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Spin polarized atom traps and fundamental symmetries

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Plans are described to couple a neutral atom trap to an upgraded version of TRIUMF's TISOL on-line mass separator. The unique properties of trapped and cooled atoms promise improvements of some symmetry tests of the Standard Model of the electroweak and strong interactions.

1. PARTICLE PHYSICS ASPECTS OF TRAPPED NEUTRAL ATOMS

The Standard Model (SM), $SU(3)_C \times SU(2)_L \times U(1)$, is now well established and compatible with all existing experimental data. It contains parameters such as fermion masses and interfermion couplings which are not accounted for by the model. Several of the SM assumptions appear to be ad hoc and unnatural: i) neutrinos are assumed to be massless; ii) $W^\pm$ gauge bosons occur only with lefthanded helicity couplings; iii) CP violation is allowed but not explained. Extensions of the SM might show up, not only at the high-energy frontier, but also at low energies, if experiments of sufficiently high accuracy (typically a few 10^{-3} for non-vanishing observables) can be carried out. For some searches it may be an advantage to be at low energy since the interference amplitudes for established (W , Z^0) physics and new physics are both real; this is not the case for experiments near the Z^0 pole. Furthermore, the multiplicity of well-defined nuclear quantum states may nevertheless allow one to select a suitable beta decay transition which allows the most sensitive test of a specific extension of the SM. Nuclear uncertainties which might obscure the new physics of interest can often be controlled to sufficient accuracy. In beta decay one can select superallowed transitions to keep the influence of nuclear matrix elements of recoil order at a negligible level [1]. At an accuracy level below 1%, anticipated in the future for studies of parity-nonconservation (PNC) in atoms, knowledge of the distributions of u- and d-quarks (or protons and neutrons) over the nuclear volume becomes important [2]. These nuclear effects can in principle be tested by performing PNC experiments with a series of isotopes.

The isotope separator TISOL, after an upgrade compatible with 10 μ A proton beam currents from TRIUMF's 520 MeV cyclotron, will be potentially the world's brightest source of mass-separated alkali atoms. In a recent test experiment with TISOL a 7 g/cm² uranium target and a surface ion source were used to measure the production rates of a range of Fr isotopes from ²⁰⁹Fr to ²²¹Fr. The yields (see Fig. 1) show a

peak of the order of 10^8 Francium atoms per s per μ A of beam protons. Isotopes with half-lives down to 5 ms were detected. With improved beam optics and shielding of the isotope production region (TISOL upgrade) thicker targets and higher beam currents can be used. Production rates of 10^{10} atoms/sec can then be envisaged for half-lives exceeding 100 ms, comparable to or larger than what is expected [3] with the new ISOLDE parameters (2-3 μ A of 1 GeV protons). These very high production rates can be exploited by coupling TISOL to a neutral atom trap. Efficient methods will have to be developed to neutralize the alkali ions. The combination of a thin Ta/Th catcher, heated either resistively, or with desorption lasers, is one of several possible neutralization schemes.

Figure 1: Yield of Francium isotopes measured recently with TISOL. The gap for A=215-217 is caused by sub-ms half-lives. The yields were severely limited by the target thickness of 7 g/cm² because of insufficient shielding around the target.

The principle of laser cooling and trapping using the efficient Zeeman optical trap (ZOT) [4] is shown schematically in Fig. 2. Laser light with its wavelength detuned to the red side of a resonance is absorbed preferentially by atoms moving against the light. Since re-emitted light is multidirectional, the net impulse from each absorption can be used to slow the atom's momentum by $\sim 2 \times 10^{-5}$ of the average momentum at room temperature. For initial cooling of the low velocity tail the ZOT is effective to obtain temperatures of typically 200 μ K. Three-dimensional magnetic field gradients, and six counterpropagating light beams of opposite (σ^+ and σ^-) polarization produce a net force directed towards the trap centre. A quantitative model to describe the dependence of the fraction of trapped atoms on laser power and beam diameter has been developed by Lindquist, Stephens and Wieman [5]. The trapping efficiency can be

increased greatly when atoms are allowed to bounce many times from the walls of a glass vessel. This requires wall coatings with short sticking times ($< 100\mu\text{s}$), low outgassing rates, and durability in the presence of intense ionizing radiation [6]. With optimized trap geometry and Titanium-sapphire ring lasers trapping efficiencies of the order of 40% might be achievable for most alkali atoms. With a second cooling mechanism, “optical molasses” [7], temperatures as low as $\sim 1\mu\text{K}$ have been obtained. By optical pumping of a particular hyperfine transition with circularly polarized light from a single laser all the population can be quickly transferred to a single hyperfine state of maximum m_F corresponding to almost complete atomic and nuclear polarization.

Figure 2: Schematic of a one-dimensional Zeeman optical trap for neutral atoms.

Finally, the cooled atoms can be held in space *without lasers* by utilizing magnetic forces on the atom’s magnetic moment [8,9]. Movement of trapped neutral atoms from one type of trap to another has also been demonstrated [9]. In the weak magnetic field of a static magnetic trap the atom’s magnetic energy is

$$U_{mag} = g_F m_F \mu_B |B|$$

where F is the total atomic spin and m_F the magnetic quantum number. This implies that the “weak field seekers”, i.e. atoms with $g_F m_F > 0$ will collect near the trap center where $|B|$ is lowest. To counteract gravity, an additional vertical magnetic field gradient can be supplied such that

$$F_g = -mg = g_F m_F \mu_B \frac{\partial B}{\partial z}.$$

Coil geometries differ depending on whether the field minimum is zero or nonzero [10]. Quadrupole traps belong to the former category; they lose atoms due to Majorana transitions in the trap center and, furthermore, the atomic cloud tends to be unpolarized because the field direction reverses when crossing the trap center. It has recently been shown by Cornell *et al.* [11] that the trap center can be moved to a region of finite B if a rotating homogeneous field is added to the quadrupole field. The atomic spin is then

rotating adiabatically with the resultant field. Other purely static configurations which are compatible with atomic polarization are the Ioffe and baseball traps [10]. Since the restoring forces in magnetic traps are produced by field gradients the oscillating atoms sample slightly different field directions. If oscillation amplitudes and/or temperature of the cloud are measured, the effective average polarization can be calculated from the known field distributions.

The unique properties of trapped neutral atoms, i.e. compact size of 1 mm, high density (up to 10^{10} atoms), and nearly complete polarization, should have an impact on future tests of fundamental symmetries. Compared to atomic PNC experiments at Colorado [12], which use atomic beams of Cs, an atom trap might achieve target densities more than two orders of magnitude larger. The price to be paid is that a method has to be developed of reliably counting the trapped atoms, e.g. via the fluorescence of atoms excited by a probe laser.

Experiments to test fundamental symmetries in nuclear beta decay have so far been carried out with either poor geometry, poor or imprecisely known nuclear polarization, or both [1]. Trapped, isotopically pure radioactive alkali atoms promise to expand the range of nuclei available for symmetry tests, with systematic errors different, and hopefully smaller, than those of previous experiments.

2. PNC IN FRANCIUM ISOTOPES

The first PNC experiments in atoms could have provided early confirmation of the Glashow-Weinberg-Salam theory of the electroweak interaction, yet the results were incorrect (see the review in ref. 13). The PNC situation has changed dramatically during the past decade, with the latest result for ^{133}Cs [12] competitive with recent LEP results [14]. The calculations of atomic matrix elements needed to extract the weak charge are now at the 1% level for alkali atoms such as Cs [15], and further improvements may be possible in the near future. With the improved luminosity of neutral atom traps compared to the atomic beam method more accurate results on more than one isotope may become available in the future.

PNC in atoms arises in the SM from γ - Z^0 interference. The PNC Hamiltonian is

$$H_{PNC} = \delta_{PNC} < \gamma_5 \rho_N(r) > + \text{spin} - \text{dependent terms}.$$

The spin-dependent terms are small ($< 1\%$) and can be obtained by experiments on different hyperfine transitions; they also allow the determination of the anapole moment, a parity-forbidden nuclear moment [16] for which no accurate data exist so far. The overwhelming first term involves the axial-vector current of the electron, Z^0 exchange, and the vector current of quarks in the nucleus

$$\delta_{PNC} = \frac{G_F}{2\sqrt{2}} Q_w$$

The ‘weak charge’ Q_w is defined by

$$Q_w = -2[C_{1u}(2Z + N) + C_{1d}(2N + Z)]$$

with C_{1u} , C_{1d} being the $Z \rightarrow q\bar{q}$ vertex factors of the standard model, i.e.

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W$$

$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W.$$

Because of vector current conservation Q_w is independent of hadron structure and QCD effects.

PNC in atoms is sensitive to new heavy particles that affect the radiative corrections. At the tree level (i.e. without radiative corrections) the weak charge $Q_w^{\text{tree}} = -N + Z(1 - 4\sin^2\theta_W)$ determines the weak mixing angle θ_W . Since we know the factor $(1 - 4\sin^2\theta_W)$ to be small (e.g. by inferring $\sin^2\theta_W$ from the mass of the W and Z^0) the radiative corrections for PNC (about 6%) are largely independent of the W properties. If one parametrizes radiative corrections involving the exchange of new heavy particles according to the parameters S and T of Peskin and Takeuchi [17], Marciano and Rosner find [18] that atomic PNC is primarily sensitive to S , the weak isospin-conserving “new physics”:

$$Q_w(^{133}\text{Cs}) = -73.20 - 0.8S - 0.005T.$$

In Fr

$$Q_w(^{87+N}\text{Fr}) = -128.22 - 1.25S - 0.003T + 0.986(136 - N)(1 + 0.008T).$$

This insensitivity to T is in contrast to high energy experiments (e.g. at LEP/LEP2) which always involve linear combinations of S and T .

The LEP and SLC data, although extremely sensitive to interactions which directly affect the Z^0 properties, are rather indifferent to new interactions which are 90° out of phase with the Z^0 amplitude at the pole. Among the latter are extra Z' bosons with small Z^0 - Z' mixing [19], leptoquarks [20], and new four-Fermi contact terms generated by models with composite fermions [21]. It was shown by Langacker [21] that PNC results of 1% accuracy can provide limits on these interactions which are significantly better than those obtainable at LEP, SLC or HERA.

Of the two techniques used to detect atomic PNC (optical rotation, or highly forbidden $nS \rightarrow (N+1)S$ transitions with deliberately introduced Stark mixing) only the latter is suitable for measurements on relatively few isotopic atoms cooled in ZOT's. In Fr the PNC effect is about 15 times larger than in Cs, allowing for more precise tests of Q_w and the atomic physics calculations. The $7S \rightarrow 8S$ transition frequency has not yet been measured, and suitable frequency standards for frequency-locking of the lasers will have to be developed.

The adaptation of neutral atom traps to the $nS \rightarrow (n+1)S$ transition/Stark mixing technique of measuring PNC in Cs is being actively pursued by a collaboration of Wieman's group at Boulder and Viera's group at LAMPF (E1303) [22]. We are hoping to collaborate with these groups for the PNC experiment on Francium at TRIUMF (E714). There are many open questions to be answered, e.g. the importance of photoionization from the $8S$ excited state, depletion of the Fr atoms in the maxima of the standing wave

laser field, energy level shifts caused by the trapping fields, the normalization of the number of atoms loaded per cycle in the trap etc. Realistically, a number of years of development will be required until one can hope to control systematic effects to sufficient accuracy.

3. SYMMETRY TESTS IN NUCLEAR BETA DECAY

Precision tests of the SM from weak interaction experiments in complex nuclei have recently been reviewed by Deutsch and Quin [1]. The nuclear beta decay probability has been formulated by Jackson, Treiman and Wyld [23] without assumptions with respect to parity, charge conjugation, and time reversal, and including the possibility of non-standard scalar and tensor couplings. The transition probability dW can then be written as

$$dW = dW_0 \xi \left(1 + \frac{\vec{p} \cdot \vec{p}_\nu}{EE_\nu} a + \frac{\Gamma m_e}{E} b + \langle \mathbf{J} \rangle \cdot \left[\frac{\vec{p}}{E} A + \frac{\vec{p}_\nu}{E_\nu} B + \frac{\vec{p} \times \vec{p}_\nu}{EE_\nu} D \right] \right. \\ \left. + \vec{\sigma} \cdot \left[\frac{\vec{p}}{E} G + \hat{p} \hat{p}_\nu \langle \mathbf{J} \rangle Q' + \langle \mathbf{J} \rangle \times \frac{\vec{p}}{E} R \right] \right)$$

In this expression $dW_0 \xi$ contains the coupling strength, Coulomb and phase space factors, $\Gamma = \sqrt{1 - (\alpha Z)^2}$ is a Coulomb factor, $\langle \mathbf{J} \rangle$ is the vector polarization of the parent nuclear state, $\vec{\sigma}$ the beta spin, $\vec{p}$ and $\vec{E}$ are momenta and energies of beta or neutrino. In the SM the Fierz interference term b and the T-violating parameters D and R vanish, whereas the $\beta - \nu$ correlation a , the β - and ν - asymmetry parameters A and B , respectively, β -polarization G , and polarization asymmetry correlation Q' depend on angular momentum and on the ratio of matrix elements $\lambda = g_A M_{GT} / g_V M_F$.

Neutral atom traps offer new opportunities because i) high (i.e. close to 100%) polarizations of the parent nucleus can be achieved, ii) particles of interest are emitted from a well localized volume, and iii) momenta of particles leaving the source volume are free of distortions because of the negligible source thickness. The most relevant parameters are the spin correlation coefficients A , B and D , and, at a later stage, when positron polarimetry is added, the R parameter. Because of the special properties of the neutral atom trap all types of measurements that have been performed with cold or ultracold neutrons could be pursued with nuclear positron emitters. It should be noted that present values for the neutron lifetime and the neutron asymmetry A_n disagree with the expectations of the SM by about 2.5 standard deviations [1].

Independent measurements for mirror transitions having mixed Fermi and Gamow-Teller transitions such as ^{19}Ne (measurements by Calaprice's group at Princeton [24]), ^{21}Na [25] and ^{37}K [26] are especially interesting because several parameters, if measured, could allow a comprehensive test of the consistency of augmenting the SM with new physics of a certain type. In Table 1 we show predictions of the SM for the mixed Gamow Teller - Fermi ground state decay of $^{123}\text{S}^{37}\text{K}$, assuming that $g_A M_{GT} / g_V M_F = -0.581$. The ft value is presently only known to an accuracy of 0.7%, however a new measurement with better than 0.1% accuracy is planned at TASCC [27]. It is seen

that statistically significant deviations of $\geq 0.2\%$ from the SM values in Table 1 would be indicative of new physics outside the SM.

Table 1. Observables in ^{37}K Positron Decay ^{a)}

observable	a	A	B	G	Q'
value ^{b)}	0.6609	-0.5729	-0.7764	1.0000	-0.5729
relative error ^{c)}	0.14%	0.06%	0.12%	0.00%	0.16%

^{a)} observables not shown (b, D, R) vanish in the Standard Model

^{b)} calculated with the Standard Model assuming $G_A M_{GT}/G_V M_F = -0.584$

^{c)} only the errors arising from an assumed 0.1% error in the ft value are shown

The significance of measurements of D, R, A and Ra (the latter being the ratio of the longitudinal polarization of betas emitted parallel and antiparallel to the nuclear polarization [28]) for the ^{37}K decay has been discussed by Deutsch [29]. His conclusions are that it will be difficult to improve the limits for an imaginary phase between axial and vector couplings established from D results for neutron and ^{19}Ne beta decays, at least in the first stages of the experiment. The accuracy required for D would be a few 10^{-4} , comparable to calculable electromagnetic final state interaction effects.

The R term requires measurement of the transverse polarization of the positron. Since $\text{Im}(C_A C_T)$ is already known to be very small from ^6Li decay [30], a 1% R measurement in ^{37}K would usefully constrain $\text{Im}(C_A C_S)$.

Both measurements of A (absolute) and Ra (relative) in ^{37}K can sensitively probe the mass M_2 of a predominantly righthanded W boson postulated in manifestly left-right symmetric models. In Fig. 3 (from ref. 29) the impact of an 0.3% A measurement and of an 0.6% Ra measurement is shown together with the allowed region due to all known beta decays (the SM value $\zeta = \delta = 0$ is excluded mainly due to ft and A for the neutron). The dashed regions are excluded by considerations of the energetics of SN1987A [31] (line labelled "SN") and by plausible assumptions on the Higgs sector [1]. The ^{37}K data are insensitive to the mixing angle ζ , but could provide very useful constraints on M_2 in the mass region ≤ 420 GeV.

The hyperfine spectrum of ^{37}K is somewhat unusual in that the $4P_{3/2}$ multiplet with $F' = 0 \rightarrow 3$ is strongly overlapping (the natural linewidth is about 6 MHz). For this reason we will provide simultaneously trapping beams for both the $4^2S_{1/2}(F=2) \rightarrow 4^2P_{3/2}(F'=3)$ and the $4^2S_{1/2}(F=1) \rightarrow 4^2P_{3/2}(F'=2)$ hyperfine transitions using AO modulators to compensate for the 240 MHz ground state hyperfine splitting. A similar scheme has been successfully applied in laser cooling and trapping of ^6Li [32]. We have worked out a possible measurement cycle which incorporates ZOT, molasses cooling, optical pumping, and magnetic trapping without lasers. A rotating homogeneous magnetic field added to a quadrupole trapping field [11] appears attractive for spin correlation observables since the asymmetry is swept past the fixed positron detectors. This feature might be important in controlling systematic effects. Bending effects of positrons in the magnetic fields are significant but not severe. Position sensitive detection of positrons

will eventually be necessary to quantitatively account for background from unpolarized atoms on the walls, yet conventional charged-particle tracking methods are inaccurate because of multiple scattering. Innovative schemes are needed to utilize walls during the ZOT trapping stage while eliminating their influence during the detection of positrons and recoils. Recoil detection using microchannel plates will allow the measurement of neutrino correlations. From direction and momentum of the positron and the relative time-of-flight of the recoil nucleus neutrino direction and momentum can be evaluated.

Figure 3: Exclusion plot of the mass of a predominantly right-handed boson W_2 versus mixing angle (from ref. 29). The curves for ^{37}K are constraints imposed by future measurements of the asymmetry A and the relative polarization Ra. The allowed region from all available beta decay data is also shown. The hatched regions "H" and "SN" are excluded as referred to in the text.

4. SUMMARY AND OUTLOOK

Radioactive neutral atoms trapped and cooled by magneto-optic forces have attractive properties for studies of fundamental symmetries of the SM. Neutral atom traps of the future promise good geometry, negligible source thickness, high polarization, and high luminosity, all important ingredients of precision measurements. Although several suitable trapping and cooling methods are now well developed, many technological problems have still to be overcome. The developments at TRIUMF are now underway, with a 1 W Titanium:sapphire ring laser in operation, and diode laser systems available at the end of this summer. An off-line setup exists to trap stable Rb and K isotopes,

and to evaluate different wall coatings. Test experiments on neutralization efficiencies have been scheduled using TISOL. For atomic PNC experiments overall efficiencies much higher than those reported so far [25,33] are required. The neutralization method has to be both efficient and compatible with robust wall coatings of the trapping vessel. For beta decay measurements lower efficiencies may suffice, however atoms on the walls could be a serious problem. The ratio of polarized atoms in the trap to unpolarized atoms, as measured by beta and recoil detectors, must be large and accurately known. For PNC studies in Francium the absence of a stable atomic reference poses new problems of frequency stabilization. There is need for both innovation and patient optimization of parameters. The goals make these efforts seem worthwhile.

REFERENCES

1. J. Deutsch and P. Quin, to be published in *Precision Tests of the Standard Electroweak Model*, ed. by Paul Langacker, (World Scientific, 1993).
2. S.J. Pollock, E.N. Fortson and L. Wilets, Phys. Rev. C 46 (1992) 2587.
3. H. Ravn, private communication.
4. E. Raab *et al.*, Phys. Rev. Lett. 59 (1987) 2631.
5. K. Lindquist, M. Stephens and C. Wieman, Phys. Rev. A 46 (1992) 4082.
6. M. Stephens and C. Wieman, Phys. Rev. Lett. 72 (1994) 3795.
7. S. Chu *et al.*, Phys. Rev. Lett. 55 (1985) 48.
8. V. Bagnato *et al.*, Phys. Rev. Lett. 58 (1987) 2194.
9. E. Cornell, C. Monroe and C.E. Wieman, Phys. Rev. Lett. 67 (1991) 2439.
10. T. Bergeman, G. Erez and H.J. Metcalf, Phys. Rev. A 35 (1987) 1535.
11. E. Cornell and W. Petrich, private communication.
12. M.C. Noecker, B.P. Masterson, and C.E. Wieman, Phys. Rev. Lett. 61 (1988) 310; D. Cho, BAPS39 (1994) 1082.
13. E.N. Fortson and L.L. Lewis, Phys. Rep. 113 (1984) 289.
14. P. Langacker, in *30 Years of Neutral Currents*, Santa Monica, California, February 1993, preprint.
15. S.A. Blundell, W.R. Johnson, and J. Sapirstein, Phys. Rev. Lett. 65 (1990) 1411.
16. Ya. B. Zel'dovich, Sov. Phys. JETP 6 (1958) 1184.
17. M.E. Peskin and T. Takeuchi, Phys. Rev. Lett. 65 (1990) 964.
18. W.J. Marciano and J.L. Rosner, Phys. Rev. Lett. 65 (1990) 2963.
19. Altarelli *et al.*, Phys. Lett. B 245 (1990) 669.
20. W. Buchmüller and D. Wyler, Phys. Lett. B 177 (1986) 377.
21. P. Langacker, Phys. Lett. B 256 (1991) 277.
22. LAMPF experiment E1303, D.J. Viera and C.E. Wieman, spokesmen.
23. J.D. Jackson, S.B. Treiman and H.W. Wyld, Phys. Rev. 106 (1957) 517; and Nucl. Phys. 4 (1957) 206.
24. A.L. Hallin *et al.*, Phys. Rev. Lett. 52 (1984) 337; 52 (1984) 1054(E).
25. Z.T. Lu *et al.*, Phys. Rev. Lett. 72 (1994) 3791.
26. T. Walker, private communication.
27. E. Hagberg, private communication.
28. P.A. Quin and T.A. Girard, Phys. Lett. B 229 (1989) 29.
29. J. Deutsch, contribution to ISAC Workshop, Lake Louise, Alberta, Feb. 17-21, 1994.
30. M. Allet *et al.*, Phys. Rev. Lett. 68 (1991) 572; M. Allet *et al.*, PANIC93 contributions 4.8, p.121; and 4.16, p.132.
31. A. Burrows, R. Gandhi and M.S. Turner, Phys. Rev. Lett. 68 (1992) 3834.
32. Z. Lin *et al.*, J. Phys. 30, No. 7B (1990) L1324.
33. G. Gwinner *et al.*, Phys. Rev. Lett. 72 (1994) 3795.