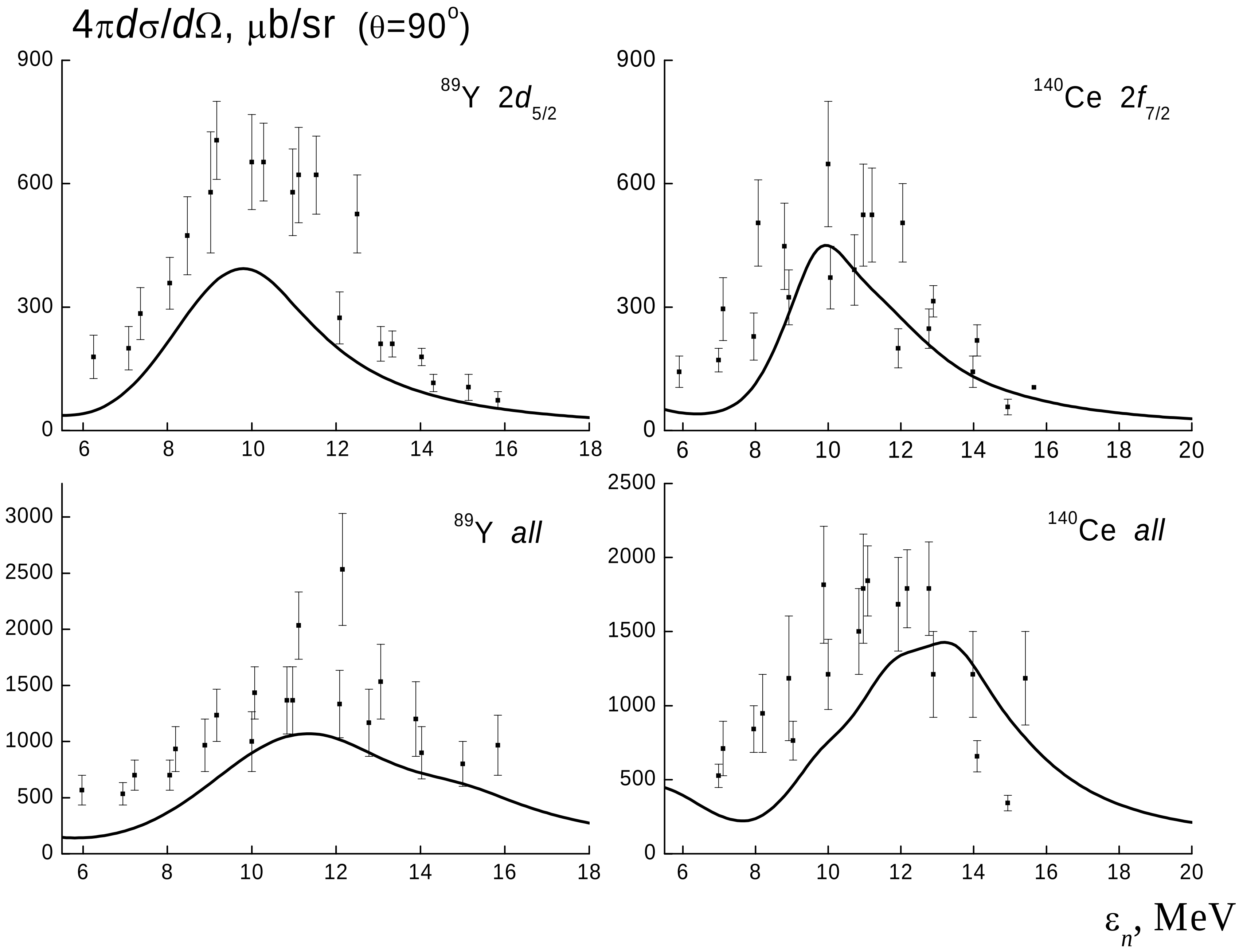
S^(3)(ω), MeV^-1 fm^4
208Pb
ω_m=21.5 MeV
600
500
400
300
200
100
0
12
14
16
18
20
22
24
26
28
30
ω, MeV



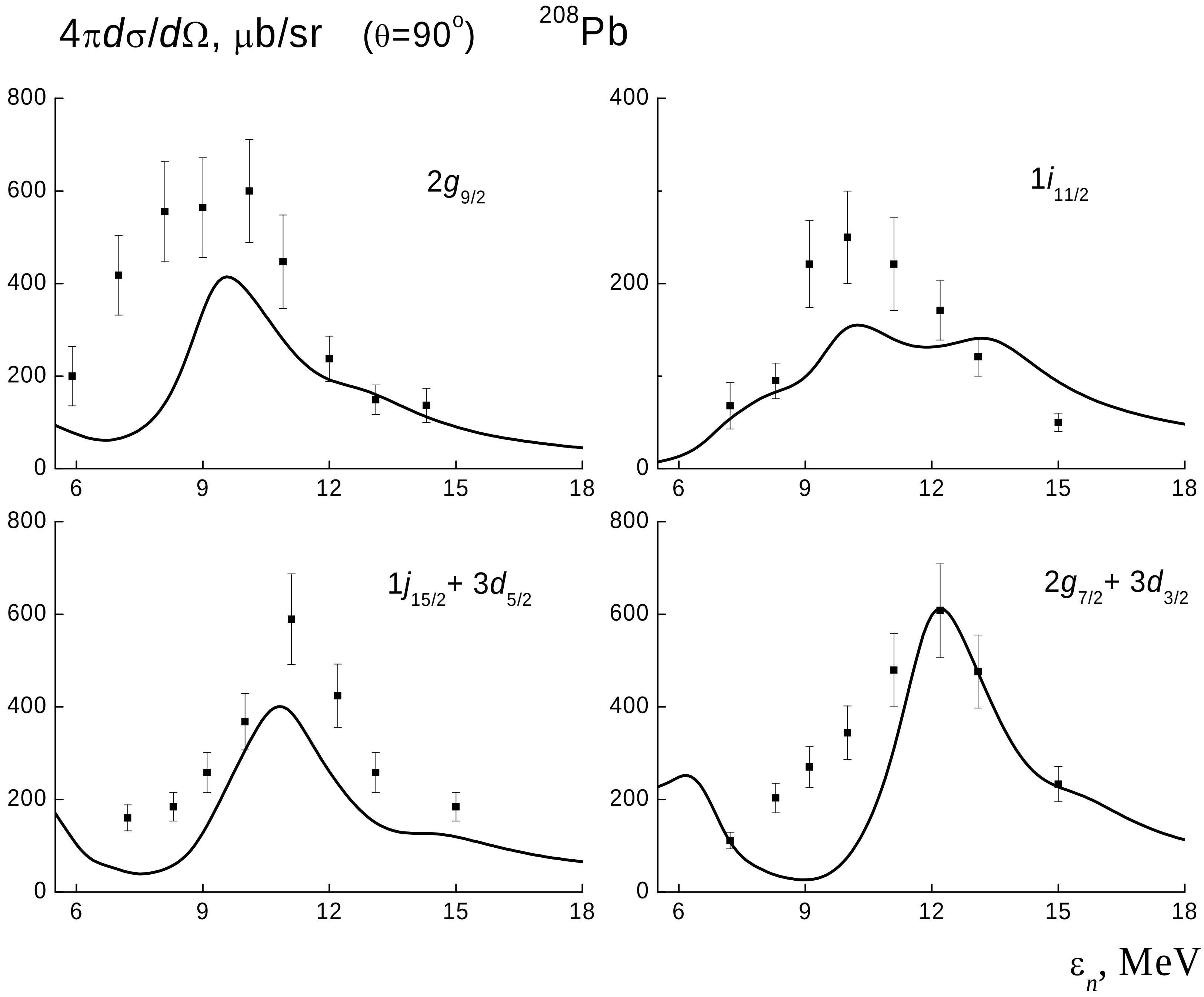
ρ^(3)(r,ω_m)
208Pb
IVGQR^(3)
arb. u.
0
2
4
6
8
10
12
14
r, fm



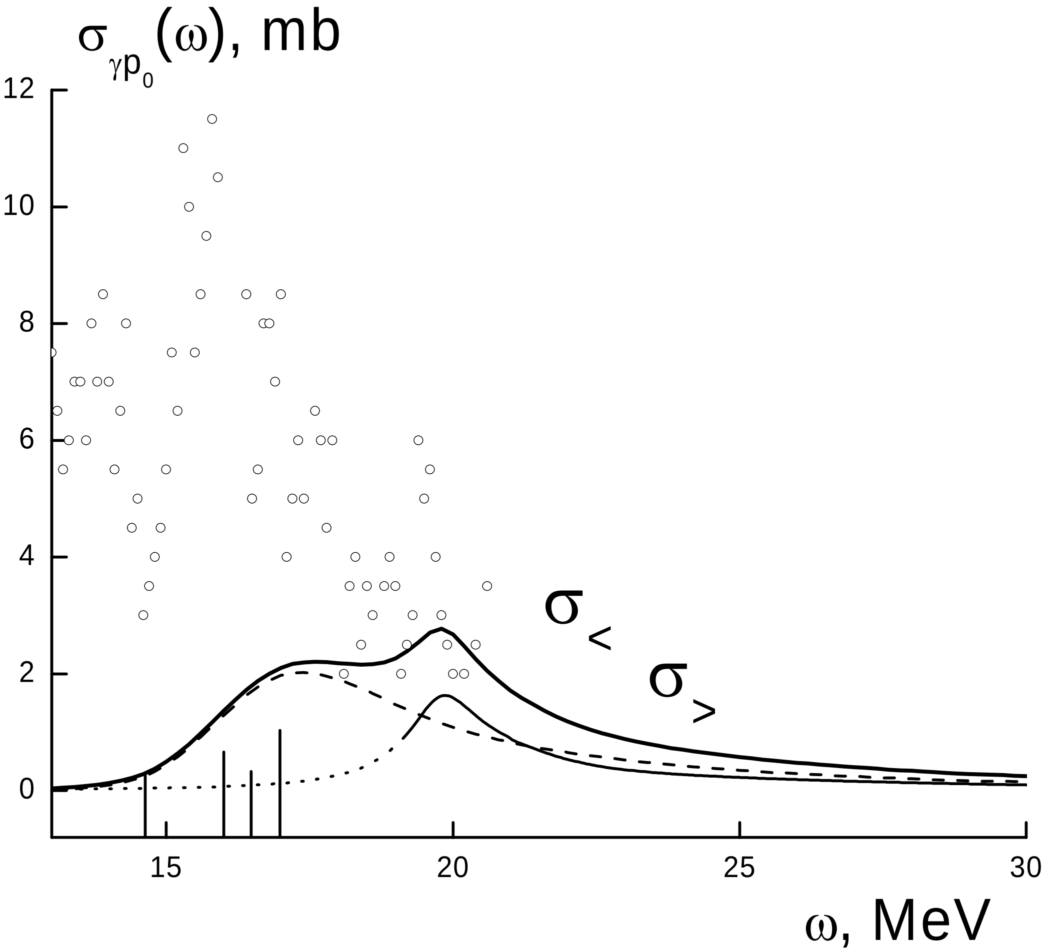
4π dσμ /dΩ, mb/sr (θ=90°)
208Pb
μ-1
3p1/2
3p3/2
2f5/2
1i13/2
2f7/2
εn=ω+εμ
25
20
15
10
5
0
10
15
20
25
30
ω, MeV



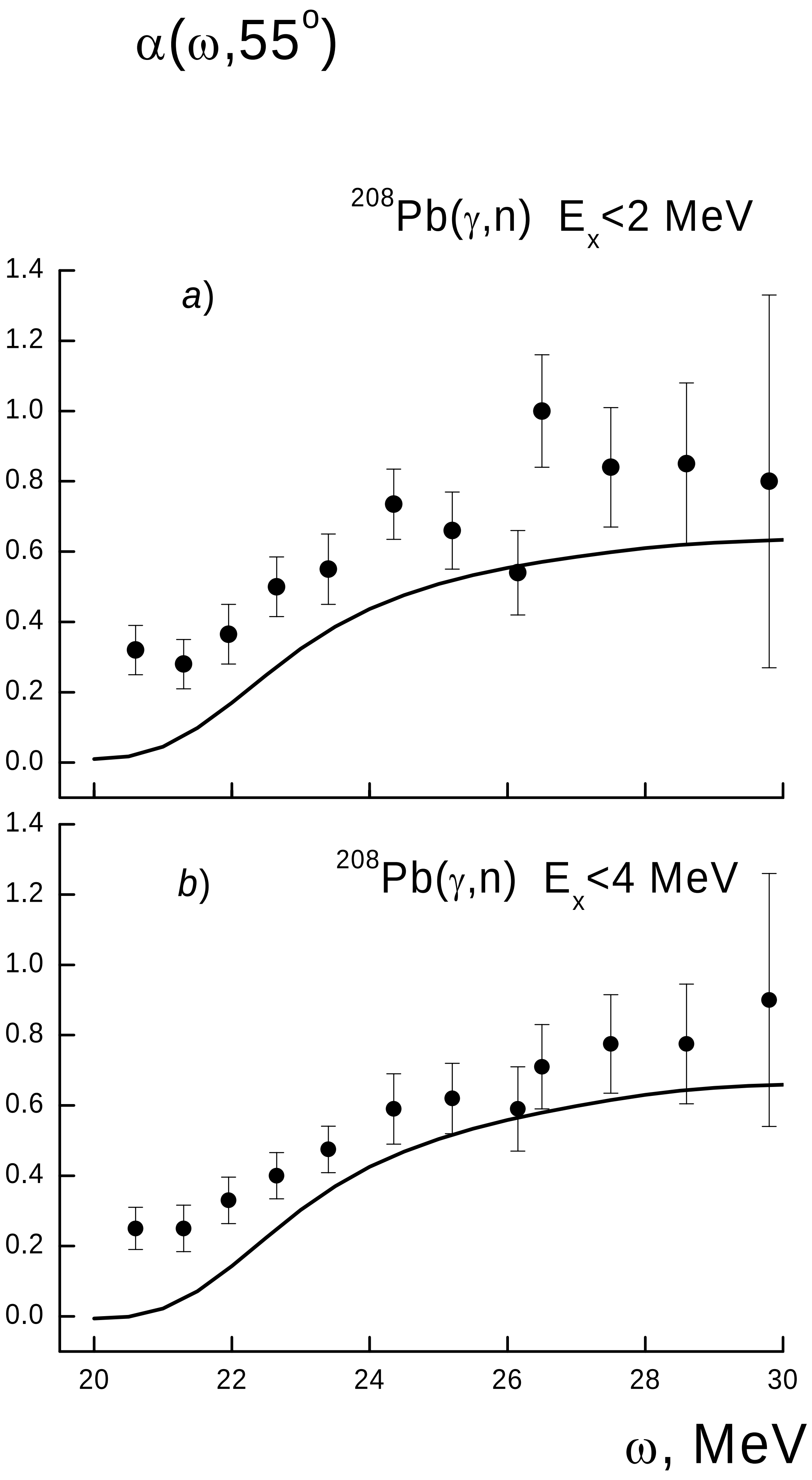
4πdσ/dΩ, μb/sr (θ=90°)
89Y 2d5/2
140Ce 2f7/2
89Y all
140Ce all
εn, MeV



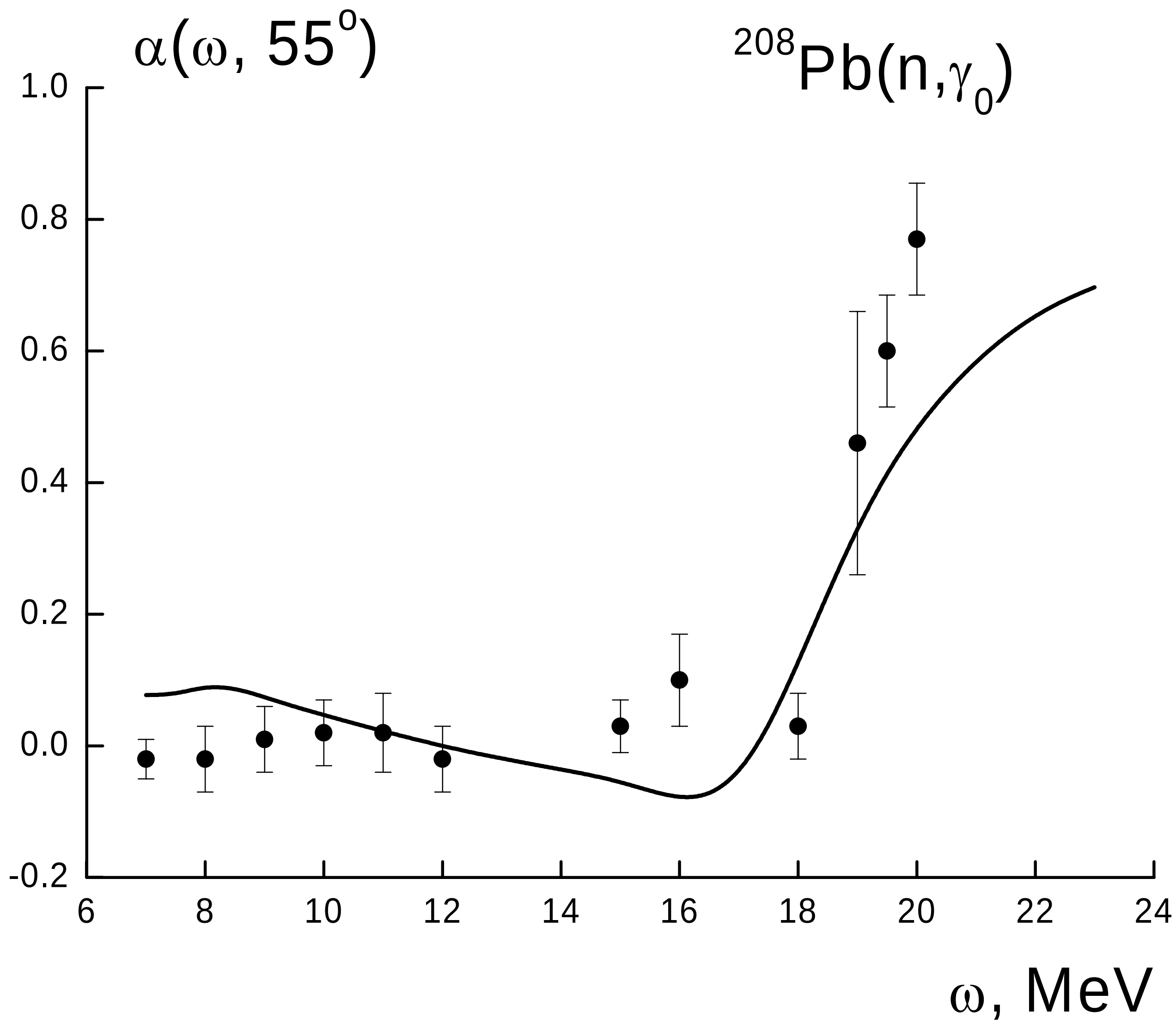
$4\pi d\sigma/d\Omega$, μb/sr (θ=90°)
^{208}Pb
$2g_{9/2}$
$1i_{11/2}$
$1j_{15/2}$ + $3d_{5/2}$
$2g_{7/2}$ + $3d_{3/2}$
0
200
400
600
800
6
9
12
15
18
ε_n, MeV



$\sigma_{\gamma p_0}(\omega)$, mb
12
10
8
6
4
2
0
15
20
25
30
$\sigma_<$
$\sigma_>$
ω, MeV



α(ω,55°)
208Pb(γ,n) Ex<2 MeV
a)
208Pb(γ,n) Ex<4 MeV
b)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
20
22
24
26
28
30
ω, MeV



α(ω, 55°)
208Pb(n,γ0)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
6
8
10
12
14
16
18
20
22
24
ω, MeV