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| **TRIUMF - EEC SUBMISSION**<br>Draft Submission<br>*Progress Report* | | **Exp. No.**<br>S1218 - *In Preparation*<br>**Date Created:**<br>2008-11-12 22:20:06 |

**Title of Experiment:**

Towards an optical parity violation experiment in francium: Spectroscopy of the 7s - 8s transition

**Name of group:**

FrPNC

**Spokesperson(s) for Group**

G. Gwinner

**Current Members of Group:**
(name, institution, status, % of research time devoted to experiment)

| | | | |
|---|---|---|---|
| G. Gwinner | University of Manitoba | Associate Professor | 50% |
| C. De Oliveira | University of Manitoba | Student (PhD) | 100% |
| A. Perez Galvan | University of Maryland | Student (PhD) | 50% |
| D. Sheng | University of Maryland | Student (PhD) | 50% |
| J.A. Behr | TRIUMF | Research Scientist | 30% |
| L.A. Orozco | University of Maryland | Professor | 30% |
| E. Gomez | San Luis Potosi, Mexico | Assistant Professor | 20% |
| M.R. Pearson | TRIUMF | Research Scientist | 20% |
| S. Aubin | William & Mary | Assistant Professor | 20% |
| D.G. Melconian | Texas A&M University | Assistant Professor | 10% |

**Beam Shifts Used:**

**Beam Shifts Remaining:**

**New Beam Requests:**

60 shifts with: BL2A/ISAC
*Comment:* Once a francium beam is available

**Basic Information:**

*Date Created:* 2008-11-12 22:20:06

*Date Experiment Ready:* 2010-06-01

*Summary:*


The 7s - 8s atomic transition in francium is considered one of the most promising candidates for an atomic parity nonconservation (APNC) experiment in heavy atoms. In francium, the APNC effect is 18 times larger than in Cs, where the best experiment so far has been carried out. In the LHC era, low energy experiments still have an important role to play, and in terms of their sensitivity to different types of #new# physics beyond the Standard Model, APNC and electron scattering experiments such as Qweak and E158 are complementary. Recently, great progress has been made in the relevant atomic structure calculations, and the PREX experiment at Jefferson Lab will provide significantly improved neutron radius information. This constitutes an excellent basis for APNC experiments in isotopes of francium.

As a first step towards APNC measurements, we propose to investigate the 7s - 8s optical transition. Spectroscopy of faint transitions on-line with a radioactive sample of atoms is naturally more challenging than work with stable atoms. It is important to develop a robust procedure that allows us first to locate the transition at all, and then to perform increasingly sophisticated experiments to explore the more subtle aspects with increasing precision. The initial setup should be as simple as possible, while a final version of the on-line trap will be capable of housing an APNC setup. We will explore the Stark-induced amplitudes and the relativistic and hyperfine-induced M1 amplitudes. Understanding these amplitudes is critical to the interpretation of APNC

data. In addition, these measurements will allow the careful development of an on-line laser trap setup capable of supporting an APNC experiment.

We will be able to exploit the strong synergies between this proposal and the already approved Fr hyperfine anomaly (E1010) and anapole (E1065) experiments by sharing essentially all the infrastructure.

*Plain Text Summary:* We propose to investigate the highly forbidden 7s-8s optical transition in laser trapped and cooled francium atoms as a precursor experiment to an atomic parity nonconservation experiment. The ultimate goal is to search for 'new' physics beyond the Standard Model of particle physics, using precise laser spectroscopy and atom trapping and cooling techniques.

*Primary Beam Line:* isac2a

## ISAC Facilities

*ISAC Facility:* Other

*ISAC-I Facility:*

*ISAC-II Facility:*

## Secondary Beam

*Isotope(s):* Fr-210

*Energy:* 30

*Energy Units:* keV

*Energy spread - maximum :*

*Time spread - maximum :*

*Angular Divergence :*

*Spot Size:*

*Intensity Requested:* 10^7 or more pps

*Minimum Intensity:* 10^6 pps

*Maximum Intensity:*

*Charge Constraints:*

*Beam Purity:*

*Special Characteristics:*

## Experiment Support

*Beam Diagnostics Required:*

*Signals for Beam Tuning:*

*DAQ Support (Summary of Requirements):*

*TRIUMF Support (Resources Needed):*

Beam line to deliver 10 keV francium ions to a neutralizer.

Electromagnetically shielded enclosure in experimental hall with temperature control and air filter for lasers and rf equipment, 5.5 m by 6 m.

Mechanical design help for radiation shielding in the neutralizer region.

*NSERC:*

- NSERC, SAPIN (G. Gwinner); Investigations toward atomic parity nonconservation and anapole measurements in francium (support through 2010)

- NSERC TRINAT project grant (J.A. Behr, K.P. Jackson, M. Pearson, G. Gwinner); continuing support through 2012 has been applied for.

- NSERC Francium project grant (G. Gwinner, J. A. Behr, M. Pearson); plan to apply for this grant in fall 2009 once actinide target plans are firm

*Other Funding:*

- NSF (USA) *Anapole moment studies in francium* (L. A. Orozco)

*Safety Issues:*

Yields of > 10^8 /sec short-lived Fr alpha emitters will be delivered to the main ISAC floor. Most of the activity is alpha radiation and will be contained in the trap region. Mechnical design support will be requested for lead or heavymet shielding near the trap volume. Mechanical pump exhausts will be filtered using the experience gained from the E929 radon EDM experiment tests with xenon. Certain masses produce long-lived 206,208,209,210 Po and will require careful precautions as polonium is quite volatile. The safety officer will be M. Pearson, who has experience gained at experiments at ISOLDE and at Stony Brook.

*EEC Reader:*

1. J. R. A. Pitcairn, D. Roberge, A. Gorelov, D. Ashery, O. Aviv, J. A. Behr, P. G. Bricault, M. Dombsky, J. D. Holt, K. P. Jackson, B. Lee, M. R. Pearson, A. Gaudin, B. Dej, C. Höhr, G. Gwinner, and D. Melconian. Tensor interaction constraints from beta decay recoil spin asymmetry of trapped atoms. *submitted to Phys. Rev. C*, October 2008.
2. C. Novotny, G. Huber, S. Karpuk, W. Nörtershäuser, S. Reinhardt, D. Bing, D. Schwalm, A. Wolf, B. Bernhardt, T. W. Hänsch, R. Holzwarth, G. Saathoff, Th. Udem, G. Ewald, C. Geppert, H.-J. Kluge, T. Kühl, T. Stöhlker, and G. Gwinner. Sub-doppler laser spectroscopy on relativistic beams and tests of lorentz invariance. *submitted to Phys. Rev. Lett.*, November 2008.
3. J. A. Behr and G. Gwinner. Standard Model tests with trapped radioactive atoms. *Journal of Physics G*, 09 2008.
4. S. Reinhardt, G. Saathoff, H. Buhr, L. A. Carlson, A. Wolf, D. Schwalm, S. Karpuk, C. Novotny, G. Huber, M. Zimmermann, R. Holzwarth, T. Udem, T. W. Hänsch, and G. Gwinner. Test of relativistic time dilation with fast optical atomic clocks at different velocities. *Nature Physics*, 3:861–864, 12 2007.
5. Z. Ke, W. Shi, G. Gwinner, K. Sharma, S. Toews, J. Dilling, and V. L. Ryjkov. A cooler ion trap for the TITAN on-line trapping facility at TRIUMF. *Hyperfine Interactions*, 173:103–111, 06 2007.
6. M. Hörndl, S. Yoshida, J. Burgdörfer, G. Gwinner, and A. Wolf. Enhanced electron ion recombination in ion storage rings. *Hyperfine Interactions*, 173:67–72, 07 2007.
7. G. Gwinner, E. Gomez, L. A. Orozco, A. Perez Galvan, D. Sheng, Y. Zhao, G. D. Sprouse, J. A. Behr, K. P. Jackson, M. R. Pearson, S. Aubin, and V. V. Flambaum. Fundamental symmetries studies with cold trapped francium atoms at ISAC. *Hyperfine Interactions*, 172:45–51, 06 2007.
8. G. Gwinner, E. Gomez, A. Perez Galvan, D. Sheng, Y. Zhao, L. A. Orozco, G. D. Sprouse, J. A. Behr, K. P. Jackson, M. R. Pearson, V. V. Flambaum, and S. Aubin. Program of parity nonconservation measurements in francium. In K. de Jager, editor, *From parity violation to hadronic structure and more... (Part III), Milos, Greece, May 16-20, 2006*, pages 171 – 175. Springer, 08 2007.
9. M. Froese, C. Champagne, J. R. Crespo López-Urrutia, S. Epp, G. Gwinner, A. Lapierre, J. Pfister, G. Sikler, J. Ullrich, and J. Dilling. A high-current electron beam ion trap as an on-line charge breeder for the high precision mass measurement TITAN experiment. *Hyperfine Interactions*, 173:85–92, 07 2007.
10. F. Fleischer, G. Gwinner, C. Hugenschmidt, K. Schreckenbach, P. Thirolf, A. Wolf, and D. Schwalm. The negative ion of positronium: Measurement of the decay rate and prospects for further experiments. *Canadian Journal of Physics*, 85:487–495, 07 2007.
11. P. Delheij, L. Blomeley, M. Froese, G. Gwinner, V. Ryjkov, M. Smith, and J. Dilling. The TITAN mass measurement facility at TRIUMF-ISAC. *Hyperfine Interactions*, 173:123–131, 07 2007.
12. J. A. Behr, J. R. A. Pitcairn, D. G. Roberge, M. R. Pearson, C. Höhr, G. Gwinner, D. Ashery, B. Dej, A. Gaudin, K. P. Jackson, and A. Gorelov. Ion detection from beta decay and two-body decay experiments with laser-cooled atoms. *Hyperfine Interactions*, 173:41–48, 07 2007.
13. D. W. Savin, G. Gwinner, M. Grieser, R. Repnow, M. Schnell, D. Schwalm, A. Wolf, S.-G. Zhou, S. Kieslich, A. Müller, S. Schippers, J. Colgan, S. D. Loch, N. R. Badnell, M. H. Chen, and M. F. Gu. Dielectronic recombination of Fe XXIII forming Fe XXII: Laboratory measurements and theoretical calculations. *Astrophys. J.*, 642(2):1275 – 85, 05 2006.
14. S. Reinhardt, G. Saathoff, S. Karpuk, C. Novotny, G. Huber, M. Zimmermann, R. Holzwarth, T. Udem, T. W. Hansch, and G. Gwinner. Iodine hyperfine structure and absolute frequency measurements at 565, 576, and 585 nm. *Optics Communications*, 261(2):282 – 290, 05 2006.

15. C. Novotny, B. Bernhardt, G. Ewald, C. Geppert, G. Gwinner, T. W. Hänsch, R. Holzwarth, G. Huber, S. Karpuk, H. J. Kluge, et al. Experimental test of special relativity by laser spectroscopy. *Hyperfine Interactions*, 171(1):57–67, 07 2006.
16. Maria Hörndl, Shuhei Yoshida, Andreas Wolf, Gerald Gwinner, Marek Seliger, and Joachim Burgdörfer. Classical dynamics of enhanced low-energy electron-ion recombination in storage rings. *Physical Review A*, 74(5):052712, 11 2006.
17. Frank Fleischer, Kai Degreif, Gerald Gwinner, Michael Lestinsky, Vitaly Liechtenstein, Florian Plenge, and Dirk Schwalm. Measurement of the decay rate of the negative ion of positronium ($Ps^-$). *Physical Review Letters*, 96(6):063401, 02 2006.
18. J. Dilling, R. Baartman, P. Bricault, M. Brodeur, L. Blomeley, F. Buchinger, J. Crawford, J. R. C. Lopez-Urrutia, P. Delheij, M. Froese, G. Gwinner, Z. Ke, J. K. P. Lee, R. B. Moore, V. Ryjkov, G. Sikler, M. Smith, J. Ullrich, and J. Vaz. Mass measurements on highly charged radioactive ions, a new approach to high precision with titan. *Int. J. Mass Spectrom.*, 251(2-3):198 – 203, 04 2006.
19. S. Schippers, G. Gwinner, C. Brandau, S. Böhm, M. Grieser, S. Kieslich, H. Knopp, A. Müller, R. Repnow, D. Schwalm, and A. Wolf. Hyperfine quenching of resonances in dielectronic recombination of zinc-like $Pt^{48+}$. *Nuclear Instruments and Methods in Physics Research B*, 235:265–269, 07 2005.
20. G. Saathoff, S. Reinhardt, H. Buhr, L. A. Carlson, D. Schwalm, A. Wolf, S. Karpuk, C. Novotny, G. Huber, and G. Gwinner. Test of time dilation by laser spectroscopy on fast ions. *Canadian Journal of Physics*, 83:425–434, 04 2005.
21. V. L. Ryjkov, L. Blomeley, M. Brodeur, P. Grothkopp, M. Smith, P. Bricault, F. Buchinger, J. Crawford, G. Gwinner, J. Lee, J. Vaz, G. Werth, and J. Dilling. TITAN project status report and a proposal for a new cooling method of highly charged ions. *European Physical Journal A Supplement*, 25:53–56, 09 2005.
22. Maria Hörndl, Shuhei Yoshida, Andreas Wolf, Gerald Gwinner, and Joachim Burgdörfer. Enhancement of low energy electron-ion recombination in a magnetic field: Influence of transient field effects. *Physical Review Letters*, 95(24):243201, 12 2005.
23. G. Gwinner. Experimental tests of time dilation in special relativity. *Modern Physics Letters A*, 20:791–805, 04 2005.
24. F. Fleischer, K. Degreif, G. Gwinner, M. Lestinsky, V. Liechtenstein, F. Plenge, H. Scheit, and D. Schwalm. A new measurement of the decay rate of the negative positronium ion: status and preliminary results. *Canadian Journal of Physics*, 83:413–423, 04 2005.
25. D. Schwalm, F. Fleischer, M. Lestinsky, K. Degreif, G. Gwinner, V. Liechtenstein, F. Plenge, and H. Scheit. Towards a new measurement of the decay rate of the negative positronium ion $Ps^-$. *Nuclear Instruments and Methods in Physics Research B*, 221:185–194, 07 2004.
26. D. Nikolić, E. Lindroth, S. Kieslich, C. Brandau, S. Schippers, W. Shi, A. Müller, G. Gwinner, M. Schnell, and A. Wolf. Dielectronic recombination resonances in $Na^{8+}$. *Phys. Rev. A*, 70(6):062723–+, 12 2004.
27. S. Kieslich, S. Schippers, W. Shi, A. Müller, G. Gwinner, M. Schnell, A. Wolf, E. Lindroth, and M. Tokman. Determination of the 2s-2p excitation energy of lithiumlike scandium using dielectronic recombination. *Phys. Rev. A*, 70(4):042714–+, 10 2004.
28. A. Wolf and G. Gwinner. Recombination measurements at ion storage rings. *Hyperfine Interactions*, 146:5–12, 01 2003.
29. E. Träbert, A. G. Calamai, G. Gwinner, E. J. Knystautas, E. H. Pinnington, and A. Wolf. M1/E2/M2 decay rates in Fe VII, Fe IX, Fe X and Fe XIII measured using a heavy-ion storage ring. *Journal of Physics B*, 36:1129–1141, 03 2003.

30. E. Träbert, P. Beiersdorfer, G. Gwinner, E. H. Pinnington, and A. Wolf. M1 transition rates from electron beam ion trap and heavy-ion storage ring. *Nuclear Instruments and Methods in Physics Research B*, 205:83–86, 05 2003.
31. E. Träbert, G. Gwinner, E. J. Knystautas, and A. Wolf. Heavy-ion storage-ring quest for atomic lifetimes in $Li^{+}$ and $Be^{2+}$. *Canadian Journal of Physics*, 81:941–952, 07 2003.
32. M. Schnell, M. E. Bannister, S. Böhm, G. Gwinner, S. Kieslich, A. Müller, S. Schippers, D. Schwalm, W. Shi, A. Wolf, and S.-G. Zhou. Trielectronic recombination in Be-like ions. *Nuclear Instruments and Methods in Physics Research B*, 205:367–369, 05 2003.
33. M. Schnell, G. Gwinner, N. R. Badnell, M. E. Bannister, S. Bohm, J. Colgan, S. Kieslich, S. D. Loch, D. Mitnik, A. Müller, M. S. Pindzola, S. Schippers, D. Schwalm, W. Shi, A. Wolf, and S.-G. Zhou. Observation of trielectronic recombination in Be-like Cl ions. *Phys. Rev. Lett.*, 91(4):043001, 07 2003.
34. D. W. Savin, S. M. Kahn, G. Gwinner, M. Grieser, R. Repnow, G. Saathoff, D. Schwalm, A. Wolf, A. Müller, S. Schippers, P. A. Závodszky, M. H. Chen, T. W. Gorczyca, O. Zatsarinny, and M. F. Gu. Dielectronic recombination of Fe XXI and Fe XXII via N=2 – N'=2 core excitations. *Astrophys. J.*, 147:421–435, 08 2003.
35. G. Saathoff, U. Eisenbarth, S. Hannemann, I. Hoog, G. Huber, S. Karpuk, S. Krohn, J. Lassen, D. Schwalm, M. Weidemüller, A. Wolf, and G. Gwinner. Toward a new test of the relativistic time dilation factor by laser spectroscopy of fast ions in a storage ring. *Hyperfine Interactions*, 146:71–75, 01 2003.
36. G. Saathoff, S. Karpuk, U. Eisenbarth, G. Huber, S. Krohn, R. M. Horta, S. Reinhardt, D. Schwalm, A. Wolf, and G. Gwinner. Improved test of time dilation in special relativity. *Physical Review Letters*, 91(19):190403, 11 2003.
37. J. Kleinert, S. Hannemann, B. Eike, U. Eisenbarth, M. Grieser, R. Grimm, G. Gwinner, S. Karpuk, G. Saathoff, U. Schramm, D. Schwalm, and M. Weidemüller. Laser-cooled ions and atoms in a storage ring. *Hyperfine Interactions*, 146:189–195, 01 2003.
38. S. Kieslich, S. Böhm, C. Brandau, A. Müller, S. Schippers, W. Shi, G. Gwinner, M. Schnell, and A. Wolf. Dielectronic recombination at low energies: Spectroscopy of doubly excited states in beryllium-like $Na^{7+}$ ions. *Nuclear Instruments and Methods in Physics Research B*, 205:99–101, 05 2003.
39. A. Al-Khalili, S. Rosén, H. Danared, A. M. Derkatch, A. Källberg, M. Larsson, A. Le Padellec, A. Neau, J. Semaniak, R. Thomas, M. Af Ugglas, L. Vikor, W. Zong, W. J. van der Zande, X. Urbain, M. J. Jensen, R. C. Bilodeau, O. Heber, H. B. Pedersen, C. P. Safvan, L. H. Andersen, M. Lange, J. Levin, G. Gwinner, L. Knoll, M. Scheffel, D. Schwalm, R. Wester, D. Zajfman, and A. Wolf. Absolute high-resolution rate coefficients for dissociative recombination of electrons with $HD^{+}$: Comparison of results from three heavy-ion storage rings. *Phys. Rev. A*, 68(4):042702–+, 10 2003.
40. E. Träbert and G. Gwinner. (M1+E2) decay rate in $Ar^{2+}$ ions measured at a heavy-ion storage ring. *Phys. Rev. A*, 65(1):014501, 01 2002.
41. E. Träbert, G. Gwinner, A. Wolf, E. J. Knystautas, H.-P. Garnir, and X. Tordoir. M1/e2 transition rates in Fe X through Fe XIII measured at a heavy-ion storage ring. *Journal of Physics B*, 35:671–689, 02 2002.
42. E. Träbert, P. Beiersdorfer, G. Gwinner, E. H. Pinnington, and A. Wolf. M1 transition rate in $Cl^{12+}$ from an electron-beam ion trap and heavy-ion storage ring. *Phys. Rev. A*, 66(5):052507–+, 11 2002.
43. E. Trabert, A. Wolf, and G. Gwinner. Measurement of EUV intercombination transition rates in Be-like ions at a heavy-ion storage ring. *Physics Letters A*, 295:44–49, 03 2002.

44. M. Tokman, N. Eklöw, P. Glans, E. Lindroth, R. Schuch, G. Gwinner, D. Schwalm, A. Wolf, A. Hoffknecht, A. Müller, and S. Schippers. Dielectronic recombination resonances in $F^{6+}$. *Phys. Rev. A*, 66(1):012703, 07 2002.
45. S. Schippers, S. Kieslich, A. Müller, G. Gwinner, M. Schnell, A. Wolf, A. Covington, M. E. Bannister, and L.-B. Zhao. Interference effects in the photorecombination of argonlike $Sc^{3+}$ ions: Storage-ring experiment and theory. *Phys. Rev. A*, 65(4):042723–+, 04 2002.
46. D. W. Savin, E. Behar, S. M. Kahn, G. Gwinner, A. A. Saghiri, M. Schmitt, M. Grieser, R. Repnow, D. Schwalm, A. Wolf, T. Bartsch, A. Müller, S. Schippers, N. R. Badnell, M. H. Chen, and T. W. Gorczyca. Dielectronic recombination (via n=2 – n'=2 core excitations) and radiative recombination of Fe XX: Laboratory measurements and theoretical calculations. *Astrophys. J. Suppl.*, 138:337–370, 02 2002.
47. H. Backe, A. Dretzke, K. Eberhardt, S. Fritzsche, C. Gruning, G. Gwinner, R. G. Haire, G. Huber, J. V. Kratz, G. Kube, et al. First determination of the ionization potential of actinium and first observation of optical transitions in fermium. *J. Nucl. Sci. Tech. Suppl.*, 3:86, 11 2002.
48. E. Träbert, A. Wolf, X. Tordoir, E. H. Pinnington, E. J. Knystautas, G. Gwinner, A. G. Calamai, and R. L. Brooks. Lifetime of metastable Ne2+ ions measured at a heavy-ion storage ring. *Canadian Journal of Physics*, 79:145–151, 02 2001.
49. S. Schippers, T. Bartsch, S. Böhm, G. Gwinner, D. Schwalm, A. Wolf, R. A. Phaneuf, R. Schuch, and A. Müller. Field enhanced dielectronic recombination of lithiumlike Ti19+ and Ni25+ ions. *Physica Scripta Volume T*, 92:391–394, 2001.
50. S. Schippers, A. Müller, G. Gwinner, J. Linkemann, A. A. Saghiri, and A. Wolf. Storage ring measurement of the C IV recombination rate coefficient. *Astrophys. J.*, 555:1027–1037, 07 2001.
51. S. Kieslich, S. Böhm, A. Müller, S. Schippers, W. Shi, G. Gwinner, M. Schnell, A. Wolf, E. Lindroth, and M. Tokman. Photorecombination of lithium-like Sc18+ at threshold: A challenge for atomic structure theory. *Physica Scripta Volume T*, 92:376–378, 2001.
52. A. Hoffknecht, S. Schippers, A. Müller, G. Gwinner, D. Schwalm, and A. Wolf. Recombination of bare Cl17+ ions in an electron cooler. *Physica Scripta Volume T*, 92:402–405, 2001.
53. G. Gwinner, D. W. Savin, D. Schwalm, A. Wolf, S. Schippers, A. Müller, N. R. Badnell, and M. H. Chen. Dielectronic recombination of iron L-shell ions. *Physica Scripta Volume T*, 92:319–321, 2001.
54. A. Wolf, G. Gwinner, J. Linkemann, A. A. Saghiri, M. Schmitt, D. Schwalm, M. Grieser, M. Beutelspacher, T. Bartsch, C. Brandau, A. Hoffknecht, A. Müller, S. Schippers, O. Uwira, and D. W. Savin. Recombination in electron coolers. *Nuclear Instruments and Methods in Physics Research A*, 441:183–190, 02 2000.
55. A. Wolf, G. Uhlenberg, U. Schramm, T. Schüßler, A. E. Livingston, G. Gwinner, G. Saathoff, and D. Schwalm. Spectroscopy using stimulated electron ion recombination. *Hyperfine Interactions*, 127:203–210, 08 2000.
56. E. Träbert, A. G. Calamai, J. D. Gillaspy, G. Gwinner, X. Tordoir, and A. Wolf. Intercombination and forbidden transition rates in C- and N-like ions (O2+, F3+, and S9+) measured at a heavy-ion storage ring. *Phys. Rev. A*, 62(2):022507, 08 2000.
57. S. Schippers, T. Bartsch, C. Brandau, A. Müller, G. Gwinner, G. Wissler, M. Beutelspacher, M. Grieser, A. Wolf, and R. A. Phaneuf. Dielectronic recombination of lithiumlike Ni25+ ions: High-resolution rate coefficients and influence of external crossed electric and magnetic fields. *Phys. Rev. A*, 62(2):022708, 08 2000.
58. G. Saathoff, G. Gwinner, T. Kühl, D. Schwalm, H. Winter, and A. Wolf. Rate predictions for two photon spectroscopy of highly charged ions through laser induced recombination. *Hyperfine Interactions*, 127:211–214, 08 2000.

59. G. Gwinner, A. Hoffknecht, T. Bartsch, M. Beutelspacher, N. Eklöw, P. Glans, M. Grieser, S. Krohn, E. Lindroth, A. Müller, A. A. Saghiri, S. Schippers, U. Schramm, D. Schwalm, M. Tokman, G. Wissler, and A. Wolf. Influence of magnetic fields on electron-ion recombination at very low energies. *Physical Review Letters*, 84:4822–4825, 05 2000.
60. A. G. Calamai, G. Gwinner, X. Tordoir, E. Träbert, and A. Wolf. Electric quadrupole and magnetic dipole transition probabilities within the ground configuration of F+. *Phys. Rev. A*, 61(6):062508, 06 2000.
61. T. Bartsch, S. Schippers, M. Beutelspacher, S. Böhm, M. Grieser, G. Gwinner, A. A. Saghiri, G. Saathoff, R. Schuch, D. Schwalm, A. Wolf, and A. Müller. Enhanced dielectronic recombination of lithium-like Ti19+ ions in external E x B fields. *Journal of Physics B*, 33:L453–L460, 06 2000.
62. E. Träbert, G. Gwinner, A. Wolf, X. Tordoir, and A. G. Calamai. Magnetic dipole transition rates in B-like and F-like titanium ions measured at a heavy-ion storage ring. *Physics Letters A*, 264(4):311–317, 1999.
63. E. Träbert, G. Gwinner, E. J. Knystautas, X. Tordoir, and A. Wolf. Precise intercombination transition rates in $C^+$ and $N^{2+}$ ions measured at a heavy-ion storage ring. *Journal of Physics B*, 32:L491–L499, 09 1999.
64. S. Schippers, T. Bartsch, C. Brandau, A. Müller, G. Gwinner, J. Linkemann, A. A. Saghiri, and A. Wolf. Photorecombination of Sc3+ and Ti4+ Ions: Search for Interference Effects and Recombination at low Energies. *Physica Scripta Volume T*, 80:314–315, 1999.
65. M. A. Rowe, S. J. Freedman, B. K. Fujikawa, G. Gwinner, S.-Q. Shang, and P. A. Vetter. Ground-state hyperfine measurement in laser-trapped radioactive $^{21}$Na. *Phys. Rev. A*, 59:1869–1873, 03 1999.
66. M. Lange, J. Levin, G. Gwinner, U. Hechtfischer, L. Knoll, D. Schwalm, R. Wester, A. Wolf, X. Urbain, and D. Zajfman. Threshold effects and ion-pair production in the dissociative recombination of HD+. *Physical Review Letters*, 83:4979–4982, 12 1999.
67. A. Hoffknecht, T. Bartsch, S. Schippers, A. Müller, N. Eklöw, P. Glans, M. Beutelspacher, M. Grieser, G. Gwinner, A. A. Saghiri, and A. Wolf. Recombination of F6+ with free electrons at very low energies. *Physica Scripta Volume T*, 80:298–300, 1999.
68. P. Glans, E. Lindroth, N. Eklöw, W. Zong, G. Gwinner, A. A. Saghiri, M. Pajek, H. Danared, and R. Schuch. Dielectronic recombination of Li-like fluorine ions. *Nuclear Instruments and Methods in Physics Research B*, 154:97–101, 06 1999.
69. C. J. Bowers, D. Budker, S. J. Freedman, G. Gwinner, J. E. Stalnaker, and D. Demille. Experimental investigation of the $6s^2\,{}^1S_0 - 5d6s\,{}^3D_{1,2}$ forbidden transitions in atomic ytterbium. *Phys. Rev. A*, 59:3513–3526, 05 1999.
70. T. Bartsch, A. Müller, W. Spies, J. Linkemann, S. Schippers, C. Brandau, H. Danared, D. R. DeWitt, H. Gao, W. Zong, R. Schuch, A. Wolf, G. Gwinner, A. A. Saghiri, M. Schmitt, M. Beutelspacher, M. Grieser, and G. H. Dunn. Field enhanced dielectronic recombination of Si11+ and Cl14+ ions. *Physica Scripta Volume T*, 80:305–306, 1999.
71. T. Bartsch, S. Schippers, A. Müller, C. Brandau, G. Gwinner, A. A. Saghiri, M. Beutelspacher, M. Grieser, D. Schwalm, A. Wolf, H. Danared, and G. H. Dunn. Experimental evidence for magnetic field effects on dielectronic recombination via high Rydberg states. *Physical Review Letters*, 82:3779–3782, 05 1999.
72. S. Schippers, T. Bartsch, C. Brandau, G. Gwinner, J. Linkemann, A. Müller, A. A. Saghiri, and A. Wolf. Photorecombination of Ti4+ ions: search for interference effects, recombination at low energies and rate coefficient in plasmas. *Journal of Physics B*, 31:4873–4886, 11 1998.
73. P. A. Voytas, J. A. Behr, A. Ghosh, G. Gwinner, L. A. Orozco, J. E. Simsarian, G. D. Sprouse,

and F. Xu. Laser traps for radioactive isotopes. *Hyperfine Interactions*, 97:527–534, 12 1996.

74. J. E. Simsarian, A. Ghosh, G. Gwinner, L. A. Orozco, G. D. Sprouse, and P. A. Voytas. Magneto-Optic Trapping of $^{210}$Fr. *Physical Review Letters*, 76:3522–3525, 05 1996.
75. P. Campbell, J. A. Behr, J. Billowes, G. Gwinner, G. D. Sprouse, and F. Xu. Magnetic dipole and electric quadrupole moments of the neutron-deficient bismuth isotopes. *Nuclear Physics A*, 598:61–81, 02 1996.
76. P. Campbell, J. Billowes, J. A. Behr, G. Gwinner, G. D. Sprouse, and F. Xu. Isotope shifts of the neutron-deficient bismuth isotopes: charge radii systematics across the Z = 82 shell closure. *Physics Letters B*, 346:21–26, 02 1995.
77. G. Gwinner, J. A. Behr, S. B. Cahn, A. Ghosh, L. A. Orozco, G. D. Sprouse, and F. Xu. Magneto-optic trapping of radioactive 79Rb. *Physical Review Letters*, 72:3795–3798, 06 1994.
78. J. A. Behr, S. B. Cahn, S. B. Dutta, A. Ghosh, G. Gwinner, C. H. Holbrow, L. A. Orozco, G. D. Sprouse, J. Urayama, and F. Xu. A low-energy ion beam from alkali heavy-ion reaction products. *Nuclear Instruments and Methods in Physics Research A*, 351(2-3):256 − 260, 12 1994.
79. J. A. Behr, S. B. Cahn, S. B. Dutta, A. Görlitz, A. Ghosh, G. Gwinner, L. A. Orozco, G. D. Sprouse, and F. Xu. Possibilities for francium spectroscopy in a light trap. *Hyperfine Interactions*, 81:197–202, 03 1993.
80. J. Schecker, A. Berger, J. Das, S. Dutta, G. Gwinner, C. H. Holbrow, T. Kühl, T. Lauritsen, G. D. Sprouse, and F. Xu. Optical isotope shifts of stable hafnium atoms in a resonance cell on-line with a heavy-ion accelerator. *Physical Review A*, 46(7):3730–3734, 10 1992.
81. A. Berger, J. Billowes, J. Das, S. Dutta, G. Gwinner, C. H. Holbrow, T. Kühl, T. Lauritsen, S. L. Rolston, J. Schecker, G. D. Sprouse, and F. Xu. A resonance cell for on-line optical spectroscopy of accelerator produced radioactive atoms. *Nuclear Instruments and Methods in Physics Research A*, 311:224–239, 01 1992.
82. J. Behr, S. Cahn, J. Das, G. Gwinner, C. H. Holbrow, T. Lauritsen, L. A. Orozco, S. Shang, J. Schecker, G. D. Sprouse, and F. Xu. Laser spectroscopy of nuclear reaction products: recent results and future prospects. *Hyperfine Interactions*, 74:23–29, 10 1992.

**Motivation: The path towards an atomic parity nonconservation experiment in francium**

This proposal aims at investigating for the first time the highly forbidden atomic transition considered most promising for an atomic parity nonconservation (APNC) experiment with francium at optical frequencies, $7s \to 8s$. Beyond detecting this exceedingly faint transition, the measurements will constitute a crucial test of relevant atomic structure calculations, in particular relativistic corrections, and ultimately provide a direct experimental basis for planning an APNC measurement.

Francium, the heaviest alkali atom ($Z = 87$), has received much attention in recent years [1]. It possesses a unique combination of structural simplicity due to its single valence s-electron and a great sensitivity to effects such as atomic parity nonconservation and possible electric dipole moments due to its high nuclear charge. Our knowledge of Fr has, however, been severely limited due to the fact that it is the least stable element among the first 103; its longest lived isotope $^{223}$Fr has a half-life of only 23 minutes. Many of its basic atomic and nuclear properties remain unknown.

The attractiveness of Fr for APNC experiments has been discussed since the early 1990s in the context of searches for 'new' physics beyond the Standard Model (SM) [2]. APNC arises from the parity-violating exchange of Z-bosons between electrons and the quarks in the nucleus, leading to a mixing of atomic levels of opposite parity [3]. As a result, otherwise forbidden electric dipole transitions can be excited between states of the same parity. APNC was first observed in the late 1970s [4]. The culmination so far has been a measurement by Wieman's group in Boulder in $^{133}$Cs [5]. APNC scales with the nuclear charge roughly as $Z^3$, favoring experiments in heavy atoms, but a successful extraction of the weak interaction physics from the measured atomic quantity also requires a detailed understanding of the atomic wavefunctions. This has limited the interpretation of Tl, Pb, and Bi data. The atomic theory of Fr, on the other hand, can be understood at a level similar to that of Cs ($Z = 55$), yet the APNC effect is almost 20 times larger [6, 7].

APNC has played an important role in uncovering the neutral current weak interaction. Shortly after the landmark e-D inelastic scattering experiment at SLAC [8] measured the parity violating part of the neutral current weak interaction, APNC confirmed these findings at a very different momentum scale. In terms of the electron-quark coupling constants $C_{1u}$ and $C_{1d}$, APNC provides constraints nearly perpendicular to those of the SLAC experiment. A sequence of increasingly refined APNC experiments throughout the 1980s tightened these constraints to well below those of scattering experiments such as e-D at SLAC and e-carbon at BATES (see e.g. the left panel in Figure 1). Until the LEP collaborations published their results, APNC provided a competitive value for $\sin^2\theta_w$. This feat is no longer possible in the post-LEP era, but nevertheless low energy experiments have a key role to play. For example, when new states are discovered at the LHC, it will be important to know their couplings to the first generation of particles. Electrons and muons can be distinguished in the detectors, but up/down quark jets cannot be distinguished from jets of other generations. APNC and other low-energy experiments are in a unique position to assist with this question. The challenge is to make them sensitive enough, which generally means part per thousand accuracy.

APNC measures the strength of the weak neutral current at very low momentum transfer. There are three types of such "low-energy" weak neutral current measurements with complementary sensitivity. The atomic weak charge is predominantly sensitive to the neutron's weak charge, as the proton weak charge is proportional to $(1 - 4\sin^2\theta_W)$ which accidentally is near zero. The Qweak electron scattering experiment on hydrogen will be sensitive to the proton's weak charge. The SLAC E158 Moeller scattering is sensitive to the electron's weak charge. Different Standard Model extensions then contribute differently [9]. The atomic weak charge is relatively insensitive to one-loop order corrections from all SUSY particles, so its measurement provides a benchmark for possible departures by the other low-energy observables. Moeller scattering is purely leptonic and has no sensitivity to leptoquarks, so APNC can then provide the sensitivity to those. The left panel of Figure 1 taken

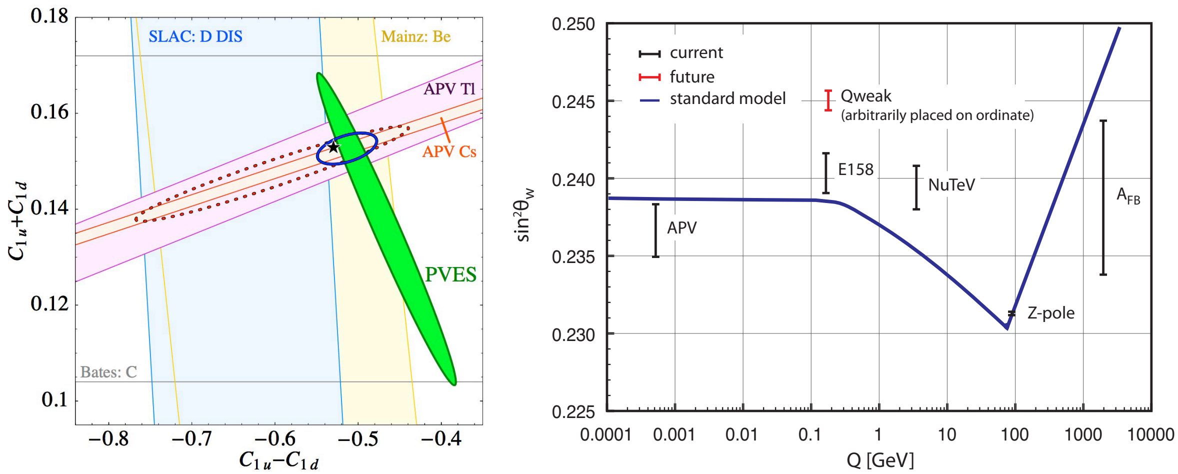


Figure 1: Left: Constraints on weak quark couplings from electron scattering and APNC taken from [10], showing their complementarity. Right: Measurements of the weak neutral current strength as a function of momentum transfer. Despite their lower precision, the low-energy experiments retain useful sensitivity to exchange of new bosons because they reside on the tail of the Standard Model Z resonance. Adapted from a figure courtesy J. Erler, see also [9, 11]. Note: recent, still unpublished atomic structure calculations have reduced the theoretical uncertainty for APNC significantly, and moved the Cs data point right onto the SM prediction; the new error bar is somewhat smaller than that of E158 [12].

from [10] shows the present constraints on weak quark couplings from parity violating electron scattering and from APNC. The latter provides a unique constraint unmatched by any other type of measurement. On the right side, results for the Weinberg angle are shown. The low-energy experiments have competitive sensitivity to certain specific Standard Model extensions compared to the LEP electroweak measurements— LEP's precision is better, but the low-energy experiments seeking terms interfering with the Z exchange can have inherently more sensitivity to tree-level exchange because they work on the tail of the Z resonance. It should be stressed that the right part of Figure 1 cannot do justice to the highly complementary nature of the low-energy experiments, as it only plots the sensitivity to one Standard Model parameter, $\sin^2\theta_W$. Since Qweak and APNC probe different quark combinations and E158 probes leptons, the sensitivities to physics beyond the SM is very different.

In addition to the leading-order *nuclear spin independent* APNC effect (i.e. an axial electron current interaction with a nuclear vector current, $A_e V_N$) discussed above, *nuclear spin dependent* APNC was unambiguously observed in the Boulder Cs experiment for the first time by extracting the dependence of APNC on the hyperfine levels involved, and hence nuclear spin. Several effects contribute to this part, but in heavy atoms the nuclear anapole moment dominates, which is a parity nonconserving, time reversal conserving moment that arises from weak interactions between the nucleons (see e.g. [16]). This has opened up the possibility to study weak nucleon-nucleon interactions via precise atomic spectroscopy. In Fr, the anapole effect is predicted to be one order of magnitude larger than in Cs, making it an excellent candidate for anapole studies [17]. An experiment to measure anapole moments in Fr isotopes in the microwave regime has been approved at TRIUMF (E1065) and is currently under development at the University of Maryland.

## Current status of APNC

The Boulder group determined the weak charge $Q_w$ of Cs with 0.6 % accuracy [5], and after inclusion of relevant radiative corrections into atomic calculations achieved agreement with the Standard Model roughly at the $1\sigma$ level. A new atomic structure calculation will reduce the uncertainty soon to 0.4 % and will center the Cs data point essentially right on the SM prediction [12]. Once a Fr measurement is in sight, these new calculations can also be performed for francium and should yield similar precision. The Budker group in Berkeley has recently made a first observation of APNC in ytterbium [13]. For Yb, atomic structure cannot be calculated nearly as well as in alkalis, but with help of the numerous stable isotopes available, isotopic ratios of APNC measurements can be harnessed to overcome this problem. They also plan to investigate anapoles. A group at Legnaro has trapped $\approx 1000$ Fr atoms and is planning to pursue APNC. The DeMille group at Yale is working towards anapole measurements in molecules [14].

**A programme to study APNC effects in francium at ISAC**

With ISAC's upcoming actinide target, TRIUMF will be the best place in the world to carry out research with francium (and other heavy atoms/ions such as radon and radium). An international collaboration with members from Canada, the United States, Mexico, and Australia has been formed to pursue weak interaction physics with laser-trapped francium at ISAC. APNC measurements are extremely demanding, among the most challenging experiments in atomic physics. A carefully laid out program of francium studies is required to achieve the ultimate goal of weak interaction measurements. The purpose is two-fold: (i) The interpretation of APNC data requires state-of-the-art knowledge of atomic structure and also of basic nuclear properties (primarily the neutron radius); a lot of information has been obtained by the work at ISOLDE in the 1980s and by the Stony Brook group over the past decade (see [1] and references therein). Nevertheless, more information is crucial, in particular detailed studies of the specific atomic transition(s) used in an APNC experiment. (ii) Atomic and nuclear structure studies are less demanding than APNC work and allow for the systematic development of the sophisticated apparatus and on-line testing, while providing interesting, and self-contained physics results.

**The proposal: Spectroscopy of the highly forbidden $7s \rightarrow 8s$ transition in Fr in a laser trap**

The excitation $ns_{1/2} \rightarrow (n{+}1)s_{1/2}$ from an alkali's electronic ground state to the first excited $s$-state is one of the faintest transitions observed in atoms (see Fig. 2); it is electric-dipole (E1) forbidden, and in the non-relativistic limit, the magnetic dipole (M1) amplitude also vanishes. Relativistic effects and the hyperfine (hf) interaction with the nuclear spin give rise to an extremely weak $\mathrm{M1}{=}\mathrm{M1}_{\mathrm{rel}} + \mathrm{M1}_{\mathrm{hf}}$ transition with tiny oscillator strength $f$ (e.g. $10^{-13}$ in Cs — allowed E1 transitions have $f \approx 1$), which has attracted a lot of interest. The exact mechanism giving rise to the relativistic $\mathrm{M1}_{\mathrm{rel}}$ amplitude had been unclear for a long time, and it is considered the most sensitive electromagnetic transition to the accuracy of the relativistic description of an atomic system [18]. In Cs, the $6s_{1/2} \rightarrow 7s_{1/2}$ transition has been the basis of the APNC measurements, and has been without doubt the single most important atomic transition for weak interaction studies. Its equivalent in Fr, $7s \rightarrow 8s$ is the leading candidate for a Fr experiment in the optical domain. The significant difficulties in observing such weak lines have prevented experiments in alkalis other than Cs so far. The near-coincidence of the $ns_{1/2} \rightarrow (n+1)s_{1/2}$ wavelengths in Rb (497 nm) and Fr (506 nm) is an opportunity to use one frequency-doubled diode laser system for detailed investigations off-line in Rb and on-line in Fr at ISAC.

Savukov et al. [18] have performed precise calculations of the $\mathrm{M1}_{\mathrm{rel}}$ amplitudes for alkalis including Fr and have demonstrated the importance of including negative-energy states (NES), i.e. the effect of electron-positron pairs, in the relativistic computation of the $\mathrm{M1}_{\mathrm{rel}}$ amplitude and discovered surprisingly large NES contributions. In case of Rb, they found a cancellation between the no-pair and the NES amplitude, reducing the predicted total $\mathrm{M1}_{\mathrm{rel}}$ amplitude by a factor of 8, providing the

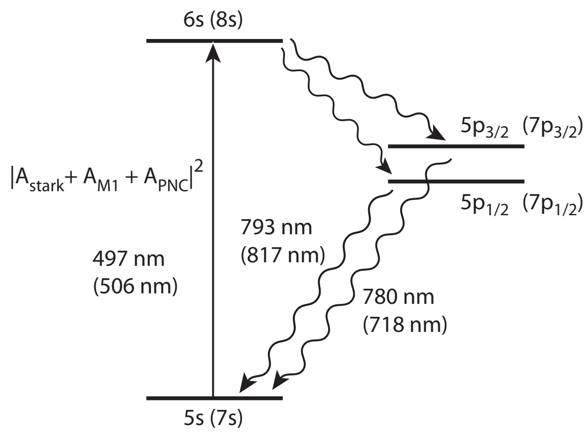


Figure 2: Excitation scheme for the $ns \rightarrow (n+1)s$ transition in Rb and Fr (brackets). The MOT operates on the $ns \rightarrow np_{3/2}$ transition

best opportunity for an experimental test of electron-positron pair contributions in atomic structure as shown in Table 1. In Fr, the no-pair contribution is much larger and dominates. In Cs, on the other hand, NES contribute at the 5 % level, whereas the discrepancy between theory and experiment is 16 %. To test the different contributions to the $M1_{rel}$ matrix element, it is clearly desirable to have good data in at least these three elements.

Understanding the M1 transition amplitude is very important in several ways. The $M1_{rel}$ amplitude is a valuable benchmark for calculations of relativistic effects and radiative corrections in the Fr atom. The original $2.3\sigma$ discrepancy between cesium APNC and electroweak unification predictions has been resolved by calculation of higher-order radiative corrections [21]. Such corrections are *ab initio*, but involve bound-state QED and are thus not exact, so it is important to test them. One of the very few tests identified is the $M1_{rel}$ transition. $M1_{rel}$ can be separated from $M_{hf}$ by their dependence on the hyperfine structure. In $\Delta F = 0$ transitions, only $M1_{rel}$ is present, in $\Delta F \neq 0$ transitions, both components contribute.

A determination of $M1_{hf}$ induced by the hyperfine interaction is a powerful way to determine the transition tensor polarizability $\beta$ in Fr, a quantity not easily measurable otherwise, but essential in the interpretation of APNC: In a Stark-interference type APNC measurement such as the Cs work done in Boulder, one measures the interference between the parity-violating amplitude $E1_{pnc}$ caused by the weak interaction and a parity-conserving amplitude $E1_{stark} = \beta E$ induced by an externally applied electric field $E$ (as in most parity violation experiments, one measures an asymmetry of the signal under parity flips). In essence, one determines the size of $E1_{pnc}$ *relative* to that of $E1_{stark}$ at a

Table 1: Contributions to reduced matrix elements of the $M1_{rel}$ operator in atomic units multiplied by a factor of $10^5$ as calculated by Savukov et al. I, lowest-order Dirac Hartree-Fock value; II no-pair, second-order no-pair contribution; II NES, negative-energy state contributions in second order; taken from [18]. Cs data by Bennett et al. [19].

| | Li | Na | K | Rb | Cs | Fr |
|---|---|---|---|---|---|---|
| $Z$ | 3 | 11 | 19 | 37 | 55 | 87 |
| I | 0.91 | 1.16 | 1.15 | 1.38 | 1.51 | 2.09 |
| II, no-pair | 0.12 | 0.03 | -0.08 | -1.86 | -10.69 | -116 |
| II, NES | 0.02 | 0.13 | 0.20 | 0.31 | 0.40 | 0.64 |
| Total | 1.05 | 1.06 | 1.27 | -0.17 | -8.78 | -113 |
| Experiment | | | | | -10.40 (0.03) | |

given field $E$. To determine $\mathrm{E1_{pnc}}$ in absolute terms, a reliable value of $\beta$ needs to be obtained. In Cs, the most precise determination of $\beta$ was performed by Bennett et al. [19] by observing the $\mathrm{E1_{stark}}$ and M1 amplitudes. In this case, the M1 amplitude is determined relative to the Stark amplitude $\beta E$ at a known field. If the M1 amplitude is known, one can go backward and get $\beta$ from $E$ and M1. From the discussion above it is clear that $\mathrm{M1_{rel}}$ is not suitable for this procedure, but $\mathrm{M1_{hf}}$ is: It can be reliably computed from the well known hyperfine splittings in the atom.

In addition, the Stark-M1 interference has been the most challenging systematic error in the Cs APNC experiments. In Fr, this term is predicted to be one order of magnitude larger compared to Cs, making a thorough investigation mandatory. Overall, it is clear that even though the M1 amplitude is not directly part of a Stark-interference type APNC measurement, it is nevertheless of fundamental importance and a cornerstone of weak interactions studies in Fr.

**An experiment to characterize the $7s \to 8s$ transition in Fr**

In the presence of an externally applied electric field, the total amplitude of the $7s \to 8s$ transition consists of a Stark-induced electric dipole, a magnetic dipole, and the weak-interaction induced, parity-violating electric dipole part:

$$A_{7s\to 8s} = E1_{\mathrm{stark}} + M1 + E1_{\mathrm{pnc}}.$$

The Stark-induced amplitude arising from the mixing of states of opposite parity in the presence of an external electric field $E$ is given by

$$E1_{\mathrm{stark}}(F,m \to F',m') = \alpha \vec{E}\cdot\vec{\epsilon}\,\delta_{F,F'}\delta_{m,m'} + i\beta(\vec{E}\times\vec{\epsilon})\cdot\langle F'm'|\vec{\sigma}|Fm\rangle,$$

and is characterized by the scalar and tensor transition polarizabilities $\alpha$ and $\beta$, respectively, which are listed in Table 2, $\vec{\sigma}$ are the Pauli matrices, and $\vec{\epsilon}$ is the oscillating electric field of the laser. For the geometry and polarization typically chosen in APNC measurements, only the $\beta$ term contributes, hence the particular need to determine $\beta$. The magnetic dipole component is given by

$$M1(F,m \to F',m') = \langle M1\rangle(\hat{k}\times\vec{\epsilon})\cdot\langle F'm'|\vec{\sigma}|Fm\rangle,$$

where $\langle M1\rangle$ is the reduced matrix element $\langle M1\rangle = \langle M1_{\mathrm{rel}}\rangle + (F-F')\langle M1_{\mathrm{hf}}\rangle$, and $\hat{k}$ a unit vector pointing along the propagation direction of the light wave. The parity violating amplitude is

$$E1_{\mathrm{pnc}}(F,m \to F',m') = i\mathrm{Im}\langle E1_{\mathrm{pnc}}\rangle\cdot\langle F'm'|\vec{\sigma}|Fm\rangle.$$

It is orders of magnitude smaller than the Stark and M1 amplitudes and will not be of significance for the measurements described in this proposal. Of course, it will play a central role in APNC measurements.

From measurements on this transition, $\alpha$, $\beta$, $\mathrm{M1_{rel}}$, $\mathrm{M1_{hf}}$, and $\mathrm{E_{pnc}}$ can be extracted (and additional static quantities such as the dc Stark shift). This proposal focuses on $\alpha$, $\beta$, $\mathrm{M1_{rel}}$, and $\mathrm{M1_{hf}}$.

We propose to measure the $7s \to 8s$ M1 amplitude in Fr by observing its interference with a much larger Stark-induced amplitude $\mathrm{E1_{stark}}$, which arises from the mixing of states of opposite parity in the presence of an external electric field, following largely the scheme developed by the Boulder group over nearly two decades [19, 24, 25]. However, there is a major difference due to the radioactive nature of Fr isotopes. The measurement in Cs used a massive thermal beam (up to $10^{15}$ $\mathrm{s^{-1}cm^{-2}}$), which is naturally not possible for Fr, as total production rates for even the isotopes with the most favorable production cross sections will not exceed approximately $10^{10}$ per second. Instead we will go the route of using cold, trapped atoms to maximize the signal. In terms of the number of atoms available

Table 2: Transition polarizabilities for Rb, Cs, and Fr in atomic units ($a_0$ is the Bohr radius). The Rb and Fr values are computed [20] and the Cs values are from the Boulder measurements.

| | Rb | Cs | Fr |
|---|---|---|---|
| $\alpha$ | $235\,a_0^3$ | $267.6(8)\,a_0^3$ | $374\,a_0^3$ |
| $\beta$ | $9\,a_0^3$ | $27.02(8)\,a_0^3$ | $74\,a_0^3$ |

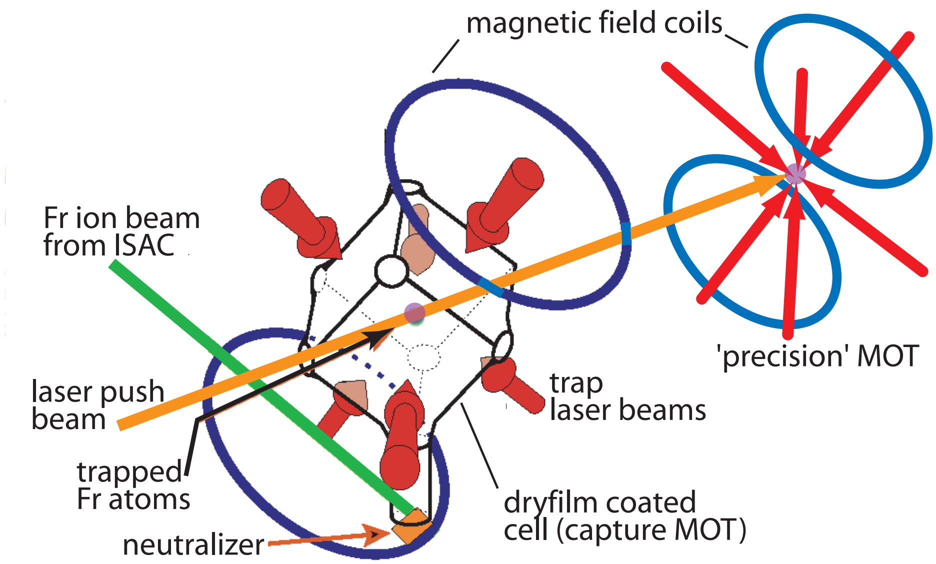


Figure 3: Schematic of a double trap with a capture MOT based on the Stony Brook design [22]. The 'precision' MOT will be a combination of a re-capture MOT that receives the atoms from the capture MOT and another trap, most likely a dipole trap, which can contain the atoms during the measurements while the MOT fields are turned off.

for the measurement, the key figure in a comparison of beam and trap based measurements is the number of atoms in resonance with the laser at any given moment. In the final version of the Boulder experiment this number was $2.2 \times 10^6$ atoms (and $2.8 \times 10^5$ in 1988). The large speed of the atomic beam, its large spatial extent and the Doppler broadening take a significant toll. In a trap on the other hand, the Doppler effect is negligible, so all atoms can contribute (however, there will be a duty factor, as some time has to be spent trapping/loading). Hence, $10^6 - 10^7$ atoms in a trap provide a similar scenario. Based on the experience with trapping of francium at Stony Brook on-line at the LINAC and from an actinium source in Boulder, it can safely be assumed that even with modest proton beam current on target, we can trap $10^6$ or more Fr atoms on-line at ISAC.

### A roadmap for increasingly difficult measurements: Learning as we move forward

Spectroscopy of faint transitions on-line with a radioactive sample of atoms is naturally more challenging than work with stable atoms. It is important to develop a robust procedure that allows us first to locate the transition at all, and then to perform increasingly sophisticated experiments to explore the more subtle aspects with increasing precision. The initial setup should be as simple as possible, while a final version of the on-line trap will be capable of housing an APNC setup.

The Fr program at ISAC will start with the approved experiment E1010 (Pearson et al.), measuring the Bohr-Weisskopf effect (also known as hyperfine anomalies) in a long chain of neutron-deficient and neutron-rich isotopes and in isomers. The trapping apparatus developed in the process will be able to accommodate the requirements for the $7s \rightarrow 8s$ measurements proposed here, at least up to the $\mathrm{E1}_{\mathrm{stark}}$ M1 interference measurement. We will establish a double MOT system as shown in Fig. 3 with a capture trap which is optimized to capture as large a fraction of the Fr atoms from ISAC as possible, using a vapor cell with anti-stick coatings. The cooled, trapped atoms are then transferred to a second MOT which is geared towards precision measurements; such a system has been developed at Stony Brook and also for TRINAT at TRIUMF. To observe Stark-induced transitions, field plates have to be mounted inside the vacuum chamber to produce a homogenous electric field of up to 3 kV/cm at the position of the trapped atom cloud. The geometry has to open enough to permit access for the six trapping beams, the $7s \rightarrow 8s$ beam and offer a large solid angle for light collection from the trap.

**The first measurement: Observation of Stark-induced transitions**

It is natural to start out with the configuration yielding the biggest signal. In francium, the Stark amplitude exceeds the magnetic dipole amplitude already for modest electric fields: In a configuration where the external field is parallel to the linear polarization of the laser light, only the term $\propto (\alpha E)^2$ contributes to the Stark transition rate, and above $E \approx 20$ V/cm exceeds the M1 contribution. Neglecting the M1 contribution, the excitation rate for $\Delta F = 0, \Delta m = 0$ transitions using a 200 mW laser focused to a 1 mm diameter spot is

$$R_\alpha = 0.00034 \times E^2/\mathrm{s},$$

where $E$ is in V/cm. With a sample of $10^6$ trapped Fr atoms, the $7s \rightarrow 8s$ excitation rate will be $3 \times 10^9$ per second. A measurement cycle would look as follows (see also Fig. 4):

- $^{210}$Fr atoms are cooled and trapped.
- The repumper (817 nm) laser is turned off and the trapping laser (718 nm) pumps all atoms into the lower hyperfine ground state, the trap goes dark, the trapping laser is turned off.
- The 506 nm laser turns on for a few milliseconds and excites the $7s \rightarrow 8s$ transition. In the subsequent decay $8s \rightarrow 7p_{1/2,3/2} \rightarrow 7s$, a sizeable fraction of atoms end up in the *upper* hyperfine level of 7s.
- Subsequently, the trapping laser is turned on again and excites atoms found in the upper hyperfine state $F = 13/2$ to $7p_{3/2}F = 15/2$ from where it can only decay back to $7s_{1/2}F = 13/2$. The atoms are cycled on this transition several hundred times, resulting in a burst of light; only atoms excited to 8s contribute to this signal, making this a clean, amplified measure of the $7s \rightarrow 8s$ transition probability.
- trap is turned on again, recaptures previously captured Fr atoms and traps new ones and the cycle is repeated.

In this scheme, each $7s \rightarrow 8s$ excitation results in hundreds of 718 nm photons. Even with modest light collection efficiency, one can achieve near 100 % detection efficiency per excitation. A beam version of this method has been successfully used in the final version of the Boulder Cs APNC experiment and also in trap based measurements such as the precise determination of the hyperfine splitting in $^{21}$Na at Berkeley [26]. This measurement can be carried out without lifting the $m$-degeneracy and disturbs the trap minimally.

In a next step, the $\Delta F = \pm 1, \Delta m = \pm 1$ transitions can be observed. In this case, the linear polarization of the 506 nm laser must be perpendicular to the externally applied electric field, and

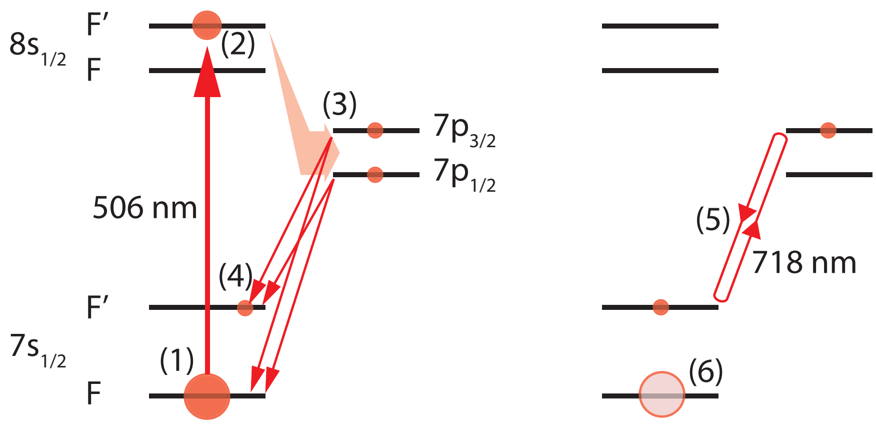


Figure 4: Using the shelving technique to amplify the fluorescence. Left: At the beginning of the measuring period, all atoms are pumped e.g. into the lower HF ground state (1). After excitation to $8s$ (2) the atoms cascade down via $7p$ (3) and about half end up in the upper, depleted HF ground state (4). Right: Then, the probe laser cycles the atom on the $7s\,F' - 7p_{3/2}\,F'+1$ transition (5); all atoms that were not excited to $8s$ remain 'dark' in $7s\,F$ (6); splittings not to scale.

the rate for the same electric field and laser intensity is about 30× lower, i.e. 100 per second per atom at 3 kV/cm. The measurement would follow the same steps, and can also be carried out in the low-magnetic field region at the center of the trap, i.e. the $m$-degeneracy does not need to be lifted.

From these measurements, approximate values for $\alpha$ and $\beta$ can be obtained (for a precise determination, the number of atoms in the trap and the laser intensity would have to be known very well, which is hard to achieve, and the MOT fields would need to be turned off carefully). However, it is possible to derive a value for the ratio $\alpha/\beta$. This ratio (calculated to be about 5 in Fr) is significantly smaller than in Cs ($\approx 10$), so it will be significantly easier as the resonances are more similar in size (the $\alpha$ resonance is more than 100× larger in Cs than the $\beta$ one, but in Fr only about 30×).

**Measurement of the M1 amplitude**

The next step is the observation of the M1 amplitude via $E1_{\text{stark}}$-M1 interference. For two reasons this is more challenging: the M1 amplitude is significantly smaller, and in addition the interference terms cancels when summed over all $m$ levels, hence the degeneracy has to be lifted via the Zeeman effect by applying a homogenous magnetic field. Working (e.g.) on $\Delta F = 1$ transition, only the $\beta$-induced Stark transition is present and at 2 kV/cm leads to a excitation rate of 40 per second per atom (again for a 200 mW laser beam focused to a 1mm diameter waist). While the M1 excitation rate on the same transition is almost 400 times weaker, one can observe the *interference* between E1 and M1. The relative phase between them will shift by 180° if either the electric field, the magnetic field, the light propagation, or the sign of $m$ is reversed. By performing these reversals, one observes an asymmetry in the fluorescence yield

$$\eta = 2\frac{|E1+M1|^2 - |E1-M1|^2}{|E1+M1|^2 + |E1-M1|^2},$$

amounting to 0.21, which is rather large. A 1 % measurement of this asymmetry requires a 0.2 % measurement of the overall transition rate. In a shot-noise limited situation, this requires the observation of 250,000 excitations. With a million atoms in the trap, and a 10 % duty factor for measurement vs. trap operation, this can be done in a fraction of a second. Of course, most effort has to be spent on studying systematics, such as imperfect reversals of the fields.

For the interference measurement, the trap environment needs to be much more carefully controlled than for the Stark transitions discussed earlier. On could load the atoms from the precision MOT into a dipole trap and apply a homogenous magnetic field to lift the $m$-degeneracy ($\approx 10$ Gauss). However, it might also be possible to quickly turn off the MOT field, leaving the atoms in free fall for a few ms. During this time, the homogeneous B and E fields are turned on. The recent development of an AC-MOT [27], which can be turned off 300 times faster than a regular MOT (in terms of the magnetic field) is a very interesting new technique for this purpose and TRINAT is setting out to develop such a trap. Otherwise, the basic trapping/measurement cycle is maintained.

The final and most difficult case is the measurement of the $\mathrm{M1_{hf}}$ amplitude, which is about an order of magnitude smaller than $\mathrm{M1_{rel}}$. The hyperfine-induced M1 can be separated from the relativistic one by its dependence on the hyperfine levels, i.e. one determines the difference in the size of the E1-M1 interference signal between the $F \rightarrow F'$ and $F' \rightarrow F$ transitions. For a 1 % measurement, the overall transition rate has then to be determined with a noise level of 0.02 %. In a shot noise limited situation, this would take about 10 seconds.

At the end of this program, $\alpha$, $\beta$, $M1_{\mathrm{rel}}$, and $M1_{\mathrm{hf}}$ will have been determined at the percent level. Together with previously measured atomic quantities and the atomic theory developed, francium will be the best understood atom in the lead - uranium region. APNC will ultimately require better knowledge of $\beta$ and hence $M1_{\mathrm{hf}}$, at the 0.1 % level. However, there is no point in carrying out such improved measurements until the actual APNC experiment is in full swing.

### Required infrastructure

The proposed experiments require a dedicated francium beamline ending in a clean room suitable for the laser equipment. However, the requirements do not go beyond those for the already approved francium experiments E1010 (hyperfine anomalies) and E1065 (anapole moments).

### Stage 2 approval

At this point, no firm date is set for the availability of an actinide target, and correspondingly a francium beam at ISAC. Therefore we do not seek stage 2 approval at this time.

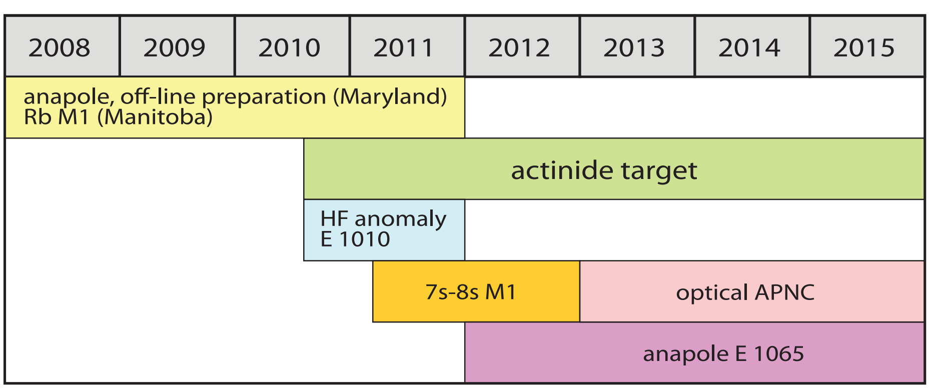


Figure 5: Estimated schedule for the Fr programme.

1. E. Gomez, L. A. Orozco, and G. D. Sprouse, Rep. Prog. Phys. 69, 79 (2006).
2. W. J. Marciano and J. L. Rosner, Phys. Rev. Lett. 65, 2963 (1990).
3. M.A. Bouchiat and C. Bouchiat, J. Phys (Paris) 35, 899 (1974).
4. See e.g. I.B. Khriplovich, Parity violation in atomic phenomena, Gordon and Breach, 1991.
5. C. S. Wood, S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, and C. E. Wieman, Science 275, 1759 (1997).
   For details see C. S. Wood et al., Can. J. Phys. 77, 7 (1999).
6. V. A. Dzuba, V. V. Flambaum, and O. P. Sushkov, Phys. Rev. A 51, 3454 (1995).
7. M. S. Safronova and W. R. Johnson, Phys. Rev. A 62, 022112 (2000).
8. Prescott CY *et al.*, Phys. Lett. B 77, 347 (1978) and Prescott CY *et al.*, Phys. Lett. B 84, 524 (1979).
9. Ramsey-Musolf MJ and Su S, Phys. Rep. 456, 1 (2008).
10. Young RD, Carlini RD, Thomas AW and Roche J, Phys. Rev. Lett. 99, 122003 (2007).
11. Erler J and Ramsey-Musolf MJ. Phys. Rev. D 72, 073003 (2005).
12. A. Derevianko, private communication.
13. Stalnaker JE, Budker D, DeMille DP, Freedman SJ and Yashchuk VV, Phys. Rev. A 66, 031403 (2002).
14. DeMille D, Cahn SB, Murphree D, Rahmlow DA and Kozlov MG, Phys. Rev. Lett. 100, 023003 (2008).
15. J. Erler, A. Kurylov, and M. J. Ramsey-Musolf, Phys. Rev. D 68, 016006 (2003).
16. W. C. Haxton and C. E. Wieman, Annu. Rev. Nucl. Part. Sci. 51, 261 (2001).
17. E. Gomez, S. Aubin, G. D. Sprouse, L. A. Orozco, D. P. DeMille, Physical Review A 75, 033418 (2007).
18. I. M. Savukov, A. Derevianko, H. G. Berry, and W. R. Johnson, Phys. Rev. Lett. 83, 2914 (1999).
19. S. C. Bennett and C. E. Wieman. Measurement of the 6s - 7s transition polarizability in atomic cesium and an improved test of the standard model. *Physical Review Letters*, 82:2484–2487, March 1999.
20. M. Safronova, W. Johnson, and A. Derevianko, Phys. Rev. A 60, 4476 (1999).
21. M. Yu. Kuchiev, and V. V. Flambaum, Phys. Rev. Lett. 89, 283002 (2002).
   A. I. Milstein, O. P. Sushkov, and I. S. Terekhov, *ibid.* 283003.
22. S. Aubin, E. Gomez, L. A. Orozco, and G. D. Sprouse, Rev. Sci. Instr. 74, 4342 (2003).
23. P. A. Vetter, D. M. Meekhof, P. K. Majumder, S. K. Lamoreaux, and E. N. Fortson, Phys. Rev. Lett. 74, 2658 (1995).
24. C. S. Wood, S. C. Bennett, J. L. Roberts, D. Cho and C. E. Wieman, Canadian Journal of Physics 77, 7 (1999).
25. S.L. Gilbert, R.N. Watts, and C.E. Wieman. *Phys. Rev. A* 29, 137 (1984)
26. M. A. Rowe, S. J. Freedman, B. K. Fujikawa, G. Gwinner, S.-Q. Shang, and P. A. Vetter, Phys. Rev. A 59, 1869 (1999).
27. Matthew Harvey and Andrew James Murray, Physical Review Letters 101, 173201 (2008).