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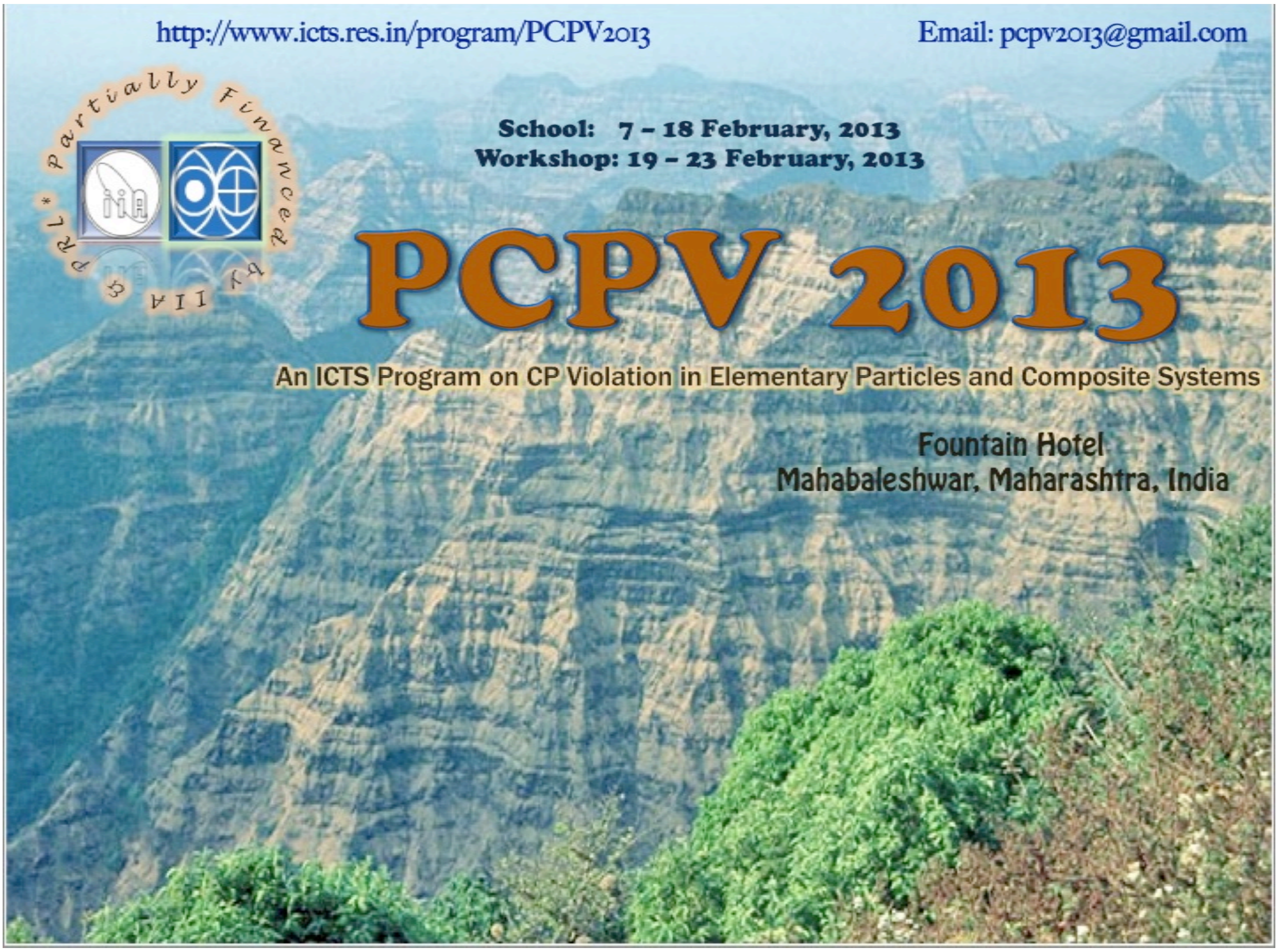
Partially Financed by IIA & PRL*

School: 7 – 18 February, 2013
Workshop: 19 – 23 February, 2013

PCPV 2013

An ICTS Program on CP Violation in Elementary Particles and Composite Systems

Fountain Hotel
Mahabaleshwar, Maharashtra, India



Topics for School

- Particle physics models
- Nuclear and atomic EDMs
- Molecular and solid state EDMs
- Principles of EDM measurements

Discussion Forum

* Models of CP violation * New physics from EDMs

Topics for Workshop

- Models of CP violation
- CP violation in K and B mesons
- EDMs from particle physics
- EDMs of atomic and molecular systems
- EDMS of solids
- Nuclear aspects of CP violation
- EDMs using lattice QCD
- CP and T violations at colliders
- CP violation in cosmology
- CP violation in neutrinos
- Unexpected results for CP violation

Organizers

B. P. Das
A. Dighe
S. Lamoreaux
N. Mahajan
R. Rangarajan
B. K. Sahoo (Convener)
Y. Sakemi
A. I. Sanda
A. D. Singh

Contact address: Dr. B. K. Sahoo, PCPV 2013, Theoretical Physics Division, PRL, Navrangpura, Ahmedabad 380009, India

Topics & Time-table for the School

Atomic and molecular physics:

1. Atomic electric dipole moments (EDM): Introdoction to simple atomic systems, basics of atomic many-body calculations, P and T violation, P and T violating interactions, atomic EDMs, Schiff theorem, electron EDM and relativistic effects, closed-shell atomic EDMs and implications, and ionic EDMs.

2. Molecular EDM: Introduction to molecular calculations, molecular EDMs.

3. Experimental techinques: Brief historical review of EDM measurements. Muon EDM experiment: experimental scheme, statistical sensitivity, systematic error sources. Molecular beam experiments. YbF experiment: experimental scheme, statistical sensitivty, systematic error sources. Nuclear EDM experiments. ^{199}Hg experiment. Solid-state EDM experiments. Brief review of upcoming experiments: Ra lattice experiment, Cs lattice experiment, HfF^+ ion trap, ThO molecular beam.

Particle physics

1. Introduction to particle physics: Discrete symmetries and their violation, K and B meson systems, Weak interactions.

2. Particle physics models: Lagrangian and a discussion of the CKM and PMNS matrices, Examples of CP violation in Physics Beyond the Standard Model.

3. Particle physics aspects of EDMs: Introduction to CP violation, examples of Lagrangians with CP violation; Basic ideas about strong CP-violation; electron and neutron EDMs; Atomic EDMs.

Date	9:30-11:00 AM	11:15 AM-12:45 PM	12:45-2:30 PM	2:30-4:00 PM	4:00-5:30 PM
7.2.13	Part Phys (SR)	At Phys (DA)			
8.2.13	Part Phys (SR)	At Phys (DA)	L	At Phys Tu (DA)	
9.2.13	Part Phys (SR)	At Phys (DA)	U	At Phys Tu (DA)	
10.2.13	Part Phys (SR)	At Phys (KL)	N	Part Phys Tu (PP)	
11.2.13	At Phys (KL)	Part Phys (SR)	C	At Phys Tu (KL)	
12.2.13	At Phys (KL)	Part Phys (SR)	H	Part Phys Tu (PP)	
13.2.13	At Phys (KL)	Part Phys (SR)		Part Phys Tu(PP)	
14.2.13	STUDENTS DAY OUT AROUND MAHABALESHWAR TOURIST PLACES				
15.2.13			R	Part Phys (NS)	
16.2.13	Expt Tech (AV)	Part Phys (NS)	E	Expt Tech (AV)	
17.2.13	Expt Tech (AV)	Mol Phys (MA)	A	Part Phys (NS)	Expt Tech(AV)
18.2.13	Mol Phys (GG)	Mol Phys (MA)	K	Part. Phys (NS)	

DA: Dilip Angom
NS: Nita Sinha
GG: Geetha Gopakumar
SR: Sreerup Raichaudhury
AV: Amar Vutha
PP: Particle physics
KL: K. V. P. Latha
MA: Minori Abe

Time-table for the Workshop

Tuesday, 19th Feb 2013

Morning session

Sl. No.	10:15-10:30	Inauguration session	
1.	10:30-11:15	G. Castelo-Branco	CP Violation in the Quark and the Lepton Sectors
		Tea break	
2.	11:30-12:15	D. P. Roy	Probing the Neutrino Mass Hierarchy & the CPV phase in the Forseeable Future Experiments
3.	12:15-13:00	M. Nakahata	Recent Results on Neutrino Oscillations and CP Violation Measurement in Neutrinos

Lunch break

Afternoon session

4	14:15-15:00	D. Budker	Nuclear-Resonance Detection of Axion Induced Oscillating Electric Dipole Moments
5	15:00-15:35	K. Jungmann	Radium atoms to search for EDMs
		Tea break and Snacks	
6	15.45-16:30	M. Bona	Status of CKM in the light of recent results
7	16:30-17:05	P. Paradisi	CP and flavour violation in the charged leptonic sector
8	17:05-17:50	TBA	TBA

Dinner (19:30 onwards)

Wednesday, 20th Feb 2013

Morning session

9.	09:30-10:15	G. Mohanty	Experimental results on CP violation in the quark sector
10.	10:15-11:00	J. Hisano	Neutron EDM in Physics beyond the Standard Model
		Tea break	
11.	11:15-12:00	A. Soni	Charming CP & all that
12.	12:00-12:45	A. Kundu	Going beyond Mahabaleshwar: Search for CPT Violation

Lunch break

Afternoon session

13.	14:15-15:45	Discussion by G. Castelo-Branco	Models of CP violation
		Tea break and Snacks	
14.	16:00-16:45	P. Geltenbort	Ultra-Cold Neutrons and Searches for an Electric Dipole Moment
15.	16:45-17:20	P. Schmidt-Wellenburg	Search for a neutron electric dipole moment at PSI
16.	17:20-17:55	E. Shitani	Nucleon EDM in lattice QCD

Dinner (19:30 onwards)

Thursday, 21th Feb 2013

Morning session

17.	09:15-10:00	T. Mibe	Measurement of muon g-2/EDM
18.	10:00-10:45	U. Yajnik	Baryon asymmetry of the Universe and CP violation
Tea break			
19.	11:00-11:35	TBA	CP violation results from BaBar
20.	11:35-12:10	A. Lytle	$K \rightarrow \pi\pi$ decays from lattice QCD

Lunch break and Outing

Dinner (19:30 onwards)

Friday, 22nd Feb 2013

Morning session

21.	09:30-10:15	Ed. Hinds	Search for the electron EDM
22.	10:15-11:00	B. P. Das	A Coupled-cluster Approach to the Prediction of P and CP Violation Effects in Atoms and Molecules: An Overview of the Recent Developments and Applications
Tea break			
23.	11:10-11:55	A. V. Titov	Study of T, P- nonconservation effects and hyperfine constants in diatomics and solids by the relativistic pseudo-potential/core-restoration method
24.	11:55-12:30	M. K. Nayak	Theoretical studies of P & T violations in heavy polar molecules
25.	12:30-13:05	M. Abe	Molecular orbital based calculations for the search of the electron EDM using the Coupled-Cluster method in the Dirac-Coulomb approximation

Lunch break

Afternoon session

26.	14:25-15:00	M. Jung	A robust limit for the EDM of the electron	
27.	15:00-16:30	Discussion by T. Fukuyama Moderated by B. P. Das	New Physics from EDMs	
Tea break and Snacks				
28.	16:45-17:10	A. Petrov	Hyperfine interaction in diatomics as a factor of influence on EDM experiments	Discussion Session On "Top and Higgs CP Violation" Led by A. Soni
29.	17:10-17:35	M. Chikamori	^{3}He comagnetometer in ^{129}Xe active spin maser for EDM measurement	
30.	17:35-18:00	S. Kanda	Ultra cold Muon for J-PARC and muon (g-2)/EDM experiment	

Dinner (19:30 onwards)

Saturday, 23rd Feb 2013

Morning session

31.	09:30-10:15	A. Vutha	The electron EDM search using thorium monoxide
32.	10:15-10:50	T. Aoki	Ultracold Rb-Sr atoms and FrSr molecules toward the search for an electron EDM
Tea break			
33.	11:05-11:40	Y. Ichikawa	Experimental search for atomic EDM in ^{129}Xe at Tokyo Tech
34.	11:40-12:15	T. Fleig	Electron Electric Dipole Moment P, T-Odd Constant for HfF^+ from Relativistic Correlated All-Electron Theory
35.	12:15-12:40	K. V. P. Lata	Electric Dipole Moments of Some Closed-shell Atoms
	12:40-12:50	Concluding session	

Lunch

Good Bye

Invited talks

Tuesday, 19th Feb 2013

CP Violation in the Quark and the Lepton Sectors

G. Castelo-Branco
CFTP, Department de Fisica, Instituto Superior de Fisica, 1049-001 Lisboa, Portugal

We present an overview of models of CP violation in the quark and lepton sectors, including explicit and spontaneous CP violation, mechanisms for the suppression of flavour-changing--neutral currents, CP-odd invariants, the search for New Physics and the generation of the observed Baryon Asymmetry of the Universe.

Probing the Neutrino Mass Hierachy & the CPV Pahse δ in the Forseeable Future Experiments

D. P. Roy
Homi Bhabha Centre for Science Education, TIFR, Mumbai 400088, India

Till 2010 we had three unknown parameters of neutrino oscillation: the third mixing angle θ_{13}, the sign of the larger mass difference $\Delta_m^2(31)$ and the CP violating phase δ. Thanks to a number of consistent experimental results since then, culminating in the recent Daya Bay reactor neutrino data, we have a definitive determination of θ_{13} now. Moreover its measured value, $\sin^2(2\theta_{13}) = 0.1$, is close to its earlier upper limit. This has promising implications for the determination of the two remaining unknown parameters from the present and proposed accelerator neutrino experiments in the foreseeable future. This talk presents a pedagogical review of these profound developments for the wider community of young physicists including university students.

Recent results on neutrino oscillations and prospects of CP violation measurement

Masayuki Nakahata
ICRR, Kamioka Observatory, University of Tokyo, Gifu 506-1205, Japan

Neutrino oscillation parameters have been measured by atmospheric, solar, accelerator, and reactor neutrino experiments. All mixing angles and the mass-square differences were determined, but the CP phase and mass hierarchy are not measured yet. Recent results of those experiments are summarized and prospects of the CP violation measurement by future large volume detectors such as Hyper-Kamiokande are presented.

Nuclear-Resonance Detection of Axion Induced Oscillating Electric Dipole Moments

D. Budker, P. Graham, M. P. Ledbetter, S. Rajendran, and A. Sushkov
Department of Physics, University of California, Berkeley, California 94720, USA

We will discuss how the existence of an oscillating coherent axion field permeating the Universe and neatly solving both the strong CP and dark matter puzzles might be detected in solid-state "EDM" experiments that resemble NMR. This technique can potentially reach the sensitivity necessary to search for axion dark matter when the axion decay constant is between the grand-unification (~ 10^{16} GeV) and Planck (~ 10^{19} GeV) scales.

Radium Atoms to search for EDMs

K. Jungmann
KVI, University of Groningen, Zernikelaan 25, NL-9747 AA, Groningen, The Netherlands

Searches for permanent Electric Dipole Moments (EDMs) of fundamental particles rank among the most important contributions to particle physics and our fundamental understanding of nature. The Ra atoms offers significant enhancements of both a potential EDM of the nucleus and of the electron [1]. Whereas the ground state with its paired electrons is sensitive to a nuclear EDM, the 7s6d 3D2 state offers a strong enhancement for an electron EDM due to the close proximity of the 7s7p 3P1 state. At KVI an experiment is underway to slow and trap Ra atoms and to expose these atoms to an electric field [2]. In preparation of this experiment and to verify the ongoing work on atomic structure theory spectroscopy of low lying states of the isotopes 223Ra has been performed [3], where the isotope (which lives some 2 weeks) was produced by radioactive decay from a 229Th source [4]. Precise spectroscopy of the 7s2 1S0 -7s7p1 P1 and 7s2 1S0 -7s7p 3P1 transitions as well as lifetime measurements of the 7s7p 3P1, 7s6d 3D1 and 7s6d 1D2 states were performed as a test of atomic theory and to prepare the system for efficient cooling and trapping of the atoms. The basic problem of efficient trapping of heavy rare earth elements has been approached with the trapping of atomic barium, where 1% efficiency has been achieved [5]. Similar research is going on at the Argonne National Laboratory in the U.S. [6].

[1] V.V. Flambaum, Phys. Rev. A 60, R2611 (1999)+ V.A. Dzuba et al., Phys. Rev. A **61**, 062509 (2000)
[2] U. Dammalapati, PhD thesis, University of Groningen (2006); S. De, , PhD thesis, University of Groningen (2006); B Santra, PhD thesis, University of Groningen (2013);
[3] U. Dammalapati et al., Eur. Phys Jour. D **53**, 1 (2009)
[4] H.W. Wilschut et al., Nucl. Phys. A **844**, 143 (2010)
[5] S. De et al., Phys. Rev. A **79**, 041402 (2009)
[6] R.H. Parker et al., Phys. Rev. C **86**, 065503 (2012)

Status of CKM in the light of recent results

M. Bona
Particle Physics Research Centre, School of Physics and Astronomy, London E1 4NS, UK

The vast amount of flavour physics results delivered in the last decade by the B factories and the Tevatron have been continuously improving our knowledge on all the B sectors allowing for precision test of the Standard Model (SM). More results are now flowing from the LHC experiments, in particular LHCb, now delivering unprecedented insight and new evidences of rare decays. The CKM picture is now showing an amazing consistency with the SM expectations setting strong constraints for the New Physics (NP) model building. The Unitarity Triangle (UT) analyses within and beyond the SM are powerful tools to summarise the state of the art and explore the possibilities for future NP searches.

CP and flavour violation in the charged leptonic sector

P. Paradisi
ISAC-CNR, Strada Prov. Lecce-Monteroni km 1, 200, 73100, Lecee, Italy

CP and flavour violation in the charged leptonic sector (LFV) are predicted to be extremely small within the SM (even if we supplement the SM with a mechanism accounting for the neutrino masses) at a level, which is far beyond any realistic experimental reach. As a result, the search for CPV and LFV in charged leptons is probably the most interesting goal of flavor physics in the next few years in the attempt to discover New Physics (NP) effects. In this talk, I will review the predictions for CPV and LFV processes in well-motivated NP extensions of the SM exploiting the correlations among observables as a tool to discriminate among different NP scenarios.

Wednesday, 20th Feb 2013

Experimental Results on CP Violation in the Quark Sector

G. Mohanty
Department of High Energy Physics, TIFR, Homi Bhabha Road, Colaba, Mumbai 400005, India

About four decades earlier Kobayashi and Maskawa proposed that the violation of charge-parity (CP) symmetry in the standard model can be explained by a single irreducible phase, which would naturally occur if there are three families of quarks. Two e+e- flavor-factory experiments -- Belle at KEK and BaBar at SLAC -- were built to verify this highly predictive scheme in the B-meson system. The two sister experiments did their job well as to be later recognized with the citation of the 2008 physics Nobel prize, awarded to the two Japanese physicists. So far all experimental data brilliantly fit to the KM scheme, although we know for sure that the latter can't be the whole story explaining the observed baryon asymmetry in universe. In this talk, we present a suite of CP violation measurements carried out with Belle and BaBar as well as at hadron collider experiments of Tevatron and LHC.

Neutron EDM in physics beyond the standard model

J. Hisano
E-ken, Theoretical Particle Physics Graduate School of Science, Nagoya, Aichi 464-5602, Japan

I will show the relation between parton-level CP violating interactions, which are induced in physics beyond the standard model, and neutron EDM. FIrst, we discuss the radiative correction for the wilson coefficients of the CP violating operators, and next, we evaluate the neutron EDM from them with the QCD sum rules. I can discuss about the EDM in the SUSY SM, which is the leading candidate of physics beyond the standard model.

Charming CP & all that

A. Soni
Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA

Our understanding of CP violation will be briefly reviewed. Importance of CP violation searches in charm sector will be emphasized. Status of experimental observations and their repercussions for the SM will be discussed.

Going beyond Mahabaleshwar: Search for CPT Violation

A. Kundu
Department of Physics, University of Kolkata, West Bengal, India

CPT is, till now, the only combination of the three discrete symmetries that is unbroken. In fact, CPT violation is linked intimately with Lorentz symmetry violation. In this talk, I discuss some possible motivations of looking for CPT violation, and the search for CPT violation in particle physics experiments, particularly in those involving B mesons. I also discuss some recent strategies proposed by us to disentangle CPT violating effects in neutral B meson mixing and decay from conventional CPT conserving new physics.

Ultra-Cold Neutrons and Searches for an Electric Dipole Moment

P. Geltenbort
Institut Laue-Langevin, 6 rue Jules Horowitz, B. P. 156, F-38042 Grenoble Cedex 9, France

Due to their outstanding property to be storable and hence observable for long periods of time (several hundreds of seconds) in suitable material or magnetic traps, ultra-cold neutrons (UCN) with energies around 100 neV are an unique tool to study fundamental properties of the free neutron. A brief introduction to the Institute Laue-Langevin (ILL) in Grenoble, France, which is a world leader in academic research with neutrons will be given. The scope of fundamental physics studies with neutrons is outlined. The main instruments provided for such studies are described and some past and current flagship experiments with ultra-cold neutrons (UCN) in this field (lifetime and quantum states) are highlighted. The properties and the production of UCN are described in detail.

For particles to have electric dipole moments, the forces concerned in their structure must be asymmetric with regard to space-parity (P) and time reversal (T). P violation is a well-known intrinsic feature of the weak interaction, which is responsible for the beta-decay of the free neutron. T violation turns out to be necessary to explain the survival of matter at the expense of antimatter after the Big Bang. By searching for an EDM of the free neutron hypothetical new channels of T-violation can be investigated. In this talk two EDM projects will be presented in detail, an experiment at room temperature that has recently been completed and a cryogenic experiment that is currently being constructed. The experiments are based on a precision measurement of the Larmor precession frequency of polarized ultracold neutrons stored in a cell in a magnetic field. An EDM would reveal itself by a response of the Larmor precession frequency of the neutron to an electric field applied over the storage volume. The room temperature experiment has been carefully analyzed. An upper limit on the absolute value of the neutron EDM of $|d_n| < 3.0 \times 10^{-26}$ e·cm (90% CL) has been found (PRL 97, 131801 (2006)). The two experiments at the ILL will be compared to competing EDM projects worldwide.

Search for a neutron electric dipole moment at PSI

P. Schmidt-Wellenburg
Department NUM, Paul Scherrer Institute, WBBA/120, CH-5232 Villigen-PSI, Switzerland

At the Paul Scherrer Institute (PSI) in Switzerland a collaboration of 14 European institutions is searching for a neutron electric dipole moment (nEDM) using ultra cold neutrons (UCN). We intend to improve the current upper limit by the RAL/Sussex/ILL collaboration, $d_n < 2.9\text{E}^{-26}$ ecm @90% C.L. [C. Baker et al. PRL 97, 131801 (2006)] by a factor ten in the next years, by using the same but improved and upgraded instrument connected to the new high intensity UCN source. Latest measurements have shown that we now have a higher statistical day to day sensitivity than the former search by RAL/Sussex/ILL. In parallel we are preparing a next generation experiment which will further improve the sensitivity by a factor 10 by making better use of the UCN source at PSI. A nEDM value larger than the Standard Model prediction (~1E^{-31} ecm) might help to explain the baryon asymmetry of the Universe, or shed light on to the strong CP problem.

Nucleon EDM in Lattice QCD

E. Schintani
RIKEN-BNL, Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

We present a review of lattice calculation of neutron (and also proton) electric dipole moment (EDM). We will also discuss about recent EDM calculation with new technique, which can increase the statistics in Monte-Carlo method.

Thursday, 21th Feb 2013

Measurement of muon g-2/EDM

T. Mibe
Institute of Particle and Nuclear Studies, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Pricision determination of dipole moments of leptons offers sensitive tests of physics beyond the standard model. Muon being 200 times heavier than electron enhances the such effects in quantum loops. The measurement of the anomalous magnetic moment (g-2) at BNL deviates from the standard model prediction more than three standard deviations. Confirmation of the deviation by upcoming experiments is urgently desired to outline the future survey of new physics.

A new measurement of g-2 and EDM of the positive muon is proposed with a novel technique utilizing an ultra-cold muons accelerated to 300 MeV/c and a 66 cm-diameter compact muon storage ring without focusing-electric field. This measurement will be complementary to the previous BNL experiment and its planned continuation at FNAL with the muon beam at the magic momentum 3.1 GeV/c in a 14 m-diameter storage ring.

In this talk, I'd like to overview the muon g-2 and EDM measurements in the past, discuss future experiments with an emphasis on the one with ultra-cold muon beam.

Baryon Asymmetry of the Universe and CP Violation

U. A. Yajnik
Department of Physics, IIT Bombay, Powai, Mumbai 400076, India

Mechanisms of baryogenesis at GUT scale and TeV scale, the role of sphalerons, CP violation in particle decays and from transient effects in phase transitions, Leptogenesis at high scale and at low scale, Connection to CP violation in neutrino mixing and Status of MSSM and SO(10) will be discussed in this talk.

K → π π Decays from Lattice QCD

A. Lytle
Department of Theoretical Physics, TIFR, Homi Bhabha Road, Colaba, Mumbai 400005, India

The Standard Model predictions for CP-violation in the kaon system require precise theoretical control of K --> π π hadronic decay amplitudes. I will explain and report on the status of physically realistic, from-first-principle QCD calculations of K → π π decays being carried out by the RBC and UKQCD collaborations. These are the first realistic ab-initio calculations of a fully hadronic decay.

Friday, 22nd Feb 2013

Search for the electron EDM

E. A. Hinds
Centre for Cold Matter, The Blackett Laboratory, Imperial College, London SW7 2BW, UK

We have made a new measurement of the electron's electric dipole moment (EDM) using a beam of YbF molecules [1,2]. By measuring atto-eV energy shifts in a molecule, this experiment probes new physics at the tera-eV energy scale. According to the standard model, this EDM is some eleven orders of magnitude below the current experimental limit. However, most extensions to the standard model predict much larger values, potentially accessible to measurement [3]. Hence, the search for the electron EDM is a search for physics beyond the standard model. I will describe our experimental method, our current results, and their implications for particle physics. I will also discuss the prospects for further major improvements in sensitivity.

[1] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, E. A. Hinds "Improved measurement of the shape of the electron", Nature 473, 493 (2011). doi:10.1038/nature10104
[2] D. M. Kara, I. J Smallman, J. J. Hudson, B. E. Sauer, M. R. Tarbutt and E A Hinds, "Measurement of the electron's electric dipole moment using YbF molecules: methods and data analysis, New J. Phys. **14** 103051, (2012).
[3] E. D. Commins, *Electric dipole moments of leptons*, in Advances in Atomic, Molecular, and Optical Physics, Vol. 40, B. Bederson and H.Walther (Eds.), Academic Press, New York, pp. 1-56 (1999).

Theory of the Electric Dipole Moments of Atoms and Molecules

B. P. Das
Theoretical Physics and Astrophysics Group, Indian Institute of Astrophysics, Bangalore 560034, India

The electric dipole moments (EDMs) of atoms and molecules originate from P and T (or CP) violating interactions involving their constituent particles and they are excellent probes of new physics beyond the Standard Model. It is possible extract limits for different CP violating coupling constants by combining the results of atomic/molecular EDM experiments and many-body calculations.

My talk will focus on the theory of EDMs of atoms and molecules arising from the EDM of the electron. In particular, I shall emphasise the importance of relativistic and many-body effects in atomic EDMs and present results for Cs and Tl EDM. I shall also discuss some important issues in the many-body theory of molecular EDMs.

Study of T,P-nonconservation effects and hyperfine constants in diatomics and solids by the relativistic pseudopotential / core-restoration method

[1]A. V. Titov, [1]A. N. Petrov, [1]L. S. Skripnikov, [1]N. S. Mosyagin and [2]A. D. Kudashov
[1]Department of Physics, Saint-Petersburg State University, Petrodvoretz 198904, Russia
[2]B. P. Konstantinov Petersburg Nuclear Physics Institute, Gatchina 188300, Russia

The relativistic pseudopotential (RPP) [1] calculations of valence (spectroscopic, chemical etc.) properties of molecules are now most efficient in general because the modern two-component RPP methods allow one to treat very accurately both correlation and relativistic effects for the valence and outer-core electrons of a molecule and to reduce dramatically the computational cost. In particular, some combined computational schemes can be applied which include both fully relativistic and highly-correlated scalar-relativistic approaches. Such combined schemes are firstly important for studying compounds of d- and f-elements, many-atomic systems and crystals. To reduce efforts, valence molecular spinors are usually smoothed in atomic cores and, therefore, direct calculation of proper densities of valence electrons near heavy nuclei within such RPP approaches is impossible. The knowledge of electronic density matrices in atomic cores is required to study hyperfine constants and other magnetic properties, time-reversal (T) and space parity (P) nonconservation effects, which are described by the operators heavily concentrated in atomic cores. For such properties the electronic structure should be well evaluated in both valence and atomic core regions of studied systems. The relativistic one-center core-restoration technique [2] developed by the authors overcomes the restrictions of the RPP method and extends its applicability to core-concentrated properties while preserving the advantages of using RPPs. The features of the two-step method (RPP study of a system followed by the electronic structure restoration in atomic cores), presented in the lecture, are compared to those of the all-electron four-component approaches.

Study of both spectroscopic and core-concentrated properties (hyperfine constants, P- and T,P-nonconservation effects) is discussed for polar heavy-atom diatomics (HfF+ [3], RaO [4], WC [5], PtH+, PbF, RaF, YbF etc.), Eu^2+ in an external electric field simulating Eu-in-Eu_{0.5}Ba_{0.5}TiO_3 and solids (PbTiO_3 etc.), which are of interest for the experimental search of the electron electric dipole moment, Schiff and anapole moments of nuclei.

[1] N.S.Mosyagin, A.V.Zaitsevskii, A.V.Titov, Int.Rev.At.Mol.Phys., 1(1), **63** (2010).
[2] A.V. Titov, N.S. Mosyagin, A.N. Petrov, T.A. Isaev, D.P. DeMille, Progr. Theor. Chem. Phys. B **15**, 253 (2006).
[3] K.C. Cossel, D.N. Gresh, L.C. Sinclair, T. Coffey, L.V. Skripnikov, A.N. Petrov, N.S. Mosyagin, A.V. Titov, R.W. Field, E.R. Meyer, E.A. Cornell, J. Ye, Chem. Phys. Lett. **546** (Frontiers) 1-11 (2012).
[4] A.D. Kudashov, A.N. Petrov, L.V. Skripnikov, N.S.Mosyagin, A.V.Titov, V.Flambaum, http://arxiv.org/abs/1211.5797, PRA, in press.
[5] J. Lee, J. Chen, L.V. Skripnikov, A.N. Petrov, A.V. Titov, N.S. Mosyagin, A.E. Leanhardt e-print: http://arxiv.org/abs/1212.5744, PRA in press.

Theoretical studies of P & T violations in heavy polar molecules

[1]M. K. Nayak, [2]H. S. Nataraj, [3]M. Kallay and [4]B. P. Das
[1]Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India
[2]Department of Physics, IIT Roorkee, Roorkee 247667, India
[3]Budapest University of Technology and Economics, Budapest, Hungary
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It is widely recognized that heavy atoms and heavy-polar diatomic molecules are the potential candidates for the experimental search for the permanent electric dipole moments (EDMs) arising from the violations of space inversion symmetry (P) and time reversal symmetry (T). The observations of non-zero P,T-odd effects in these systems at the presently accessible (expected) level of experimental sensitivity would signal new physics beyond the Standard Model (SM) of electroweak and strong interactions [1]. This is undoubtedly of fundamental importance in physics. Despite the well known limitations of the SM, there is very little experimental data available which would be in direct contradiction with this theory [2]. Some popular extensions of the SM, which overcome its disadvantages are yet to be confirmed experimentally.

In this presentation, the evaluations of the P,T-odd interaction strengths Wd and Ws using the relativistic many-body theory will be discussed. The former arises from the interaction of electron EDM de with the molecular electric field, and the latter arises due to the electron-nucleus scalar-pseudoscalar (S-PS) interaction. The knowledge of Wd is essential in obtaining a reliable limit on the electron EDM de, while that of Ws is necessary to extract the information related to the electron-nucleus (S-PS) coupling constant ks, and the two together, to test the SM of particle physics. The most recent results of Wd and Ws for the ground state of YbF obtained using a state-of-the-art coupled cluster (CC) approach will be presented and compared with those estimated earlier [2,3].

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Molecular orbital based calculations for the search of the electron EDM using the Coupled-Cluster method in the Dirac-Coulomb approximation

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We have developed a theory and programs to calculate effective electric field (Eeff) interacting with the electric dipole moment (EDM) of the electron in polar molecules. We have used the relativistic coupled cluster singles and doubles (RCCSD) method based on the Dirac-Coulomb Hamiltonian. We have modified and combined the UTChem and DIRAC08 codes for this purpose. We have calculated Eeff for molecular YbF with several types of basis sets in both contracted and uncontracted forms. We have found that the the calculations with Dyall's contracted quadruple zeta (QZ) basis sets reproduce well the previous reported spectroscopic constants with Dyall's uncontracted QZ basis sets. We discuss the dependence of Eeff on the basis sets and the correlation orbital space used in our RCCSD calculations.

A robust limit for the EDM of the electron

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Given the experimental and theoretical progress in the field of EDMs and more generally in particle physics, the necessity for more reliable bounds than the ones usually employed emerges. A recent proposal for an improved extraction of the EDM of the electron and the relevant coefficient of the electron-nucleon coupling is presented, taking into account theoretical uncertainties and possible cancellations, to be used in model-dependent analyses. Furthermore the prospects for future improvements are examined and upper limits for the EDMs of several paramagnetic systems presently under investigation are derived.

Saturday, 23rd Feb 2013

The electron EDM search using thorium monoxide

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Measurement of a non-zero electric dipole moment (EDM) of the electron within a few orders of magnitude of the current upper limit, $d_e < 1.05 \times 10^{-27}$ e-cm [Hudson et al., Nature 473, 493 (2011)], would be an indication of CP-violation originating in physics beyond the Standard Model. The ACME Collaboration is searching for an electron EDM by performing a precision measurement of electron spin precession in the metastable H $^3\Delta_1$ state of thorium monoxide (ThO), using a novel molecular beam source. Based on a data set acquired from 14 hours of running time over a period of 2 days, we have achieved a 1-sigma statistical uncertainty of $\delta d\_e = 1\times10^{-28} /\sqrt{T}$ e cm, where T is the running time in days. I will discuss the current status of the experiment and progress towards an improved measurement of the electron EDM.

Ultracold Rb-Sr atoms and FrSr molecules toward the search for an electron-EDM

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Exploring an electron's electric dipole moment (e-EDM) is one of the most fundamental problems in physics. Sensitivity of EDM measurement can be enhanced using heavy polar molecules which has the stronger electric field inside the molecules than that achieved in laboratory.

We suggested an alternative approach to prepare the ultracold molecules produced by associating laser cooled two-species atoms at the vicinity of a Feshbach resonance. Associating a diamagnetic atom and a paramagnetic Fr atom results in producing a paramagnetic molecule with an electron spin which enables us to measure e-EDM. Producing paramagnetic molecules from ultracold Fr and Sr atoms should be expected to

elongate the interaction time, and to dramatically enhance effective electric field compared with conventional Fr atomic experiments and molecular beam experiments.

We observed the simultaneous magneto-optical trapping (MOT) of Rb and Sr, which is a proof-of-principle experiment for realizing MOT of Fr and Sr.

Experimental search for atomic EDM in ^{129}Xe at Tokyo Tech.

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We aim to measure the electric dipole moment (EDM) of a diamagnetic atom ^{129}Xe to a size of 10^{-28} e-cm. Such the EDM search requires an improvement in the frequency precision down to 1 nHz. In this study, an active nuclear spin maser, which enables us to sustain the spin precession of ^{129}Xe in a long measurement duration, is employed. The developments in the frequency precision using the active spin maser and the current status of the EDM measurement will be presented.

Electron Electric Dipole Moment P,T-Odd Constant for HfF^+ from Relativistic Correlated All-Electron Theory

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We present a new and rigorous method for accurate ab-initio calculations of the electron electric dipole moment P,T-odd constant. The approach uses string-based Configuration Interaction wavefunctions and Dirac four-component spinors as one-particle basis functions, and the P,T-odd constant is obtained as an expectation value over these correlated wavefunctions. The method has been applied to the HfF^+ molecular ion to determine spectroscopic constants for four low-lying electronic states. For one of these states ($\Omega = 1$) we have determined a new accurate benchmark value for the effective electric field E_{eff} correlating 34 valence and outer atomic core electrons and using wavefunction expansions with nearly $5 \bullet 10^8$ coefficients.

The talk will also cover aspects of modern all-electron relativistic many-body approaches applicable to both atoms and molecules, and perspectives for the treatment of other interesting candidate systemsand P- or P,T- non-conserving effects in molecular systems.

Hyperfine Interaction in Diatomic as a Factor of Influence on EDM Experiments

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The interest in theoretical study of diatomics is motivated by the planned experiments to search for the electric dipole moment of the electron (EDM) [1]. The knowledge of the hyperfine structure is essential for estimating the size of the theoretical uncertainties for the calculated effective electric field on the electron (Eeff). The latter value is required for interpretation of the results of planned experiments in terms of eEDM. In this work we use the generalized relativistic effective core potential for calculation of hyperfine structure and Eeff in HfF+, PbF, PbO, and WC systems. The effect on hyperfine structure coming from interaction with different electronic states is studied. We show that in order to reproduce the experimental hyperfine structure of PbF obtained in [2] with high accuracy one must take into account the dependence of the hyperfine constants on inter nuclear distance. Besides we show that the diatomics with hyperfine structure may have advantages for measuring the electron EDM. The first advantage comes from the larger Eeff being applied to the electron at a given external electric field as compared to the diatomics with spinless nuclei. The second advantage comes from the fact that difference between g-factors for the Omaga-doublet levels can be converged to zero for some electric field [3]. The latter is important for the suppression of systematic effects in the EDM search experiment and is one of the factors which determine the sensitivity limit for the electron EDM experiment.

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Other abstracts

A Coupled Cluster Approach to the Prediction of P and CP Violating Effects in Atoms and Molecules : An Overview of the Recent Developments and Applications

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In this overview talk, we wiould highlight the current status of the computation of P and CP violating effects in Atoms and Molecules using the Coupled Cluster (CC) Approach. The CC methodologies for predicting properties other than energy have been very successful in the realm of both non-relativistic and relativistic situations. The CC methods are not variational, but its effectiveness surpasses the limitations that one may perceive they would have. We will illustrate by examples that the most commendable aspects of the CC methodology are (i) compact and efficient treatment of strong correlation, which by far outweighs the many-body perturbation theories, (ii) easy access of the CC machinery to the effects of relativity via Dirac-Coulomb or Dirac-Coulomb-Breit hamiltonian, (iii) dovetailing of the CC methods via a Lagrangian formulation to generate compact formulations of Atomic or Molecular properties. The aspect (iii) is a very redeeming feature, since the Lagrangian formulation for the computation of properties via the inherently non-variational CC methods restores such desirable properties as the Wigner (2n+1)-rule. The emphasis of this talk would be to summarize the various salient features, current successes, comparison with other allied theories and expound our future outlook.

Electric Dipole Moments of Some Closed-shell atoms

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In this talk, I would like to describe EDM calculations of few closed-shell atoms of experimental interest. The calculations performed, illustrate the role of electron-correlation in determining its value. Important many-body contributions to final EDM of these atoms are highlighted.

The Atomic and Molecular EDM Calculations

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It is presumed that the elementary particles possess the electric dipole moment (EDM), a property which requires a simultaneous violation of both parity and time-reversal symmetries. The intrinsic EDMs of electrons and quarks and their symmetry violating interactions manifest in enhancing the EDM for atoms and molecules. We report the recent development of the state-of-the-art many-body program for the high precision calculations of various symmetry violating interactions in atoms and molecules. The details of the calculations together with the summary of the latest results will be presented.

Signal of New Physics in B Decays to $\varphi \rightarrow K_2^*$

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If the new physics(NP) is absent or the pattern of NP is alike of the standard model (SM) amplitude, there are some relations among observables that are consistent with the SM relations. The violation of these relations is a clear signal of NP and the pattern of NP will be different from the SM. If any of them ($\Delta\varphi_{\backslash|}$, $\Delta\varphi_{\perp}$ and $\Delta\delta_0$) has large value, there will be clear violation the SM relations among observables. Recent data from HFAG is showing that the value of $\Delta\varphi_{\backslash|}$ is indeed large in the decay mode B $\rightarrow$ K_2^{*0} but with large exp. error. Hence, there is clear violation of the SM relation among observables in the decay mode on the basis of the central values. We hope that there will be more precise experimental data for $\Delta\varphi_{\backslash|}$ in decay mode B $\rightarrow$ K_2^{*0} in near future If we assume that the pattern of NP is different from that of the SM, then it is possible to isolate the SM and the NP from the experimental data in B $\rightarrow$ K_2^{*0}. We have seen that that current data in the above decay mode is indicating some room for NP.

Theoretical Approach for the Study P- and P,T- Odd Effects in Polar Molecules

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Heavy polar diatomic molecules such as BaF, YbF, TlF, PbO, etc. are the prime experimental probes for the search of violation of inversion symmetry (P) and time-reversal invariance (T). The experimental detection of such effects has great importance [1, 2] for the theory of fundamental interactions or for physics beyond the standard model [3, 4]. Experiments on YbF, BaF molecules have significant effect to the study of symmetry violation in nature, as these experiments have the potential to detect effects due to the electron EDM. These accurate theoretical calculations are also necessary to interpret this ongoing (and perhaps forthcoming) experimental outcome [5]. The P- and T-odd effects in heavy polar diatomics can obtained by calculating the values of related P- and T-violating operators and making use of them with experimental values.

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Calculation of the Parity and Time Reversal Violating Interactions in Crystals

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One of the most intriguing fundamental problems of modern physics is the search for a permanent electric dipole moment (EDM) of elementary particles. A nonzero value of EDM implies manifestation of interactions which are not symmetric with respect to both spatial and time inversions (P,T-odd interactions). The observation of electron EDM at a level significantly greater than 10^{-38} would indicate the presence of a "new physics" beyond the standard model; popular extensions of the standard model predict the magnitude of the electron EDM at the level of 10^{-26} – 10^{-28} [1]. To date, the most rigid restrictions on the electron EDM value were obtained in atomic [2] and molecular experiments [3]. However, recently a new series of experiments toward the search of the electron EDM were performed on a Eu0.5Ba0.5TiO3 crystal [4]. A feature of all these experiments is that the interpretation of their results in terms of quantum particles EDM requires knowledge of the magnitude of an internal effective electric field, which cannot be measured experimentally, and is the problem of a theoretical research. Such calculation is not a routine task because both relativistic (systems under considerations should contain heavy atom(s)) and the electron correlation effects should be taken into account. In the last decades a number of such calculations were performed by our and other groups for atoms and molecules. However, calculation of an effective field in solid is not a well-developed technology and it is considerably more challenging problem for a theoretical investigation. Up to now there were only a few rather simple models considered for such a study. In these models a local electronic structure in the vicinity of the heavy atom nucleus was simulated by a cluster of nearest atoms [5] or by some spherical potential ("jelly model") [6]. In the present work a new approach of calculation of effective fields in crystals is proposed. It is based on the two-step concept of core-properties calculations [7]. The approach is implemented in a new program codes. It is used to calculate internal effective fields in a number of perovskite structures such as the $PbTiO_3$ crystal. The results are compared with the previous model calculations. Suggested approach can be used to calculate a number of other "core" properties such as hyperfine structure constants, chemical shifts, nuclear quadrupole coupling constants, etc. in solids.

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Ab intio Studies on Ground and Excited States of Open/closed-shell Polar Molecules for Ultracold Matter Studies

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I will talk about basic calculations in diatomic molecules and will discuss the application to lattice clocks, mp/me variation studies and nuclear EDM studies in closed shell diatomic molecules. In the nuclear EDM studies again, I am not yet ready to present any numbers on nuclear EDM but we are looking at a particular candidate inspired from atomic calculations and looking at the energy structure to help experimentalists to device their experimental setup.

Ultra Cold Muon for J-PARC μ g-2/EDM Experiment

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There is 3.3 sigma discrepancy between the measured value of muon g-2 and theoretical its value in standard model. We are going to measure the precision value of muon g-2 and search for the physics beyond standard model. In addition, we can search for muon EDM which violates CP symmetry. CP violation in charged lepton sector is currently not found. We are developing the "Ultra Cold Muon Beam" instead of tertiary muon beam with electric focusing. Ultra cold muon is realized by laser ionization of muonium (bind state of muon and electron) from the production target. Increase of muonium yield is quite important for our experimental goal; 0.1 ppm statistical precision. Muonium production experiment in J-PARC MUSE is planned in this winter.

Neutron, Deuteron and Mercury EDM in Supersymmetry

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We present a detailed analysis together with numerical calculations on one-loop contributions (as opposed to two loop contributions reported in literature) to the neutron, deuteron, and mercury electric dipole moment from supersymmetry without R parity.It turns out that neutron and deuteron electric dipole moments (EDMs) receive much stronger contributions than the mercury EDM and any null result at the future deuteron EDM experiment or Los Alamos neutron EDM experiment can lead to extraordinary constraints on RPV parameter space.Even if R-parity violating couplings are real,Cabibbo-Kobayashi-Maskawa (CKM) phase does induce RPV contribution and for some cases such a contribution is as strong as the contribution from phases in the R-parity violating couplings.Interestingly, even if slepton mass and/or 0 is as high as 1 TeV, it still leads to neutron EDM that is an order of magnitude larger than the sensitivity at the Los Alamos experiment. Since the results are not much sensitive to tan(β), our constraints will survive even if other observables tighten the constraints on tan(β).

^{3}He Comagnetometer in ^{129}Xe Active Spin Maser for EDM Maesurement

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We aim to measure the electric dipole moment (EDM) of a diamagnetic atom ^{129}Xe to a size of 10^{-28} e-cm. Such the EDM search requires the improvement of the precision in frequency down to a level of 1 nHz. The previous developments of the active nuclear spin maser have improved the precision of frequency determination to about 10 nHz for a one-shot measurement. However, systematic uncertainty arises from a long-term drift in frequency originating from in the external magnetic field. A comagnetoneter using ^{3}He has been incorporated to the system in order to cancel out a long-term drift in the external magnetic field. The developments in the comagnetometer will be discussed in the presentation.

Strong CP Solution Predicts nEDM, Leptonic Phases

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We show using the left-right symmetric model extended with a vectorlike quark family that parity (P) with CP can solve the strong CP problem without the need for an axion. Neutron EDM is radiatively generated when P and CP break softly or spontaneously and is at an experimentally interesting range, even if all new physics is at a very high scale such as the GUT scale. This is unlike models with axions where beyond the standard model contributions to neutron EDM vanish with the increasing scale of new physics. Tree level leptonic CP violation is absent in the minimal model and we also show more generally that discovery of absence of leptonic CP violation would be a signal for models with CP and an additional symmetry such as P, Z_2 , Z_4 , etc.

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3) hep-ph/1209.3031 "P stabilizes dark matter and with CP can predict leptonic phases"

All about magicwavelengths

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It has been known for some time that atoms can be trapped and manipulated by the gradient forces of light waves. However, for any two internal states of an atom, the Stark shifts caused due to the trap light are different which affects the fidelity of the experiment. Katori et al. [1] suggested a solution to this problem that the trapping laser can be tuned to wavelength, "magic", where the differential ac Stark shifts of the transition vanishes. Knowledge of magic wavelengths is necessary in many areas of physics. In particular, these wavelengths have unavoidable application for atomic clocks and quantum computing. For example, a major concern for the accuracy of optical lattice clocks is the ability to cancel the large light shifts created by the trapping potential of the lattice. Similarly, for most of the quantum computational schemes, it is often desirable to optically trap neutral atoms without affecting the internal energy-level spacing for the atoms. Over the years, there has been quite a large number of calculations of the magic wavelengths of alkali-metal atoms for linearly polarized traps, with rather fewer calculations of the magic wavelengths for the circularly polarized traps. Using the circularly polarized light may be advantageous owing to the dominant role played by vector polarizabilities in estimating the ac Stark shifts. These poalrizability contributions are absent in the linearly polarized light. In this talk, I will discuss our recent work on investigation of magic wavelengths for linearly and circularly polarized light for various alkali-metal atoms. Further, I will discuss application of magic wavelengths for experiments which involve simultaneous trapping of different alkali atoms in the same optical traps. This will be accomplished by matching the oscillation frequencies of different species held in the same optical trap. Use of bichromatic laser beams for state-insensitive trapping of species will be discussed in the end. This scheme allows to select convenient and easily available laser wavelength for experiments where it is essential to precisely localize and control neutral atoms with minimum decoherence.

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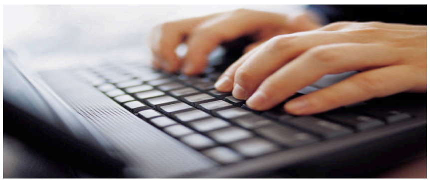

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