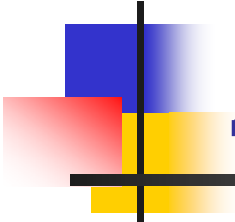
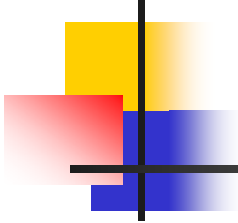


Принцип эквивалентности и элементарные частицы



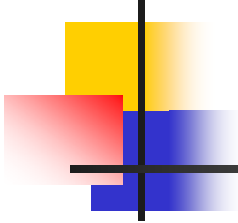
Всероссийское совещание по прецизионной физике
и фундаментальным физическим константам
Дубна, ОИЯИ 4 декабря 2009 г.

О.В. Теряев
ЛТФ ОИЯИ



Main Topics

- Equivalence Principle and Spin
- Gravitational formfactors
- Direct and Indirect tests of Equivalence Principle
- Extension of Equivalence Principle (validity separately for quarks and gluons)
- EP for Spin-1 hadrons

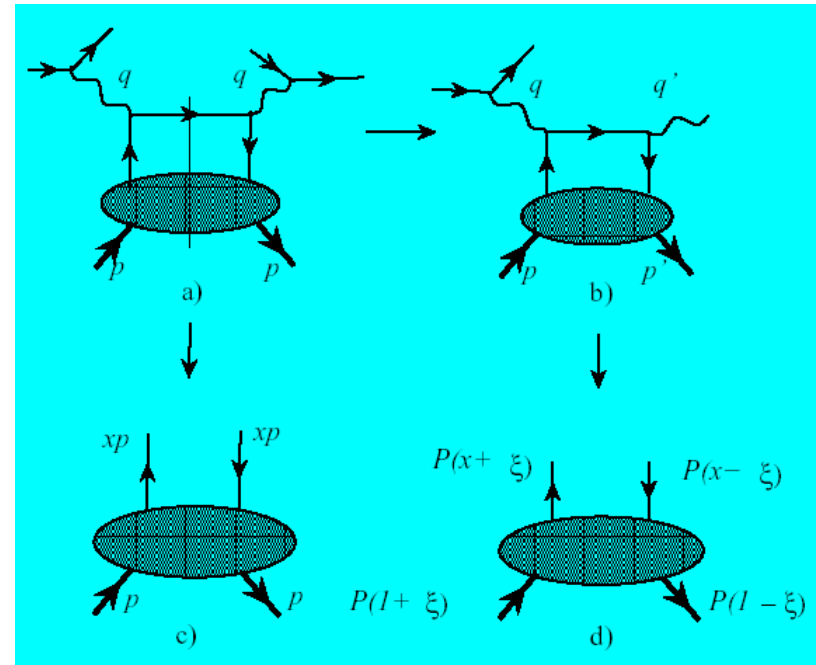


Equivalence principle

- Newtonian – “Falling elevator” – well known and checked (also for elementary (anti)particles – S. Karshenboim)
- Post-Newtonian – gravity action on SPIN – known since 1962 (Kobzarev and Okun’); rederived from conservation laws - Kobzarev and Zakharov
- In the context of GPDs = Ji’s sum rules (1996!)
- Anomalous gravitomagnetic (and electric-CP-odd) moment is ZERO or
- Classical and QUANTUM rotators behave in the SAME way
- - not checked on purpose but in fact checked in atomic spins experiments at % level (Silenko, OT’07)

GPDs (generalization of DA's (talk of S. Mikhailov)

- Inclusive $\rightarrow$ exclusive
- Forward $\rightarrow$ non-forward (= skewed = generalized)



1-st moments - EM, 2-nd - Gravitational Formfactors

$$\langle p' | T_{q,g}^{\mu\nu} | p \rangle = \bar{u}(p') \left[A_{q,g}(\Delta^2) \gamma^{(\mu} p^{\nu)} + B_{q,g}(\Delta^2) P^{(\mu} i \sigma^{\nu)\alpha} \Delta_\alpha / 2M \right] u(p)$$

- Conservation laws - zero Anomalous Gravitomagnetic Moment : $\mu_G = J$ (g=2)

$$P_{q,g} = A_{q,g}(0) \quad A_q(0) + A_g(0) = 1$$

$$J_{q,g} = \frac{1}{2} [A_{q,g}(0) + B_{q,g}(0)] \quad A_q(0) + B_q(0) + A_g(0) + B_g(0) = 1$$

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons
- Describe interaction with both classical and TeV gravity

GPDs – models for both EM and Gravitational formfactors (Selyugin, OT '09)

- Smaller mass square radius (attraction vs repulsion!?)

$$\rho(b) = \sum_q e_q \int dx q(x, b) = \int d^2q F_1(Q^2 = q^2) e^{i\vec{q} \cdot \vec{b}}$$

$$= \int_0^\infty \frac{q dq}{2\pi} J_0(qb) \frac{G_E(q^2) + \tau G_M(q^2)}{1 + \tau}$$

$$\rho_0^{\text{Gr}}(b) = \frac{1}{2\pi} \int_0^\infty dq q J_0(qb) A(q^2)$$

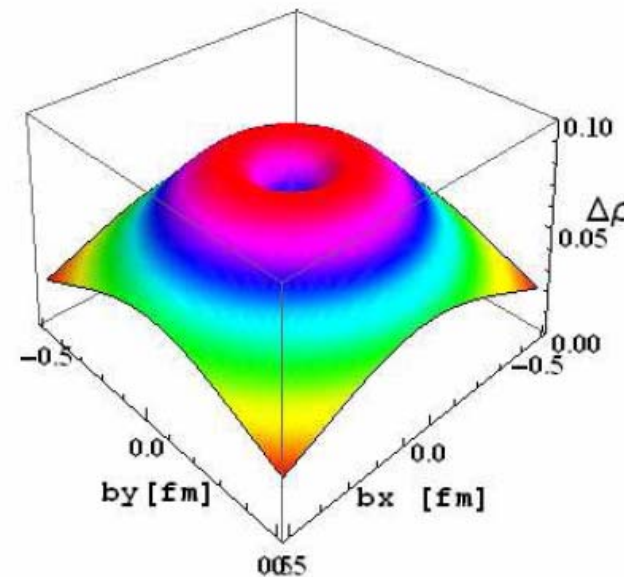
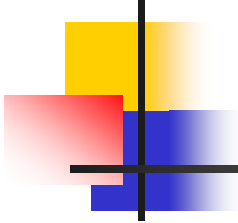


FIG. 17: Difference in the forms of charge density F_1^P and "matter" density (A)



Electromagnetism vs Gravity

- Interaction – field vs metric deviation

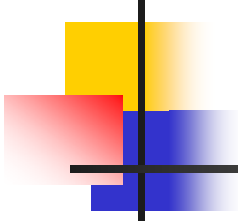
$$M = \langle P' | J_q^\mu | P \rangle A_\mu(q) \qquad M = \frac{1}{2} \sum_{q,G} \langle P' | T_{q,G}^{\mu\nu} | P \rangle h_{\mu\nu}(q)$$

- Static limit

$$\langle P | J_q^\mu | P \rangle = 2e_q P^\mu \qquad \sum_{q,G} \langle P | T_i^{\mu\nu} | P \rangle = 2P^\mu P^\nu$$
$$h_{00} = 2\phi(x)$$

$$M_0 = \langle P | J_q^\mu | P \rangle A_\mu = 2e_q M \phi(q) \qquad M_0 = \frac{1}{2} \sum_{q,G} \langle P | T_i^{\mu\nu} | P \rangle h_{\mu\nu} = 2M \cdot M \phi(q)$$

- Mass as charge – equivalence principle



Gravitomagnetism

- Gravitomagnetic field (weak, except in gravity waves) – action on spin from $M = \frac{1}{2} \sum_{q,G} \langle P' | T_{q,G}^{\mu\nu} | P \rangle h_{\mu\nu}(q)$

$$\vec{H}_J = \frac{1}{2} \text{rot} \vec{g}; \quad \vec{g}_i \equiv g_{0i}$$

spin dragging twice
smaller than EM

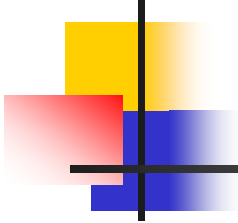
- Lorentz force – similar to EM case: factor 1/2 cancelled with 2 from frequency same as EM

$$h_{00} = 2\phi(x)$$

Larmor

$$\omega_J = \frac{\mu_G}{J} H_J = \frac{H_L}{2} = \omega_L \quad \vec{H}_L = \text{rot} \vec{g}$$

- Orbital and Spin momenta dragging – the same - Equivalence principle



Experimental test of PNEP

- Reinterpretation of the data on G(EDM) search

PHYSICAL REVIEW
LETTERS

VOLUME 68

13 JANUARY 1992

NUMBER 2

Search for a Coupling of the Earth's Gravitational Field to Nuclear Spins in Atomic Mercury

B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson

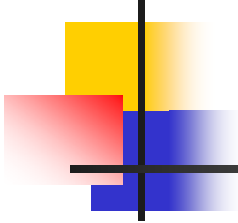
Physics Department, FM-15, University of Washington, Seattle, Washington 98195

(Received 25 September 1991)

- If (CP-odd!) $G_{EDM}=0 \rightarrow$ constraint for AGM (A. Silenko, OT'07)

$$\mathcal{H} = -g\mu_N \mathbf{B} \cdot \mathbf{S} - \zeta \hbar \boldsymbol{\omega} \cdot \mathbf{S}, \quad \zeta = 1 + \chi$$

$$|\chi(^{201}\text{Hg}) + 0.369\chi(^{199}\text{Hg})| < 0.042 \quad (95\% \text{C.L.})$$

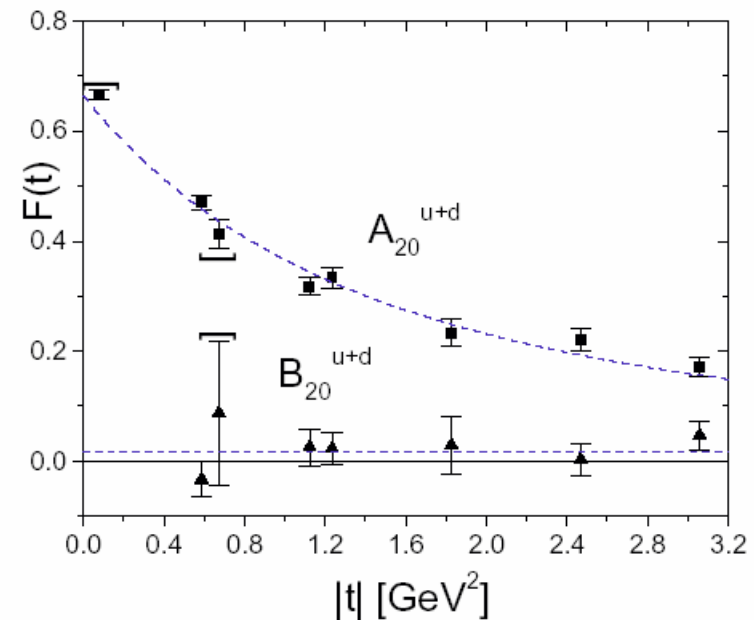
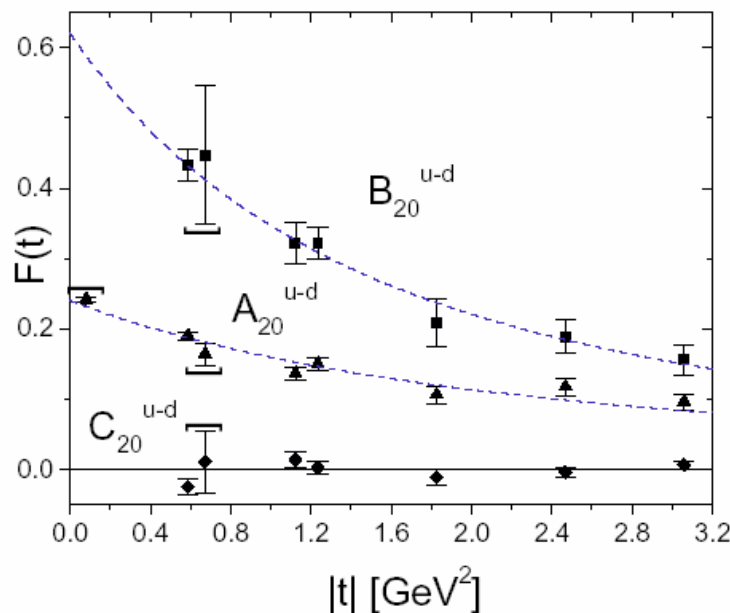


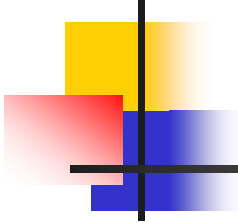
Equivalence principle for moving particles

- Compare gravity and acceleration: gravity provides EXTRA space components of metrics $h_{zz} = h_{xx} = h_{yy} = h_{00}$
- Matrix elements DIFFER
$$\mathcal{M}_g = (\epsilon^2 + p^2)h_{00}(q), \quad \mathcal{M}_a = \epsilon^2 h_{00}(q)$$
- Ratio of accelerations: $R = \frac{\epsilon^2 + p^2}{\epsilon^2}$ - confirmed by explicit solution of Dirac equation (Silenko, OT, '05)
- Non-stationary (weak approximation to Kerr) – Obukov, Silenko, OT '09

Generalization of Equivalence principle

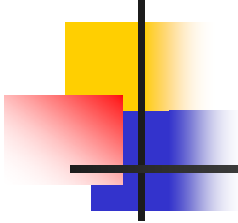
- Various arguments: $AGM \approx 0$ separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)





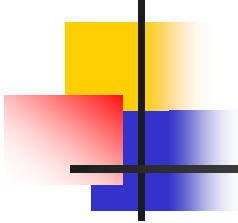
Extended Equivalence Principle=Exact EquiPartition

- In pQCD – violated
- Reason – in the case of EEP- no smooth transition for zero fermion mass limit (Milton, 73)
- Conjecture (O.T., 2001 – prior to lattice data) – valid in NP QCD – zero quark mass limit is safe due to chiral symmetry breaking
- Supported by smallness of E (isoscalar AMM)



Vector mesons and EEP

- $J=1/2 \rightarrow J=1$. QCD SR (Samsonov) calculation of Rho's AMM gives g close to 2.
- Maybe because of similarity of moments
- $g-2 = \langle E(x) \rangle$; $B = \langle xE(x) \rangle$
- Directly for charged Rho (combinations like $p+n$ for nucleons unnecessary!). Not reduced to non-extended EP: Gluons momentum fraction sizable



EEP and AdS/QCD

- Recent development – calculation of Rho formfactors in Holographic QCD (Grigoryan, Radyushkin)
- Provides $g=2$ identically!
- Experimental test at time –like region possible

Another (**new!**) manifestation of post-Newtonian (E)EP for spin 1 hadrons

- Tensor polarization - coupling of EMT to spin in forward matrix elements - inclusive processes
- Second moments of tensor distributions should sum to zero

$$\langle P, S | \bar{\psi}(0) \gamma^\nu D^{\nu_1} \dots D^{\nu_n} \psi(0) | P, S \rangle_{\mu^2} = i^{-n} M^2 S^{\nu\nu_1} P^{\nu_2} \dots P^{\nu_n} \int_0^1 C_q^T(x) x^n dx$$

$$\sum_q \langle P, S | T_i^{\mu\nu} | P, S \rangle_{\mu^2} = 2P^\mu P^\nu (1 - \delta(\mu^2)) + 2M^2 S^{\mu\nu} \delta_1(\mu^2)$$

$$\langle P, S | T_g^{\mu\nu} | P, S \rangle_{\mu^2} = 2P^\mu P^\nu \delta(\mu^2) - 2M^2 S^{\mu\nu} \delta_1(\mu^2)$$

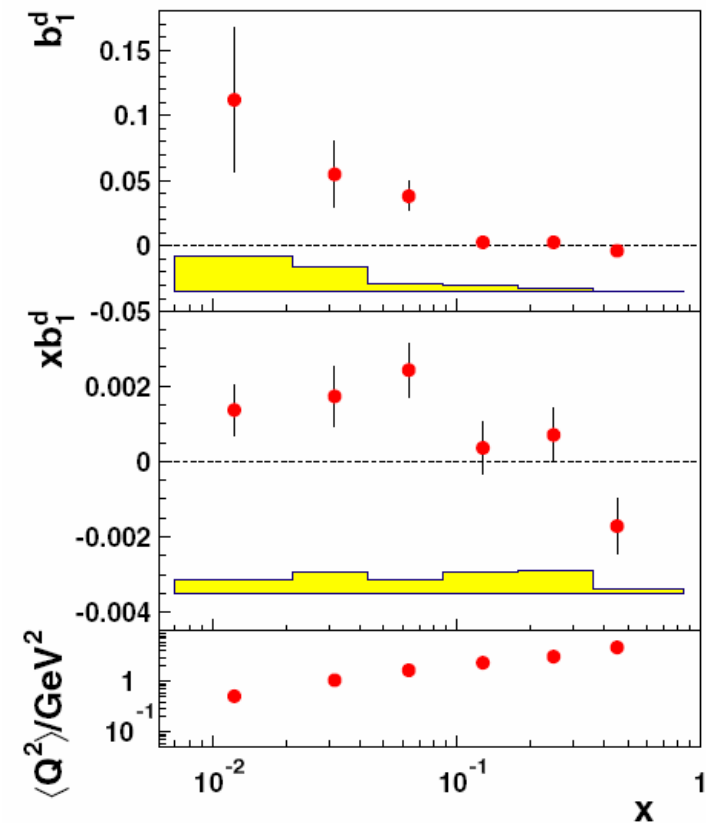
$$\sum_q \int_0^1 C_i^T(x) x dx = \delta_1(\mu^2) = 0 \text{ for EEP}$$

HERMES – data on tensor spin structure function

PRL 95, 242001 (2005)

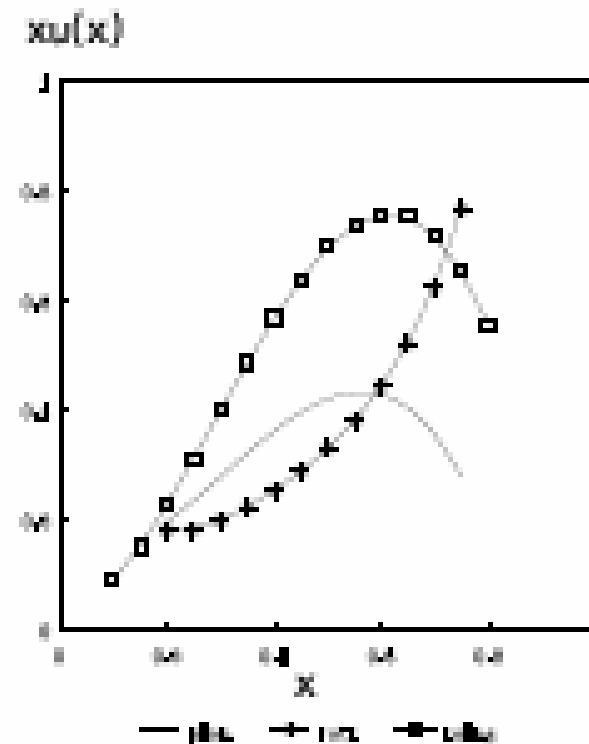
- Isoscalar target – proportional to the sum of u and d quarks – combination required by EEP
- Second moments – compatible to zero better than the first one (collective glue << sea) – for valence:

$$\int_0^1 C_i^T(x) dx = 0.$$



What about vector mesons – sum rules (A. Oganesian, Phys.Atom.Nucl.71:1439-1444,2008)

- Very different for longitudinal and transverse rho
- Reason – smallness of tensor polarization dependent part?



Another relation of Gravitational FF and NP QCD (first reported at 1992: **hep-ph/9303228**)

- BELINFANTE (relocalization) invariance :

decreasing in coordinate –

$$M^{\mu,\nu\rho} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} J_{S\sigma}^5 + x^\nu T^{\mu\rho} - x^\rho T^{\mu\nu}$$

smoothness in momentum space

$$M^{\mu,\nu\rho} = x^\nu T_B^{\mu\rho} - x^\rho T_B^{\mu\nu}$$

- Leads to absence of massless pole in singlet channel – U_A(1)

$$\epsilon_{\mu\nu\rho\alpha} M^{\mu,\nu\rho} = 0.$$

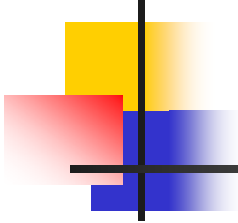
- Delicate effect of NP QCD

$$(g_{\rho\nu}g_{\alpha\mu} - g_{\rho\mu}g_{\alpha\nu})\partial^\rho(J_{5S}^\alpha x^\nu) = 0$$

- Equipartition – deeply related to relocalization invariance by QCD evolution

$$q^2 \frac{\partial}{\partial q^\alpha} \langle P | J_{5S}^\alpha | P + q \rangle = (q^\beta \frac{\partial}{\partial q^\beta} - 1) q_\gamma \langle P | J_{5S}^\gamma | P + q \rangle$$

$$\langle P, S | J_\mu^5(0) | P + q, S \rangle = 2MS_\mu G_1 + q_\mu (Sq) G_2, \\ q^2 G_2|_0 = 0$$



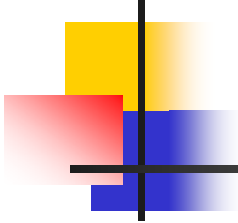
Relocalization and EEP (OT'98)

- Evolution of orbital and TOTAL angular momentum (at LO) – related due to non-trivial relations between DGLAP kernels

$$\frac{d}{dt} \begin{pmatrix} J_q \\ J_G \end{pmatrix} = \frac{\alpha(t)}{2\pi} \begin{pmatrix} \int_0^1 dx (x-1) P_{qq}(x) & 2n_f \int_0^1 dx x P_{qG}(x) \\ \int_0^1 dx x P_{Gq}(x) & -2n_f \int_0^1 dx x P_{qG}(x) \end{pmatrix} \begin{pmatrix} J_q \\ J_G \end{pmatrix}$$

- RI: $P_{ij}^{JJ(1)} = P_{ij}^{LL(1)} \quad \int_0^1 dx x \Delta P_{Gq}(x) = \frac{1}{2} \int_0^1 dx x P_{Gq}(x)$

- EEP: $P^{LL(1)} = P^{TT(2)}$



CONCLUSIONS

- EP with spin – new problem for particle physics
- Direct (motion in gravitational fields/accelerated frames) and indirect (extraction from precise accelerator data)
- Spin-1 hadrons – also in inclusive processes
- A number of evidences for validity of EP for quarks and gluons separately