SPIN AS A PROBE OF SPACE-TIME SYMMETRIES IN LOW AND INTERMEDIATE ENERGY REGION

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Topics on parity violation in hadronic interactions and time reversal violation in low energy region are presented. The helicity asymmetry for p-p scattering is being measured at 221 MeV, where the $^1S_0$-$^3P_0$ amplitude vanishes. On the other hand, large enhancements of the parity violation effect have been observed in low energy neutron resonance absorption in various nuclei. The phenomena can be explained by the s-p mixing model and suggest the possibility of the test of time reversal violation.
The recent progress of the measurements of the neutron EDM with ultra cold neutrons as well as a new approach to observe the neutron EDM making use of non-centrosymmetric crystal are shown. Atomic EDM measurements of new generation are also mentioned, with which the accuracy is improved by factor of 10 to 100.

1 Introduction

The spin has been one of the most important probes to search for phenomena of parity violation and time reversal violation for long time. In recent years, measurements of asymmetries related to the spin in hadronic interactions have been shown to be one of the promising ways to study the weak interaction in hadronic systems. In particular, the helicity asymmetries for hadron-hadron interactions provide a window on the interplay between the weak and strong interactions. We will report recent experiments of helicity asymmetries for p-p scattering and those for low energy neutron resonance absorption in various nuclei, since these observables give the keys to understand the parity violating interaction in nuclei.

Time reversal violation has not been found , even though experimental efforts have been devoted to find these phenomena for 50 years. Since the measurements of EDM's of the neutron and atoms provide a sensitive test of T and P violations, recent experimental results and new possibilities to improve them will be shown below. A possible measurement of time reversal violation making use of the phenomena of the enhancement of parity-violation in neutron-nucleus interactions will also be mentioned.

2 Parity Violation in Hadron-Hadron Interaction

So far little information on parity violation in non-leptonic interactions is available because of the difficulty of accurate measurement of small effect of the interplay between the weak and strong interactions in hadronic reactions.

The simplest contribution to parity violation in the coupling between nucleons is a single W or Z^0 exchange. The diagrams give rise to effective pseudoscalar potentials between two nucleons. However, the effect is greatly suppressed, since the strong N-N interaction is repulsive at very short distance. Therefore, the largest contribution to the weak N-N interaction comes from the exchange of a single meson (π,ρ,ω) where one of the vertices is governed by the strong interaction, and the other by the weak interaction. The ratio of parity non-conserving (V_{PNC}) to parity-conserving (V_0) potential is estimated as

$$\frac{V_{PNC}}{V_0} \cong G_F m_\pi{}^2 \cong 2\times 10^{-7}. \tag{1}$$

Therefore, the order of magnitude of the parity non-conserving helicity asymmetry in N-N scattering is about 10^{-7} in low energy region. Assuming one-boson exchanges, Desplanque et al. calculated a set of six weak meson-nucleon coupling constants $f_\pi^1, h_\rho^0, h_\rho^1, h_\rho^2, h_\varpi^0, h_\varpi^1$, where the subscripts indicate the exchanged mesons and the superscripts the isospin changes.

The helicity asymmetries in the total cross section A_L in p-p scattering were measured at 13.6 MeV in Bonn and at 45 MeV in PSI. The results are

$$A_L = (-0.93 \pm 0.20 \pm 0.05)\times 10^{-7} \quad \text{at 13.5 MeV [1)]} \tag{2}$$

$$= (-1.57 \pm 0.23)\times 10^{-7} \quad \text{at 45 MeV.[2)]} \tag{3}$$

The results can be explained with the interference between $^1S_0$ and $^3P_0$ amplitudes qualitatively in the model of one-boson exchange. An experiment was performed at higher energy at Los Alamos. The result is

$$A_L = (0.24 \pm 0.11)\times 10^{-6} \quad \text{at 800 MeV.[3)]} \tag{4}$$

In this energy region the $^3P_2$-$^1D_2$ amplitude in addition to the $^1S_0$-$^3P_0$ amplitude contributes significantly to the helicity asymmetry.

An experiment to measure A_L at 221 MeV is in progress using TRIUMF cyclotron.[4)] At this energy, the $^1S_0$-$^3P_0$ amplitude is expected to be zero. In terms of the single meson exchange model, this experiment can determine the weak ρ-proton-proton coupling constant, h_ρ^{pp}, which is shown as

$$h_\rho^{pp} = h_p^0 + h_\rho^1 + h_\rho^2/\sqrt{6}. \tag{5}$$

A very preliminary result based on the data in February 1997 shows

$$A_L = (0.34 \pm 0.67)\times 10^{-7}. \tag{6}$$

Data taking and analysis of the measurement is in progress. The goal is the accuracy of $\Delta A_L = \pm 0.2\times 10^{-7}$. Calculation of A_L by Driscoll and Miller[5)] using Bonn potential for nucleon wave functions and the weak coupling constants of Desplanques et al. can be compared to the TRIUMF result as shown in Fig.1.

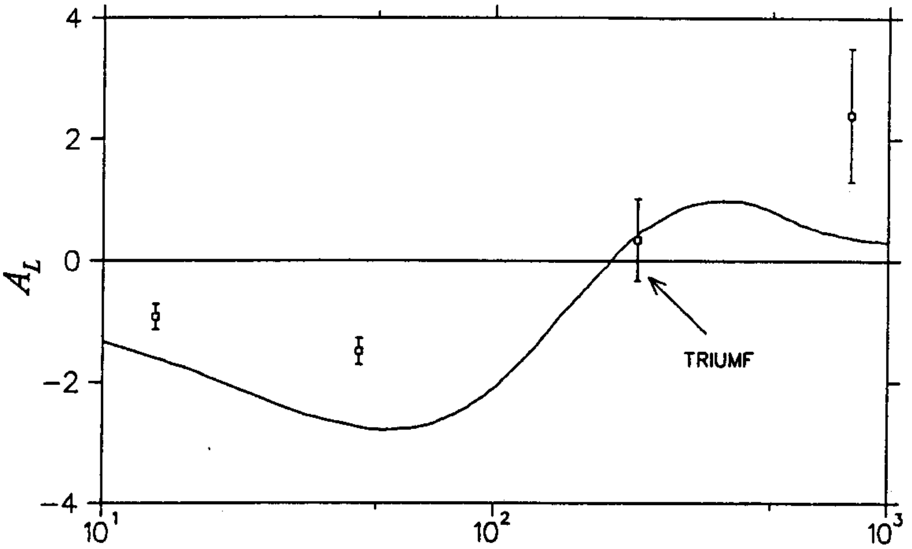

Fig.1. Preliminary result of the helicity asymmetry A_L for p-p scattering at 221 MeV as well as other results in the energy region less than 1 GeV are shown.[4] The solid line is the theoretical curve by Discoll and Miller.

3 Measurement of Parity Violation in Neutron Capture Reactions

In recent years measurements of the longitudinal asymmetries have been performed in nuetron-nucleus reactions where parity non-conserving (PNC) effects are enhanced due to the interference between very close energy levels of the same spin but opposite parities. A Dubna group[6] and a KEK-Kyoto group[7] found a surprising large helicity asymmetry at the 0.734 eV p-wave resonance in the n + ^{139}La reaction. The experimental result of the KEK-Kyoto group is

$$A_L = (9.5\pm0.3)\times10^{-2}, \tag{7}$$

which has been obtained by means of the detection of γ-rays in radiative capture reactions and also by the transmission method. If we compare the result with those in p-p scattering, the enhancement of parity-violation effect is in the order of 10^6. Such enormous enhancement can be explained in the frame work of s- and p-wave mixing[8], in which the interference term becomes remarkably large due to long lifetimes of compound states, small difference in the resonance energies for s- and p-wave neutrons and large centrifugal potential barriers for p-wave neutrons. In the case with only one p-wave resonance and one s-wave resonance the helicity-asymmetry term satisfies

$$A_L = \frac{2xW}{E_p - E_s}\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} \,, \tag{8}$$

where E_p and E_s are the resonance energies, Γ_p^n and Γ_s^n are the neutron widths of the p- and s-wave resonances, respectively. The W is the weak matrix element in the interference between the s- and p-wave resonances and x is given as $x^2 = \Gamma_{p\frac{1}{2}}^n / \Gamma_p^n$, where $\Gamma_{p\frac{1}{2}}^n$ is the partial neutron width for j=1/2 p-wave neutrons.

In order to study the origin of the large enhancement, longitudinal asymmetries in many p-wave resonances in E_n=1 eV ~ 350 eV, have been measured for many nuclei in the mass region of A= 107~238 using the pulsed neutron beam produced by 800 MeV protons at LANSCE in Los Alamos.[9),10)] The longitudinal asymmetries on the targets ^{238}U, ^{232}Th, ^{127}I, ^{115}In, ^{133}Cs, ^{93}Nb and natural Ag and Xe were measured using transmission detectors made of ^{10}B-loaded liquid scintillator. In addition, the data on ^{113}Cd and natural Pd and Sb were taken using both the neutron transmission detectors and captureγ-ray detectors made of BaF_2. Preliminary results of helicity asymmetries on ^{127}I are shown in Fig.2.

In the analysis of the results statistical treatment of the asymmetries has been carried out, since there are many p-wave resonances interfered with several neighboring s-wave resonances. The parity violating asymmetry P_i for the i th p-wave resonance can be written as

$$P_i = \sum_j \left(\frac{2x_i V_{ij}}{(E_{sj} - E_{pi})}\sqrt{\Gamma_{sj}^n / \Gamma_{pi}^n}\right), \text{ where } V_{ij} \equiv \langle \varphi_{sj} | H_W | \varphi_{pi} \rangle \,. \tag{9}$$

According to the statistical model of the compound nucleus, the neutron decay widths and the weak matrix elements V_{ij}'s are Gaussian random variables with zero mean. If the spin of the target nucleus is zero, parity violation takes place for the resonance with spin 1/2, then x_i=1, where the asymmetries are mean-zero with variance

$$\langle P_i^2 \rangle = M^2 \left(\sum_j \frac{2}{(E_{sj} - E_{pi})}\sqrt{\Gamma_{sj}^n / \Gamma_{pi}^n}\right)^2, \text{ where } M^2 = \langle V_{ij}^2 \rangle \,. \qquad 10)$$

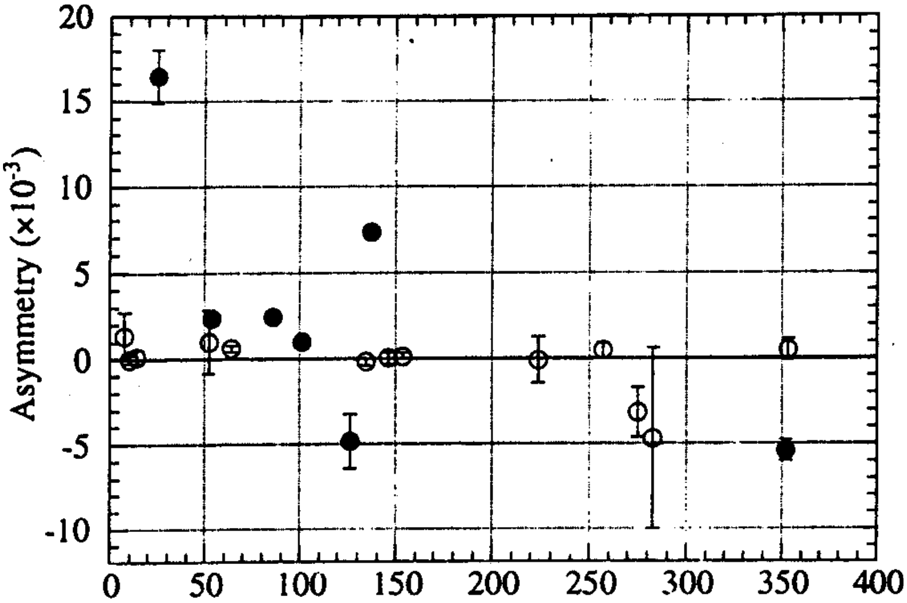

Fig. 2. Preliminary results of the helicity asymmetries for the neutron absorptions on p-wave resonances of ^{127}I.[10] Closed circles show the asymmetries whose statistical significances are greater than 3σ.

In the case of targets with spin non-zero we must treat x_i as a random variable with a probability density function, that is not Gaussian, since $\Gamma^n_{p\frac{1}{2}} + \Gamma^n_{p\frac{3}{2}}$ is fixed for each p-wave resonance. The values of M^2 are being calculated with measured asymmetries by means of a likelihood analysis. Then the weak spreading width $\Gamma_W = 2\pi M^2 / D$ is determined from the experimental values of the asymmetries, where D is the average level spacing of the compound resonances. Based on the s-p mixing model, the value of Γ_W can be estimated to be of the order of 10^{-7} eV. The weak spreading widths Γ_W 's as a function of the mass number A are shown in Fig.3. No strong mass dependence on the target mass number has been observed.[10] The result makes the statistical treatment of weak matrix element convincing. It is concluded that the enhancement of parity violation effect in the p-wave resonances is not the phenomena only for few resonances, but is a prevalent feature of p-wave resonances located near s-wave resonances.

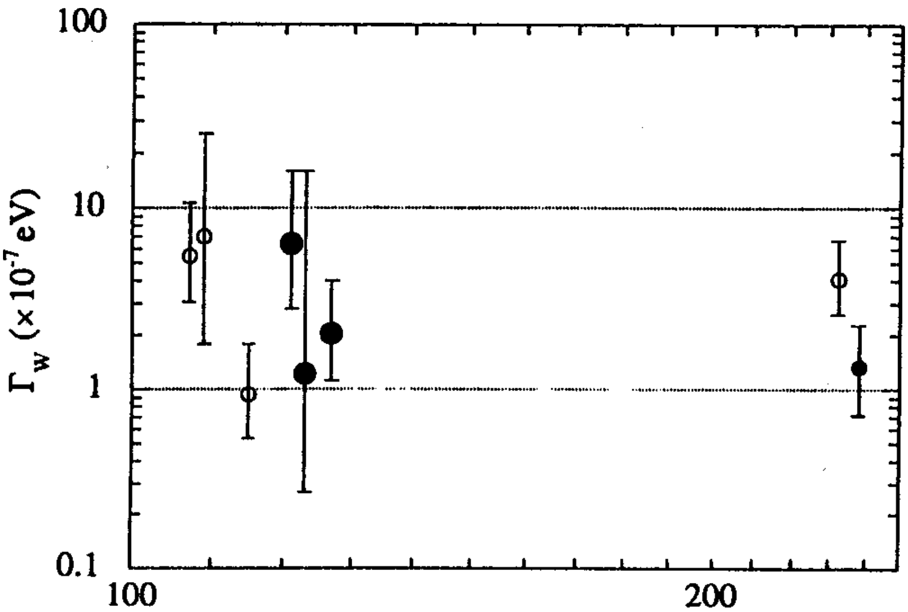

Fig. 3. The weak spreading width Γ_W as a function of the mass number.[10)]

4 Precession of Neutron Spin near the p-wave Resonance of ^{139}La

The neutron spin precesses around the neutron momentum upon transmission through matter due to the weak interaction. The magnitude of the spin rotation Φ is proportional to the real part of the difference between the forward scattering amplitudes for two opposite neutron helicities, in contrast to the helicity asymmetry A_L ,which is proportional to the imaginary part of the difference.

$$\Phi = -\frac{4\pi}{k} nl \operatorname{Re}(f(0)_+ - f(0)_-), \tag{11}$$

$$A_L = \frac{4\pi}{k} \operatorname{Im}(f(0)_+ - f(0)_-), \tag{12}$$

where n is the nuclear number density and l is length of the matter. It has been expected that the magnitude of the spin rotation is enhanced near the p-wave resonance.

In the s-p mixing model, the neutron spin rotation near the p-wave resonance is described in the formula

$$\Phi = \frac{4\pi n g}{k^2} \cdot \frac{xW(\Gamma_s^n \Gamma_p^n)^{1/2}}{\left[(E-E_s)^2 - \frac{1}{4}\Gamma_s^2\right] \cdot \left[(E-E_p)^2 + \frac{1}{4}\Gamma_p^2\right]} \cdot \left[(E-E_s)(E-E_p) - \frac{1}{4}\Gamma_s \Gamma_p\right] \quad (13)$$

where $g = (2J+1)/2(2I+1)$ is a statistical factor, and E is the incident neutron energy.

Recently, the spin rotation has been measured near the p-wave resonance of the reaction ^{139}La+n at E=0.734 eV at KEK[11], Los Alamos[12] and ILL[13].

At ILL neutrons are polarized upon transmission through magnetic crystal of CoFe adjusted to the Bragg condition in Laue geometry. The first Mezei coil (X-coil) set the neutron polarization along Y axis. (X and Y axes are perpendicular to the beam direction Z). After the neutron passed through the La crystal, the second Mezei coil (Y-coil) transformed the X-component of the polarization into longitudinal one, while the Y component remained the same. Finally the longitudinal component of the neutron spin was analyzed by transmission through a cell with ^{3}He gas which is polarized optically. The preliminary results are shown in Fig.4, in which the effect of the resonance at E_n=0.734 eV is clearly demonstrated.

A Japan-US group measured the same parameter with a ^{3}He polarizer and a ^{3}He analyser[12].

The s-p mixing can be confirmed by these experiments.

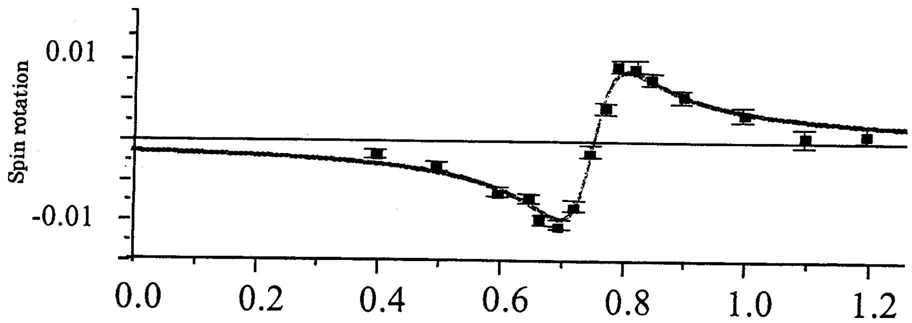

Fig. 4. Preliminary results of the neutron spin rotation near the p-wave resonance of ^{139}La at E=0.734 eV with a La target of 5 cm in thickness. The solid line shows the theoretical prediction.[13]

5 Measurement of Time Reversal Violation in Neutron Resonance Absorption

The observation of the enhancement of parity violation at p-wave resonances encourages us to promote the measurement of time reversal violation using polarized slow neutrons. If there is the same order of resonance enhancement for T-violation as for P-violation, it is possible to observe T-violation effect in neutron-capture reactions with good accuracy. The asymmetries of the order of 10^{-4} in these reactions correspond to the neutron EDM of 10^{-26} e·cm. The $\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I})$ is an example of T-odd term, where $\vec{\sigma}_n$ is the neutron spin, $\vec{k}_n$ the neutron momentum and $\vec{I}$ the spin of La target. One of the possible experiments is the measurement of the difference between the helicity flip (+→–) and that of (–→+) upon transmission of neutrons through a transversely polarized target. It is a "spin detailed balance". The difference between the probability of the spin non-flip (+→+) of vertically polarized neutron upon transmission through a target which is polarized perpendicular to the direction of the beam and the neutron spin and the probability of spin non-flip (–→–) in the same target is also a T-odd parameter[14)]. These parameters are free from final state interactions since all the observables are related to forward scattering amplitudes.

In these experiments the La target must be polarized. The $LaAlO_3$ crystal has been proposed as a polarized ^{139}La target, since La nuclei in $LaAlO_3$ containing Nd^{3+} can be polarized by means of the dynamic method. The La polarization of more than 70% has been obtained in a dilution refrigerator by a Kyoto-PSI group[15)].

6 Electric Dipole Moment of Neutron

Purcell and Ramsey pointed out the importance of searching for the electric dipole moment (EDM) of the neutron in 1950[16)]. The EDM must vanish if there is symmetry under either the parity transformation (P) or the time reversal transformation (T). Since the orientation of the particle can only be specified by the orientation of its spin, the EDM ($\vec{d}_n$) and the spin must transfer their signs in the same way under P and T, if $\vec{d}_n$ has a non-zero value.

Searches for the electric dipole moment have been carried out increasingly for almost 50 years. If the neutron makes a transition from a state with m=-1 to m=+1, the frequency (ν_0) for the transition is given by

$$h\nu_0 = 2\vec{\mu}_M \cdot \vec{B} + 2\vec{d}_n \cdot \vec{E}, \tag{14}$$

where $\vec{\mu}_M$ is the magnetic dipole moment, $\vec{B}$ the magnetic field and $\vec{E}$ the electric field.

Smith, Purcell and Ramsey constructed a neutron magnetic resonance equipment with a strong electric field between two separated oscillatory fields and measured the change in resonance frequency when the relative orientation of the electric and magnetic fields were reversed. In the first experiment they lowered the limit to $d_n = 5\times10^{-20}$ but found no electric dipole moment[17]. The experimental result in 1977 using cold neutrons from the ILL reactor at Grenoble was $(4\pm15)\times10^{-25}$ e·cm[18].

Recent experiments on the neutron EDM at Grenoble and Gatchina involve ultra cold neutrons (UCN's), of which velocities are less than 7m/sec. UCN's can be trapped in a box by neutron total reflection on the inner surface of the box. Such storage experiments could give higher sensitivity than beam experiments due to longer observation time. Furthermore, the systematic errors due to nonparallel $\vec{E}$ and $\vec{B}$ fields would be greatly suppressed, where the magnetic field generated by $\vec{v}\times\vec{E}$ results in the major systematic error. At ILL UCN's were obtained with a turbine developed by Steyerl et al[19]. Combining all the results of the measurements using UCN at ILL until 1998 give a 90% confidence upper limit of 6×10^{-26} e·cm[20]. It is a few times higher than the value predicted by the Weinberg's multi-Higgs model. The experiment will run continuously till 2001, improving the counting rate slowly.

In order to obtain high-density UCN, a superthermal UCN source in which neutrons are cooled down to the energy less than 2.5×10^{-7} eV using super-fluid helium was proposed by Golub and Pendlebury[21]. On the intersection of the neutron dispersion relation with that of superfluid ^{4}He quasi-particles at 8.8 Å a single phonon in superhelium takes away the energy of the incoming cold neutron. The UCN produced by means of the superthermal method was observed by Golub et al[22]. The production of the UCN on the intersection of the both dispersion curves was confirmed by Yoshiki et al. at JAERI[23]. It will be hopeful to use the method to increase UCN density.

7 EDM measurement Using Crystal Techniques

The electric fields in vacuum used in EDM measurements are limited to about 2×10^4 V/cm. On the other hand, non-centrosymmetric crystals exhibit Coulomb fields much higher than this. Typical examples are SiO_2 with a field of 2×10^8 V/cm, and $Bi_{12}Ge_{12}O_{20}$(BGO) with several times 10^9 V/cm. Thus scattering of the neutron on such crystals provides a good probe of EDM. In the Born approximation, the coherent spin scattering amplitude due to EDM is shown as

$$b_E'' = id_n \vec{\sigma} \cdot (\vec{k} - \vec{k}') \frac{2m}{\hbar^2} \frac{1}{q^2} \cdot e(Z - f_e(q)), \quad (15)$$

and that due to the Schwinger-type spin-orbit interaction is

$$b_S'' = 2i\mu \cdot \vec{\sigma} \cdot (\vec{k} \times \vec{k}') \frac{1}{\hbar c} \frac{1}{q^2} \cdot e(Z - f_e(q)), \quad (16)$$

where $f_e(q)$ is the atomic charge form factor. In forward and backward scattering the b_S'' term vanishes, whereas in the case of $\vec{k}' = -\vec{k}$ the term b_E'' term has the maximum value.

An experiment using dual polarized neutron beams (DPB) on non-centrosymmetric "perfect crystal" is being performed by Zeyen, Otake, Tabaru and Toperverg[24]. The test experiment has shown the feasibility for detection of the neutron EDM by means of the observation of spin rotation effect occured in transmission through the crystal as shown in Fig.5.

The goal is the measurement of EDM to the level of $<10^{-26}$ e·cm.

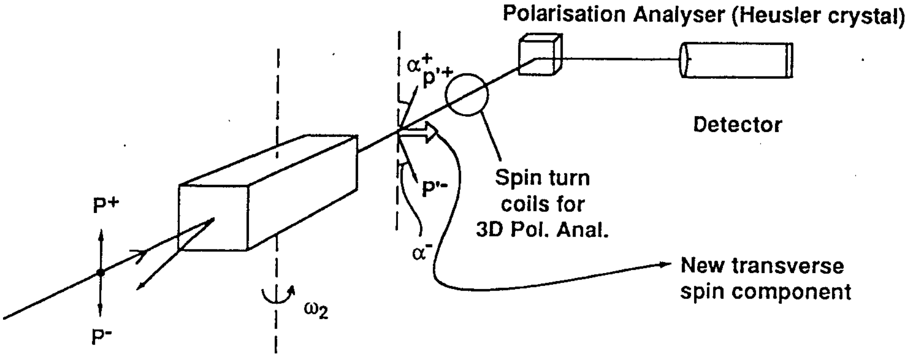

Fig. 5. Schematic view of the EDM measurement using dual polarized beams transmitted through a non-centrosymmetric crystal.[24]

8 Measurement of Atomic Electric Dipole Moments

The atomic electric dipole moments arise from EDM's of nucleons, electrons and/or interactions among nucleons and electrons. However, Schiff pointed out that the EDM of an atom vanishes even in the case that atomic constituents have EDM's, assuming that the atom consists of non-relativistic particles which interact each other only electrostatically, and the distribution of the electric dipole moment of each constituent is identical to its charge distribution[25]. The theorem works well for the ground state of hydrogen atom. However, it fails badly for heavy atoms. In fact, the atomic EDM induced by an electron in a heavy paramagnetic atom can be enhanced by 1~3 orders of magnitude. The atomic EDM (d_A) is written schematically as

$$d_A = Rd_e + C_N, \tag{17}$$

where R is the enhancement/suppression factor which depends upon the given atom, d_e is the EDM of electron, whereas C_N is the nuclear contribution. States with opposite parities mix with each other and cause the enhancement of EDM.

The standard model predicts that the electron EDM is less than 10^{-37}e·cm. A possibility of the EDM on the level of present experimental sensitivity was shown using the multi-Higgs model.

The EDM of the ground state of ^{133}Cs was measured by Hunter et al. to be d (^{133}Cs)= $-(1.8 \pm 6.7 \pm 1.8) \times 10^{-24}\, e \cdot cm,$ which implies $d_e = -(1.5 \pm 5.5 \pm 1.5) \times 10^{-26}\, e \cdot cm$ [26].

Commins et al. measured the EDM of ^{205}Tl. The result shows[27] $d(^{205}Tl) \leq 5.9 \times 10^{-24}\, e \cdot cm$, which yields $d_e = -(1.8 \pm 1.2 \pm 1.0) \times 10^{-27}\, e \cdot cm$, assuming $R = -585$.

A new measurement of the EDM of ^{205} Tl is now under way at Berkeley, with laser optical pumping for polarizer and analyzer, counter-propagating vertical atomic beam and Na beam for checking the systematic errors. The goal is the improvement of an order of magnitude.

At present, the best limit on the EDM of a diamagnetic atom comes from an experiment with ^{199}Hg at Seattle[28]. Improvements of the measurement are planned using laser beam and higher density Hg.

New measurements on ^{129}Xe EDM are going on at Michigan and TIT in Japan with use of high power laser to optically pump and polarize Rb.

A new-generation atomic EDM measurement is being pursued by Yabuzaki and Takahashi at Kyoto[29]. Yb atoms have been cooled with a laser beam down to less than 1μK and trapped in a MOT to be compressed to $\geq 10^9$/cm^3. Then the atoms have been pushed up with a laser. Near the top of the trajectory the atoms have been loaded into blue-detuned dipole-force trap. The rotation of the spin in a high electric field is being measured by the Faraday rotation method. They expect a sensitivity of d_{Yb} to be10^{-29} e·cm, which corresponds to d_e ~10^{-31} e·cm.

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