Laser Trapping of Radioactive Atoms

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Abstract

Light forces acting on radioactive atoms confine them in very dense and cold samples achieving large phase space density. We describe the processes of radioactive atom production, reduction of their velocity and capture. The trapped atoms form excellent sources for the study of atomic parity non-conservation, β decay asymmetry, other weak force processes, and α decay asymmetry.

Contents

1 INTRODUCTION

The compression of atoms in six-dimentional phase space opens new possibilities for experiments in many different fields. Most applications use stable atoms that are abundant and easily available. There are unique experiments which can be done with radioactive atoms: Atomic parity non conservation measurements and time reversal violation searches with unstable atoms such as francium, and experiments that observe the decay radiations of polarized radioactive nuclei. Radioactive atoms are produced in very small quantities, and need special techniques to confine and cool them with minimal loss and within a time short compared to the radioactive lifetime. The purpose of this paper is to review the field that addresses these experimental problems for studies that can test our understanding of the basic forces of nature, in particular the weak force.

The development of new experimental methods has continually increased the density of particles in phase space. The tools available for enhancing the phase space density differ greatly depending on the kind of particle. If the particles have charge, confinement and cooling is possible through the electromagnetic interactions. Among the more recent successes for this kind of phase space enhancement are electron cooling and stochastic cooling in particle accelerators. When the particles do not have charge, the mechanisms for confinement and cooling are more limited. The simplest confinement environment for a neutron or a sample of radioactive atoms is still a bottle made of an appropriate material. Cooling usually requires thermal contact of the particles with a cold surface, and in the case of atoms, they can condense on the walls making it useless for further studies. Another confinement environment is a crystal, which limits both the position and momentum spread of the neutral atoms. However, the electric and magnetic fields felt by the individual

atoms can be many orders of magnitude larger than those produced in the laboratory, greatly modifying their basic atomic structure.

When Wu, Ambler, Hayward, Hoppes and Hudson performed their landmark experiment to observe the β decay asymmetry at the National Bureau of Standards in Washington [1], they limited the phase space available to the spins of the ^{60}Co nuclei, by placing the sample in thermal contact with a cerium magnesium nitrate salt. The salt was cooled via an adiabatic demagnetizing process. They observed a different number of electrons emitted in the direction of the magnetic field than opposite the magnetic field, experimentally establishing the violation of parity by the weak force.

The preparation of a sample of polarized nuclei became easier with the development by Kastler and Brossel of the techniques of optical pumping (see the review by W. Happer [2]). By repeated absorption of circularly polarized light by an atomic gas, the population among the hyperfine and Zeeman sublevels of the atoms can change creating a net polarization of the atoms. The hyperfine interaction transfers the atomic polarization to the nuclei, aligning all the spins in a particular direction. The problem remains that the sample occupies a very large region of phase space and the density is very small. The size and energy distribution of the source limits the precision of the study of the angular distribution of emitted α and β particles.

The situation improved after the pioneering experiments of Phillips and Metcalf [3] demonstrating laser cooling of atoms. By the repeated interaction of an atom with near resonant radiation it is possible to lower its velocity, and also to remove some of the thermal energy of the atoms. The invention of the magneto-optical trap [4] (MOT) greatly facilitated the confinement of cold atoms.

It is now possible to capture and trap atoms with optical fields. (See Fig. 1 for a sample of about 1000 ^{210}Fr atoms captured in a MOT). The phase space densities achieved can be ten orders of magnitude higher than at room temperature. Using the appropriate trap and excitation light the sample can be fully polarized. The time the atoms can remain captured depends on the quality of the vacuum and it is not difficult to reach minutes.

A sample of fully polarized radioactive atoms with a very high phase space density is an ideal source for many experiments probing the weak force. The overall physics problems being currently addressed fall into two groups: Atomic parity and time reversal non-conservation experiments with radioactive atoms, and correlation measurements associated with β and α decay.

Figure 1: False color image of about 1000 ^{210}Fr atoms captured in a MOT

A phenomenon that provides a probe of the standard model is atomic parity non-conservation, a manifestation of the Z^0 heavy neutral gauge boson [5]. Experiments by the group of Prof. Carl Wieman [6] of the University of Colorado and JILA at Boulder have achieved experimental precisions of a fraction of a percent. The results obtained in atomic parity non-conservation test the radiative electroweak corrections and are very sensitive to extensions of the standard model [7]. Despite being a low-energy experiment, atomic parity non-conservation is sensitive to additional gauge bosons. Such experiments can provide evidence for Z' bosons via deviations from standard model predictions. Although great progress is being made at improving the precision of high energy experiments, this work is concentrated around the Z^0 pole. The atomic physics experiment, however is far from the Z^0 pole, and is more sensitive to certain particles [8].

Parity violation has its origin in the fact that the Z^0 gauge boson can couple to the vector or axial-vector components of the electronic

and nucleonic currents. We restrict the discussion to a vector-axial vector type weak force (V-A). The coupling of the electronic axial vector current with the hadronic vector current dominates, since all quarks contribute coherently. Only the valence nucleons contribute to the axial hadron current resulting in a much weaker nuclear-spin dependent part of the force.

The parity violating interaction between the nucleus and an electron leads to a mixing of electronic states with opposite parity, in particular between S and P states. For example an S state will have a very small amount of a P state mixed with it (a typical number for a heavy atom is 1×10^{-11}). This results in an electric dipole transition amplitude between two states of the same parity, which would otherwise be forbidden.

The measured amount of P state mixing is proportional to the weak charge, defined as $Q_W \approx -N + Z(1 - 4sin^2(\theta_W))$, times an atomic matrix element, $\langle\gamma^5\rangle$. This matrix element must be calculated by ab-initio methods in order to extract the weak force information from a measurement of the mixing. The calculation is simpler for alkali atoms with only a single S electron in the outer shell. The interaction scales a little bit faster than Z^3 [5, 9], favoring heavy atoms. The enhancement comes for various reasons: A heavy nucleus has more nucleons for the electron to exchange a Z^0, the electron spends more time in a larger nucleus with a larger charge, and the electron has a higher momentum that enhances relativistic effects.

Performing a parity non-conservation measurement with different isotopes of a heavy atom such as francium could have the benefit of canceling some of the uncertainty of the atomic calculation if it is possible to measure two different isotopes to high precision and determine the ratio. [10].

Another manifestation of parity violation is the presence of a nuclear anapole moment, which arises from parity mixing in the nuclear wave function. Charged-current hadronic interactions of the Z^0 can be studied in strangeness-changing and charm-changing decays, but the neutral current interactions can only be studied in nucleon-nucleon interactions, where parity violation provides the signature to separate the weak interaction from the much larger strong and electromagnetic interactions. The measurement of a nuclear anapole moment provides a unique possiblity to test this interaction, as long as the nuclear system is sufficiently well understood to allow interpretation of the measurement. Wood *et al.* [6] made the first definitive measurement of an anapole moment in Cs, and the results are in good agreement with theoretical

calculations [11, 12]. The measurements require determing the nuclear spin dependence of the PNC effect, and require extreme precision. Since the anapole moment scales as $A^{2/3}$, heavy atoms are favored for future measurments, and francium is an excellent candidate.

Since the discovery that the K mesons violated CP and because of the strong belief in CPT invariance, the search for time reversal non-conservation has been an important pursuit. The presence of an electric dipole moment (edm) in the neutron or in the electron is a manifestation of time reversal non-conservation [13]. Schiff [14] pointed out that relativistic effects, the presence of non-electrostatic forces, spin-orbit interactions, and finite size effects would allow an atomic edm. Sandars [15] showed that in some atoms an electron edm moment can induce an atomic edm many times bigger than that of the atom. The ratio of the atomic to the electron electric dipole moments scale as $Z^3\alpha^2\chi$, where χ is the electric polarizability of the atom. Searches for the electric dipole moment of heavy atoms provide sensitive tests for an electron edm. The measurements place limits on various sources of T violations depending on the particular interactions considered. It is a major undertaking to interpret the various limits in terms of possible models of T violation that will not be attempted here. The present limits on the atomic edm, consistent with zero, are set by the Hg experiment of the Seattle group [16]. Francium with its high Z and simple atomic structure is a possible candidate for experiments that search for an electron edm through an atomic edm.

Another kind of experiment realizable with trapped radioactive atoms is studies of β decay [17]. The standard model proposes a maximally parity violating, left-handed $V - A$ current-current interaction to describe the vertices in neutron decay. This interaction is proportional to V_{ud}, the quark mixing matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Nuclear β-decay experiments determine V_{ud} and can explore the left handed structure of the weak Hamiltonian by measuring the spatial and spin dependent correlations of the β particle and daughter nucleus after a decay.

For more complicated nuclei it is necessary to modify the simple picture between quarks to include the appropriate proton and neutron correlations, but these effects do not limit the precision of current experiments. For Fermi (vector current) transitions between mirror nuclei and between $J^\pi = 0^+$ states, the nucleon modifications are straightforward. In these transitions the conserved-vector-current hypothesis gives V_{ud} unrenormalized by the strong interactions.

In an atom trap, many of the systematic errors associated with source

scattering can be eliminated and the recoiling daughter nucleus can be observed, providing a reconstruction of the decay including the undetected neutrino. However, the rearrangement of the electrons in the daughter atom after the decay, can make the exact determination of the neutrino momentum and energy difficult.

Mirror decays are particularly simple, and there are two examples in radioactive alkali atoms: ^{21}Na(22.5sec) $\rightarrow$ ^{21}Ne, and ^{37}K(1.23s) $\rightarrow$ ^{37}Ar. These mirror beta decays are an interesting 'laboratory' for studying the fundamental weak interaction. An accurate measurement of the β asymmetry is a precision test of the $V - A$ structure of the weak interaction, and may put more stringent limits to the existence of right handed neutral currents.

The experiments are not limited to vector boson exchange models. Unlike vector boson exchange, a scalar interaction demands like helicities for both leptons and antileptons. Vector boson exchange forbids back-to-back emission of the leptons while back-to-back emission is maximal for scalar exchange. Limits on the scalar interaction are poor, both from beta decay [18] and from high energy physics. Even a 1% measurement of the β-ν correlation coefficient a would greatly enhance our knowledge of this particular interaction.

The study of angular distributions of α particle emission from deformed nuclei can shed light on the α decay process. Recent work by Delion *et al.* [19] and others have proposed that the α anisotropy results from preferential tunneling through a deformed barrier which varies with angle relative to the nuclear symmetry axis. Schuurman et al [20] have recently measured α anisotropies of At and Rn nuclei. The α decay is predominantly L=0, and the anisotropy results from small L=2 admixtures in the decay amplitudes. These authors argue that the systematic behavior of the L=2 admixtures correlates strongly with the neutron holes created as neutrons are removed from the N=126 closed shell, and is not correlated with deformation.

All experiments to date have used the strong hyperfine fields in ferromagnetic materials and cryogenic temperatures to polarize the nuclei. Incomplete polarization and the presence of some nuclei at sites where there is no hyperfine field attenuates the anisotropy, especially of the higher moments of the angular distribution. Laser polarized nuclei can be prepared in a single m-state, and the complete angular distribution should be measurable with a single detector by rotating the polarization axis and detecting the decay products as a function of time. Measurement of the higher moments of the angular distribution with trapped atoms may help to better understand the α decay process.

2 DECELERATION AND TRAPPING

2.1 *The Light Forces*

Last century physicists discovered light pressure, but the mechanical effects, given the available sources, were extremely small. Einstein studied the thermodynamics of emission and absorption of radiation in his paper on blackbody radiation [21]. He predicted the transfer of momentum in spontaneous emission and stated that 'the smallness of the impulse transmitted by the radiation field implies that these can almost always be neglected in practice'. In 1933 Frisch observed the deflection of an atomic beam of Na by resonant light from a Na lamp [22]. In the 1970s the advent of tunable lasers with very narrow linewidths changed the situation. Hänsch and Schawlow [23] and Wineland and Dehmelt [24] realized that high brightness sources could exert a substantial force on atoms or ions and potentially cooling their velocity distributions. Since then a long list of scientists have contributed to advances in the field of laser cooling and trapping. There are excellent reviews and summer school proceedings in the literature [25, 26, 27] and in this section we treat only very general aspects without the careful detail given in the above papers. However, the reader should have enough information after studying this section to understand the basic mechanisms for laser cooling and trapping in their application to radioactive atoms.

Successful trapping needs position dependent and velocity dependent forces. The first provides the spring constant to restore the atom to the center of the trap, and the second, velocity dependent force, provides the damping for the atoms to fall into the trap, and then cool to the lowest temperature possible. In the following we will try to understand how to generate such forces by the interaction of light near resonance with an allowed transition of an atom.

The origin of the light force is the momentum transferred when an atom absorbs a photon from a laser beam. The momentum of the atom changes by $\hbar\mathbf{k}$, where $\mathbf{k}$ is the wave vector of the incoming photon. If this excitation is followed by stimulated emission into the same laser beam, the outgoing photon will again carry away $\hbar\mathbf{k}$, so there is no momentum transferred. However, for spontaneous emission, the emission can be in any direction, but because the electromagnetic interaction preserves parity, the emission will be in a symmetric pattern with respect to the incoming photon. In this case the recoil momentum summed over many absorption and emission cycles will average to zero. The atom then gains momentum in the direction of the wave vector of the incoming

laser beam. The variance of the momentum transferred does not vanish, and the atom performs a random walk in momentum space as it emits spontaneously. These fluctuations limit the lowest temperature in a trap when the laser beam is present.

The repeated transfer of momentum from a light beam to the atom by absorption and spontaneous emission provides the spontaneous light force. In order to profit from this force it is necessary to scatter many photons out of the atom using the same atomic transition, i.e., the atom must return to the same state so that it can be re-excited by the same laser beam. Such a transition is called a cycling transition. In alkali atoms with nuclear spin I and total angular momentum F, the transition from the $S_{1/2}$ ground state with $F = I+1/2$ to the $P_{3/2}$ state with $F = I + 3/2$ satisfies the cycling condition, since the excited state can not decay to the other hyperfine level ($F = I - 1/2$) of the ground state because of the $\Delta F = 0, \pm 1$ selection rule. This is the transition commonly used for trapping alkalis.

2.1.1 Velocity dependent force

Let us start with the simplest atomic system, the two-level atom interacting with light. For this case the spontaneous force is the rate of fluorescence R_{sp} times the momentum transferred by one photon. The fluorescence depends on the amount of power available for the excitation (governed by the saturation parameter S_0) and the full width half maximum Γ of the Lorentzian lineshape. The radiative lifetime of the transition $\tau = 1/\ \Gamma$ is the inverse of the Einstein A-coefficient. The fluorescent rate is:

$$R_{sp}(\Delta) \ = \ \frac{\Gamma}{2} \ \frac{S_0}{1 + S_0 + \frac{4\Delta^2}{\Gamma^2}}. \tag{1}$$

where Δ is the detuning from resonance,

$$\Delta \ = \ \omega_{\text{laser}} - \omega_{\text{atom}} \tag{2}$$

and the on-resonance saturation parameter $S_0 = I_{exp}/I_{sat}$ is the ratio between the available intensity I_{exp} and the saturation intensity I_{sat}. At $S_0 = 1$ the atom scatters at half of the maximum possible rate. There are different definitions of S_0 in the literature depending on particular definitions of I_{sat} and the reader has to pay attention to the particular one used. Here we follow the work of Citron *et al.* [28].

$$I_{sat} \ = \ \frac{h\pi c\Gamma}{3\lambda^3}, \tag{3}$$

With this definition, an intensity of I_{sat} corresponds to providing the energy of one photon ($\hbar\omega$) every two lifetimes ($2/\Gamma$) over the area of the radiative cross section of the two-level transition ($3\lambda^2/2\pi$). The rate of fluorescence (see eq. 1) depends on the detuning Δ between the atom and the laser. Because the resonance condition of an atom depends on its velocity $\mathbf{v}$ through the Doppler shift $\mathbf{k}\cdot\mathbf{v}$, the spontaneous force $\mathbf{F}_{\text{spont}}$ is a velocity dependent force.

$$\mathbf{F}_{\text{spont}} \;=\; \hbar\mathbf{k}\,\frac{\Gamma}{2}\,\frac{S_0}{1+S_0+\frac{4(\Delta-\mathbf{k}\cdot\mathbf{v})^2}{\Gamma^2}}. \tag{4}$$

This force saturates at $\hbar k\Gamma/2$ and is limited by the spontaneous decay time of the atomic level. The force felt by an atom when the intensities are large ($S_0 \approx 1$) are more complicated since stimulated emission is significant. We limit the discussion to the case where those processes are negligible. The velocity range of the force is significant for atoms with velocity such that their Doppler detuning keeps them within one linewidth of the Lorentzian of eq. 4. This condition states that:

$$|\Delta - \mathbf{k}\cdot\mathbf{v}| \leq \frac{\Gamma}{2}\sqrt{1+S_0} \tag{5}$$

Velocity dependent forces are necessary to cool an atom and reduce its velocity. They do not confine the atom, but they provide what has been termed 'optical molasses'. The damping felt by the atoms is substantial and the study of the cooling mechanisms has been discussed in numerous papers (see for example the review paper of Metcalf and van der Straten [25]).

In order to see the behavior of the Doppler force, let us focus the discussion to one dimension and in the limit where there are no stimulated emission processes $S_0 \ll 1$. The argument can easily be extended to two and three dimensions. An atom subject to two laser beams in opposite directions will feel a force $\mathbf{F}(\mathbf{v})$ coming from its interaction with both beams. If the couterpropagating laser beams are detuned to the red of the zero velocity atomic resonance, a moving atom will see the light of the opposing beam blue shifted in its rest frame. The beam in the same direction as the atom will be further red shifted in its rest frame. The force opposing the motion will always be larger than the force in the direction of the motion, and this leads to Doppler cooling.

$$\mathbf{F}(\mathbf{v}) \;=\; \mathbf{F}_{\text{spont}}(\mathbf{k}) + \mathbf{F}_{\text{spont}}(-\mathbf{k}) \tag{6}$$

The sum of the two forces gives in the limit where $v^4 \ll (\Gamma/k)^4$

$$\mathbf{F}(\mathbf{v}) \approx \frac{8\hbar k^2 S_0 \Delta}{\Gamma(1+\frac{2\Delta^2}{\Gamma^2}+S_0)^2}\mathbf{v} \tag{7}$$

Equation 7 shows that the force is proportional to the velocity of the atom. Figure 2 shows the Doppler cooling force in one dimension as a function of velocity and detuning for the D_2 line of francium. This force is limited by the spontaneous decay time of the atomic level. Typical numbers for the force limit its effect to atoms moving at about $1/20th$ of the room temperature velocity. This gives an idea of the limitations of laser Doppler cooling: Only a very small fraction of the thermal distribution of atoms at room temperature can be cooled. A reasonable estimate for the maximum velocity an atom can have and still feel the light force is when the Doppler shift is equal to the laser detuning from the transition:

$$v_{max} \approx \frac{\hbar\lambda\Delta}{2\pi} \tag{8}$$

Optical molasses provides a velocity dependent force. In the three-dimensional configuration atoms get slowed wherever they are in the region defined by the overlap of the six orthogonal beams. Large laser beams will increase the total number of cooled atoms, but the atomic density remains constant. Because of the variance of the momentum coming from the repeated random spontaneous emission, atoms can diffuse out of the molasses region. The competition between the cooling process and the diffusion of the momentum reaches an equilibrium [25]. The temperature associated with this energy is called the Doppler cooling limit T_{Doppler}.

$$T_{\text{Doppler}} = \frac{\hbar\Gamma}{2k_B} \tag{9}$$

The final temperature in optical molasses is independent of the optical wavelength, atomic mass, and, in the limit of low intensity, also of laser intensity. The only atomic parameter that enters is the rate of spontaneous emission Γ.

2.1.2 Position dependent force

The position dependent force is more subtle than the velocity dependent force. A series of no trapping theorems constrain the distribution

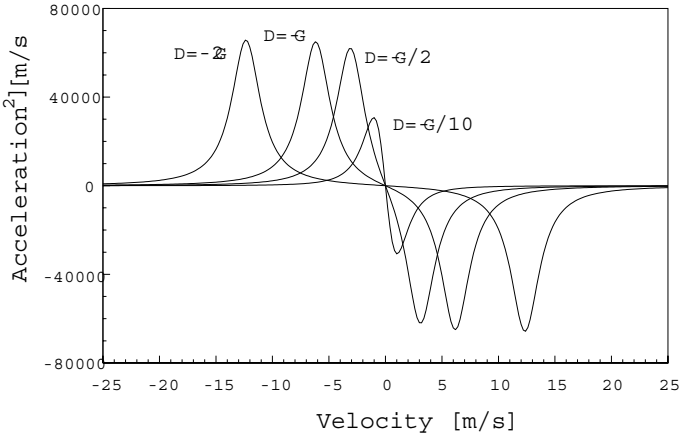

Figure 2: Doppler cooling in one-dimensional optical molasses. The numerical values are for the francium D_2 line at $S_0 = 1$.

of electric and magnetic fields for capturing neutral atoms. (See the contribution by S. Chu in Ref. [26]). J. Dalibard proposed a solution to the neutral atom trapping using the spontaneous light force. His idea became the basis of the Magneto-Optical Trap (MOT). The solution of Dalibard was to add a spatially varying magnetic field, so that the shifts in the energy levels make the light force dependent on the position. Soon afterwards this scheme was generalized to three dimensions and it was successfully demonstrated with Na atoms by Raab *et al.* [4]. Despite many new developments the MOT remains the workhorse of laser trapping due to its robustness, large volume and capture range. We will discuss this trap in more detail since this type has been used in the successful trapping of radioactive atoms [29, 30, 33, 34, 35].

2.2 *The Magneto-Optical Trap*

This section presents a simplified one-dimensional model to explain the trapping scheme in a $J=0 \rightarrow J=1$ transition.

Figure 3 shows a configuration similar to optical molasses. Two counterpropagating, circularly polarized beams of equal helicity are detuned by Δ to the red of the transition. In addition there is a magnetic field gradient, splitting the $J=1$ excited state into three magnetic sub-

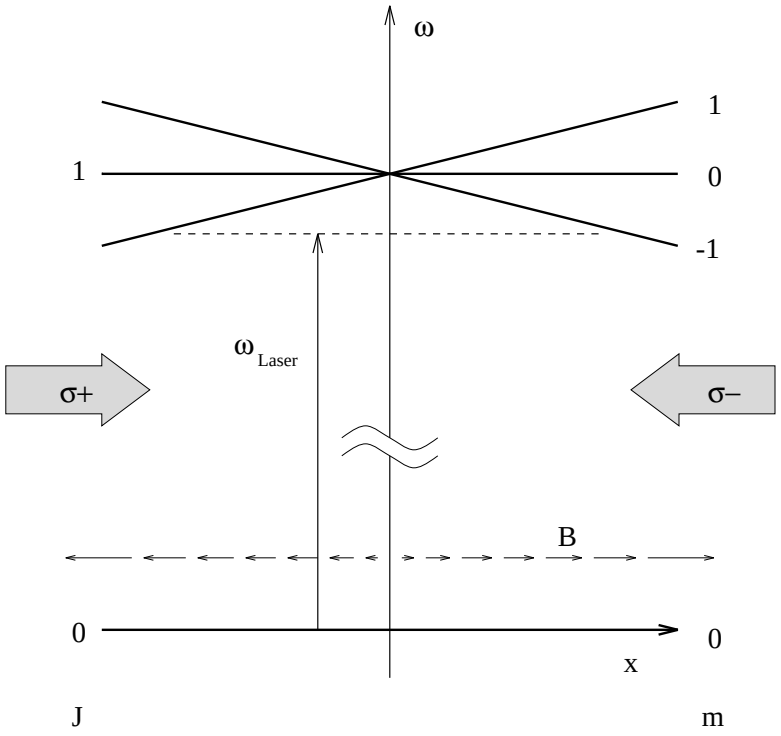

Figure 3: Simple 1-D model of the MOT

levels. If an atom is located to the left of the center, defined by the zero of the magnetic field, its $J = 0 \rightarrow J = 1, m = 1$ transition is closer to the laser frequency than the transitions to the other m-levels. However, $\Delta m = +1$ transitions are driven by σ^+ light. Atoms on the left are more in resonance with the beam coming from the left, pushing them towards the center. The same argument holds for atoms on the right side. This provides a position dependent force. The Doppler-cooling mechanism is also still valid, providing the velocity dependent force. Writing the Zeeman shift as βx, where x is the coordinate with respect to the center, the total force is:

$$F_{\mathrm{MOT}} = \frac{\hbar k \Gamma}{2} \left[\frac{S_0}{1 + S_0 + \frac{4(\Delta - \xi)^2}{\Gamma^2}} - \frac{S_0}{1 + S_0 + \frac{4(\Delta + \xi)^2}{\Gamma^2}} \right]. \qquad (10)$$

where

$$\xi = kv + \beta x \tag{11}$$

For small detunings, expansion of the fractions in the same way as in Eq. 7, shows the force proportional to ξ (see W.D. Phillips in, [26]). In the small-field, low-velocity limit the system behaves as a damped harmonic oscillator.

The real world requires three-dimensional trapping, and in alkalis a $J=0 \rightarrow J=1$ transition is hard to find. For an alkali atom with non-vanishing nuclear spin the ground state ($nS_{1/2}$) splits into two levels. The transition to the first $P_{3/2}$ excited state has four levels (for $J < I$), yet the trap works quite well under these conditions. Ideally, the transition from the upper ground state to the highest excited state F-level is cycling, and one can almost ignore the other states. Due to finite linewidths, off resonance excitation, and other energy levels the cycling is not perfect. An atom can get out of the cycling transition and an extra beam, a weak 'repump' laser, can transfer atoms from the 'dark' lower ground state to the upper one. In certain alkali atom cases, it is possible to perform the repumping with FM sidebands on the main trapping laser, but it depends on the specific hyperfine splitting of the ground state.

A magnetic quadrupole field, as produced by circular coils in the anti-Helmholtz configuration, provides a suitable field gradient in all three dimensions. The exact shape of the field is not very critical, and the separation between the two coils does not have to be equal to the radius. Typical gradients are 10 G/cm.

A large variety of optical configurations are available for the MOT. The main condition is to cover a closed volume with areas normal to the $\mathbf{k}$ vectors of the laser beams with the appropriate polarized light. The realization with three retro-reflected beams in orthogonal directions requires quarter-wave plates before entering the interaction region. In order to have the appropriate polarization on the retro-reflected beam the phase has to advance half a wavelength. The usual arrangement is to place a quarter wave plate in front of a plane mirror, but two reflections can also provide the same phase shift [29]. The development of a MOT with only one beam and a conical reflector [31] simplifies the optics significantly and permits the creation of a continuous slow beam of atoms.

The intensity of the laser beams should provide a saturation parameter $S_0 \approx 1$. The MOT can work with significantly less intensity but

it becomes more sensitive to alignment. In general the MOT is a very forgiving trap as far as polarization and intensities. The retro-reflecting technique for traps, despite the scatter losses in the uncoated windows and the beam divergence as it propagates, works very well.

The typical well depth of a MOT is set by the maximum capture velocity v_{max} of Eq. 8. For alkali atoms and $\Delta \approx 2\Gamma$ they tend to be close to 1 K. The background pressure around the MOT limits its lifetime and consequently the maximum number of atoms in steady state. Room temperature atoms colliding with the captured and cold atoms can transfer enough energy to expel some of the atoms out of the shallow well. A pressure of 1×10^{-8} Torr produces a trap lifetime of the order of 1 s.

In 1988 the NIST group [36] discovered that the temperature of sodium atoms in optical molasses was a factor of six lower than the Doppler cooling limit. The quantitative understanding of this result requires the inclusion of all the energy levels that are present in an atom, the effects of the polarization of the different laser beams and the non-adiabatic response of a moving atom to the light field. There are mechanisms of optical pumping among the many levels that intervene in the cooling process as well as the presence of polarization gradients that are responsible for sub-Doppler cooling [37, 38]. The temperatures reached in a well formed MOT are below the Doppler cooling limit. The sample in a MOT is sufficiently Doppler-free for the experiments discussed later. There is a lower limit, also called the recoil limit, that the trapped atoms in a MOT do not reach because of the inherent diffusion in phase space from spontaneous emission. This temperature limit $T_r = (\hbar k)^2/mk_B$is equal to the recoil energy acquired by an atom when it spontaneously emits a photon.

2.3 *Loading of a MOT*

Although we now have a possible trap for radioactive atoms in the MOT, the well depth of the trap is small (typically a Kelvin corresponding to a capture velocity of a few meters per second). In the case of naturally abundant alkali isotopes there are enough atoms from the available vapor pressure to capture, despite the small fraction that are slow enough to fall into the trap. With radioactive atoms the situation changes, as every possible atom must be trapped. The key is to slow down the atoms efficiently to a low enough velocity such that they can fall into the trap. The slowing process has to act on as many of the available atoms as possible. There have been two general approaches to this problem. The

first is to decelerate an atomic beam with a laser, and the second is to use a coated glass cell to thermalize the atoms on the walls and then capture from the low energy tail of the Maxwell Boltzmann distribution.

2.3.1 Zeeman slowing

A collimated atomic beam can decelerate and cool by repeated excitation from a counter-propagating laser beam that is red de-tuned from a resonant cycling transition. As the atoms slow down the Doppler shift changes and the atoms are no longer resonant with the laser. There are several methods to keep the slowing atoms on resonance. The most common approach uses the Zeeman effect in a tapered solenoid to tune the atomic energy levels with the changing velocity. The magnetic field is shaped to optimize the match between velocity and Zeeman detuning to keep a strong scattering of photons along the solenoid [3]. T. Lu *et al.* [30] used this technique to slow down their beam of radioactive ^{21}Na. The slowing works very well, but the diffusion process associated with the cooling increases significantly the divergence in the transverse direction. The Berkeley group has added transverse cooling to reduce this last problem. The initial atomic flux out of the source is usually much larger than the beam directed into the solenoid, losing a significant fraction of the scarce radioactive atoms. Table 1 gives typical lengths for a Zeeman slower, required to bring an atom with a velocity $v_{\rm thermal} = \sqrt{2kT/M}$ to a halt by driving it on a fully staturated transition. If the transiton is only driven at an intensity of I_{sat} the stopping distance is twice as long.

Another method to slow atoms in a beam is to chirp the frequency of the laser maintaining the resonant interaction with a group of atoms and leaving the others without deceleration [39]. This approach has not been used for radioactive atoms because it does not act on all of the available atoms. There have been other realizations of slowers using broad band light [40] and diffuse light [41], but they have only been used with stable istotopes.

2.3.2 Vapor cell method

The first experiments with a MOT by Raab *et al.* [4] reported the capture of atoms from the residual background gas in the vacuum chamber without need of deceleration. In 1990 Monroe *et al.* [42] showed trapping in a glass cell from the residual vapor pressure of a Cs metal reservoir. If the vapor pressure of an element is sufficiently high, a MOT

Table 1: Trapping and cooling parameters for alkali atoms from a source at 1000 K.

Atom	A	λ_{D_2} [nm]	τ_{D_2} [nsec]	$T_{Dop.}$ [μK]	l_{Zeeman} [cm]
Na	23	589	16.2	235	40
K	39	766	26.3	145	84
Rb	87	780	26.2	145	85
Cs	133	852	30.4	125	108
Fr	210	718	21.0	181	63

inside a cell filled with a vapor continuously captures atoms from the low-velocity tail of the Maxwell-Boltzmann distribution. The remaining atoms thermalize during wall collisions and form a new Maxwell-Boltzmann distribution. From this the MOT can again capture the low velocity atoms. The trapping efficiency depends on the number of wall contacts that an atom can make before leaving the system. Since alkali atoms tend to chemisorb in the glass walls, special coatings can prevent the loss of an atom [43]. If the wall is coated, the atom physi-sorbs for a short time, thermalizes and then is free to again cross the capture region and fall into the trap. Stephens and Wieman captured 6 % of all atoms introduced into their vapor cell [44].

Most groups working with radioactive atoms use the vapor cell method. The capture range of the MOT is enhanced with the help of large and intense laser beams. Gibble *et al.* [45] reported that for their large trap they captured atoms with initial velocities below about 18 % of the average thermal velocity at room temperature. However, the fraction of the Maxwell-Boltzmann distribution of atom velocities below the capture velocity of the trap is too small to capture a significant fraction of scarce radioactive atoms on a single pass through the cell. Wall collisions are critical to provide multiple opportunities for capture in the vapor cell technique. On the one hand they provide the thermalization process, but they also increase the possibility of losing the atom by chemically adsorbing to the wall.

No significant vapor pressure of stable alkali atoms normally builds up unless the walls of the glass cell are coated by a mono-layer of the atom to be trapped. For most radioactive samples this is impossible, and also not desired since that will create a source of background for the study of the decay products. An alternative is to coat the cell

with a special non-stick coating. The coatings are in general silanes and have been extensively studied for optical pumping applications of alkali atoms. Collisions with the bare glass walls destroy the atomic polarization and the coatings can provide a 'soft surface' for reflection. The Stony Brook group uses one commercially identified by the name of Dryfilm (a mixture of dichlorodimethylsilane and methyltrichlorosilane). The coating procedure follows the techniques of Swenson *et al.* [43]. The choice of a particular coating depends on many issues. For example: The difficulties in the application of the coating to the surface, how well the coating withstands high temperatures present nearby in the experimental apparatus. The coating of choice constrains the attainable background pressure in the cell and the geometry of the vacuum container. Nevertheless the vapor cell is appealingly simple. As long as a coating is known to work for a stable alkali it seems to work for the radioactive ones. The Colorado group has studied different coatings extensively [46], and have developed curing procedures to optimize the performance of the coatings.

The glass cell method relies on the non-stick coatings and works well for alkali atoms, but for other elements it may not be so easily implemented and the Zeeman slower could prove more effective.

2.4 *Other traps and further manipulation*

Although the MOT is a proven trap for radioactive atoms, it may not be the ideal environment for some of the experiments now planned. The atoms are not polarized because there are all helicities present in the laser field, and the magnetic field is inhomogeneous. There have been a series of traps developed in conjunction with the pursuit of Bose Einstein condensation (BEC) that may have application in the field of radioactive atom trapping. In this quest for even higher phase space densities, new techniques for transport and manipulation of cold atoms have also appeared.

2.4.1 Cold atom manipulation

To move the accumulated atoms in a MOT to a different environment requires some care. Simply turning the trapping and cooling fields off will cause the atoms to fall ballistically. The trajectories out of the trap will map out the original velocity distribution of the captured atoms, dispersing the atoms significantly as they fall. An auxiliary laser beam can push the atoms in one direction, but it has a limited interaction

range since the atoms accelerate until they are shifted out of resonance by their Doppler shift. The acceleration is in only one direction and there is still ballistic expansion of the cold atoms. Gibble et al. [47] created a moving molasses with the six beams of the MOT. By appropriate shifting of the frequencies of the beams, the atoms accelerate in the 111 direction (along the diagonal of the cube formed by the beams), but they are kept cold by the continuous interaction with the six beams. Modifications and variations of the method can increase the effectiveness of the transfer. The Colorado group has favored pushing with one laser. They first optically pump all of the atoms into a weak-field seeking m state and apply a weak magnetic field to guide the atoms through a small diameter tube that connects the two chambers [51]. The TRIUMF group transfers atoms to a second MOT, 50 cm away, where they have the nuclear detectors(see Figure 5). They lower the power of the lasers in the vapor cell trap for 20 ms and shift them less to the red to make the atoms colder, and apply a spatially narrow push beam to kick the atoms out of the trap. 25 cm downstream, a 2-d Zeeman optical trap (a 'funnel') compresses the expanding atoms back into a smaller volume. Efficiency of transfer for stable ^{41}K is now routinely greater than 50%.

Several methods of producing a cold beam of atoms have been developed. By opening a hole in one set of the optical elements that form the MOT [32], the atoms in the central region of the trap find a force imbalance, and some of them leak through the hole. This process can be continuous, and can also be switched off with a transverse beam to push the atoms back into the trapping fields. The atoms have transverse expansion as there is no active cooling once the atoms are launched from the trap.

2.4.2 Other traps

Dark state traps When the number of atoms in a MOT is very high, there is considerable attenuation of the laser beams, and this limits the number of atoms confinable since only the outer atoms keep scattering photons. The atoms inside may absorb some of the scattered photons that are not red-detuned, resulting in a force of the opposite sign to the trapping and cooling forces. The trap readjusts itself by changing its shape and decreasing the density of atoms. The dynamics of a filled MOT are complex.

To increase the density of atoms and the number of atoms beyond the point where the repelling force turns on, Ketterle *et al.* [41] developed

the dark MOT. The repumping beams are blocked from the central region of the trap. The trap maintains the atoms in a non-cycling state and only repumps them to the cycling transition when they stray to the edge of the trapping volume. This approach works with alkali atoms since the ground state hyperfine splitting already requires a repumping laser. It permits densities as high as 10^{11} atoms/cm^3.

The dipole force trap An electric or magnetic dipole in an inhomogeneous electric or magnetic field feels an attractive or repulsive force depending on the specific conditions. A strong laser field can induce an electric dipole in an atom. In 1968 Letokhov [54]proposed laser traps based on the interaction of this induced electric dipole moment with the laser field. Later, Ashkin [55] proposed a trap that combined this dipole force and the scattering force. The first laser trap for neutral atoms was of this type [56]. The trap depth is proportional to the laser intensity divided by the detuning. In order to minimize heating from spontaneous emission, the frequency of the intense laser is tuned hundreds of thousands of linewidths away from resonance. The heating is greatly reduced since the emission rate is proportional to the laser intensity divided by the square of the laser detuning. The off-resonance nature of the trap requires very intense beams with an extremely tight focus, and is often referred to as a Far Off Resonance Trap (FORT). The well depth is very small, fractions of a milliKelvin, depending on precooled atoms and very good vacuum for an extended residence in the trap. The atoms reside in a conservative trap and can cool down further by other mechanisms like evaporative cooling [57]. This kind of trap has found applications in the manipulation of extended objects as a form of optical tweezers.

2.4.3 Beyond the recoil limit

The search for traps for neutral atoms that permit lower temperatures than the recoil limit (T_r) has produced a large variety of conservative magnetic traps. In these, atoms are trapped in the weak-field seeking state since Maxwell's equations do not allow for a maximum of a static magnetic field in free space. All these traps require polarized samples where all the atoms are in the same m sub-level of the manifold. There are in general two classes of static magnetic traps [60]. A first class that has a zero in the magnetic field, and the potential is proportional to the magnitude of the magnetic field. The second class has a finite bias field with a parabolic potential (Ioffe-Pritchard trap).

The Top Trap The existence of a zero of the magnetic field greatly damages the confinement since there can be Majorana flips in the spins of the trapped atoms. Cornell *et al.* [58, 59] implemented a rotating magnetic trap (TOP) that moves the zero of the magnetic field faster than the atoms can follow, but still slower than the Larmor frequency so that the atoms follow the field adiabatically. The philosophy behind this solution is very similar to the Paul RF traps for ions, and the resulting time-averaged potential is harmonic. This trap has interesting possibilities for β-decay and α-decay experiments since the magnetic field rotates and a single detector in space can measure a whole set of directions as a function of time. The MIT group of Prof. Ketterle [49] developed another approach to keep the atoms away from the zero of magnetic field. They used an intense blue detuned laser to repel the cold atoms and plug the leak in the zero field area.

The Ioffe-Pritchard trap Originally developed for plasma confinement, the Ioffe-Pritchard configuration can consist in one implementation of four parallel bars in a quadrupole arrangement with neighboring bars having opposite currents. Two coils at the ends of the bars 'pinch' the field to form a magnetic mirror. Several variants of this configuration include the baseball trap or the yin-yang trap [60]. These traps are now favored by the MIT [50] and Colorado Bose-Einstein Condensation(BEC) groups [51]. The Rice BEC group first used one of this traps with permanent magnets [52, 53], with the disadvantage that the field can not be changed.

Circularly- Polarized Far Off Resonance Trap The Boulder group has demonstrated a novel dipole optical trap [61, 62] that selectively holds only chosen m states. This trap utilizes the dependence of the AC Stark shift on the magnetic spin state of an atom in a circularly polarized light field. By changing the trap detuning different m levels are confined in the circular FORT and the number of trapped atoms vs wavelength agrees well with a theoretical model. The trapping potential provides novel ways to cool, probe, and enhance the loading of atoms in a FORT.

3 TARGETS, SOURCES AND DELIVERY

Trapping radioactive elements from very dilute constituents of a target or source requires their removal and concentration in a short time

compared to the half-life of the isotope involved. We next review the different strategies followed to achieve this task.

3.1 *Targets*

The alkali atoms have been and will continue to be the focus of most radioactive atom trapping because of their favorable atomic level schemes, but also because their volatility at elevated temperatures helps immensely for their rapid diffusion out of solid or molten targets.

The basic methods of extracting different radioactive species from targets has been highly developed at ISOLDE [63], and most target-related work has relied heavily on the ISOLDE methods. As for radioactive sources, the method developed by the Lethokov [64] group for extracting Fr from a thorium source has also been used recently to trap Fr [35].

The choices of target-projectile combination to make a particular isotope depends on many factors: Available beams and their energies, the chemical nature and physical state of the target, and the cross sections for the desired reaction and for any competing reactions. An important consideration is the specific energy loss of the projectile in passing through the target, since the total number of radioactive nuclei is proportional to the thickness of the target where the energy is sufficient to initiate the reaction of interest. Since energy loss is a strong function of the projectile charge, high energy ($\approx$1GeV) protons and deuterons are the beams of choice, and the high intensities of radioactive elements produced are a result of the long range of the protons, along with the large beam currents available at major accelerator facilities. Table 2 summarize the targets used and production rates achieved by different groups in radioactive atom trapping experiments.

After the nuclear reaction, the radioactive atoms must rapidly leave the target. Many different techniques involve raising the target temperature to speed up the diffusion processes in the target. Since the diffusion time is proportional to d^2, where d is the distance to the surface, it is clear that small granular target material could enhance removal from the target into the vapor phase, where mobility is much higher. With the advent of macroscopic quantities of nano-particles becoming available, it may be possible to further improve on the speed of diffusion out of a target. The self diffusion of the particles can lead to sintering of the target material, so dilution of the target with an inert higher temperature powder such as C, has been used with some success.

Table 2: Target and Beam Parameters

Atom	Reaction	Energy [MeV]	Beam [pμA]	Target	Rate	Ref.
^{21}Na	$^{24}Mg(p,\alpha)$	25	1	MgO	1×10^9	[30]
^{37}K	$^{40}Ca(p,\alpha)$	11	2	CaO	3×10^4	[66]
^{38}K	$^{40}Ca(d,\alpha)$	11	0.8	CaO	5×10^5	[66]
^{37}K	$^{40}Ca(p,\alpha)$	500	1	CaO	1×10^7	[65]
^{38}K	$^{40}Ca(p,2pn)$	500	1	CaO	3×10^8	[65]
^{79}Rb	$^{51}V(^{31}P,2np)$	90	0.05	V	4×10^5	[29]
^{210}Fr	$^{197}Au(^{18}O,5n)$	100	0.3	Au	2×10^6	[33]
^{221}Fr	source				2×10^3	[35]

3.1.1 *Special targets*

Several of the targets in Table 2 require some special explanation. The naturally monoisotopic vanadium target used in the first ^{79}Rb experiments was physically separated from the Au 'catcher', and the recoiling nuclei traveled through vacuum and were implanted into the heated Au for subsequent evaporation. The beam power dissipated in the thin vanadium foil heated it to over 1200 C, which served to clean the surface facing the catcher from any buildup of evaporated or sputtered Au.

In order to enhance the signal to noise in an experiment by increasing the number of atoms it is possible to use an accumulation-release cycle sometimes called 'bunched-release' [67]. The activity from the target accumulates at another point in the transport system from the target to the trap. In the ^{79}Rb experiments it accumulated in the neutralizer [29]. The Rb was released in a short time with a much higher intensity than the average production rate.

The ^{18}O $+^{197}$Au projectile-target combination is favorable for many different reasons. The Au target is monoisotopic, which does not dilute the production with other isotopes, and allows copious target material. Gold is chemically inert, and with a low vapor pressure at elevated temperatures, which makes it a very favorable target. A fortunate property of gold was discovered in the course of the atom trapping work. At target temperatures of about 1000 K, 50 degrees lower than the melting point, a sharp transition occurs and the amount of Fr released from the target increases by at least a factor of 3. This phenomenon has been suggested

as resulting from 'surface melting' in which the increased stress near the surface gives rise to more vacancies and enhanced diffusion rates. The temperature must be carefully balanced by adjusting the heater power and the additional heating brought by the 100 MeV ^{18}O beam in order to maintain the target above the transition but below the melting point where it is destroyed.

An alternative scheme ^{12}C +^{205}Tl would have produced the preferred longer lived ^{212}Fr, but the Tl does not readily release the produced Fr unless it is heated to a temperature where the Tl itself evaporates readily. The chemical nature of these target-projectile combinations to produce alkalis are reproduced in other rows of the periodic table. Oxygen beams on Cu or Ag are also good combinations to produce Rb or Cs, while carbon beams on Ga or In are less favorable because of the target volatility.

3.2 *Radioactive sources*

Radioactive sources are an obvious source for radioactive atoms. They are readily available, and can provide a steady source of atoms which do not require access to an accelerator facility. If a source made of the atoms of interest exists, then the source must usually be heated to extract the atoms as a vapor. The number of radioactive atoms in a sample, N, is related to the decay rate dN/dt by:

$$\frac{dN}{dt} = N\tau, \tag{12}$$

where τ is the mean life. Isotopes with long half-lives such as ^{137}Cs (30.1yr) provide a large number of atoms (5×10^{16} atoms/mCurie), but present a long-term radiation safety hazard, since the apparatus will inevitably remain contaminated for a long time. On the other hand, isotopes with the shortest lifetimes available as sources, such as ^{127}Cs (6.25 hr), do not have as many atoms(5×10^{3} atoms/mCurie) but also present a radiation safety hazard due to the large specific activity required to get a sufficient number of atoms. An alternative which has been successful is to have a long-lived radioactive parent from which the radioactive daughter element is periodically removed and transported into the apparatus. The group of Prof. Lethokov first used this method to obtain a sample of ^{221}Fr (4.9 min) from a source of ^{229}Th (7340 yr) for a resonance ionization source of Fr. A thin layer of the ^{229}Th was covered with a thin Ta foil, and the recoil momentum from the α decay

knocked some of the daughter ^{225}Ra (14.9d) into the Ta foil. After accumulation for a period of about 15 days, the Ta foil was removed from the Th source and placed in the apparatus. The ^{225}Ra then β decays to ^{225}Ac(10d) which then α-decays to ^{221}Fr. The Ta foil is heated to release the Fr, and the observed rate of production of ^{221}Fr atoms from the decay of ^{225}Ac was 800 atoms/sec. This basic method has been used by the University of Colorado/Lawrence Berkeley National Laboratory collaboration to obtain a source of about 10^4 ^{221}Fr atoms/sec for injection into a MOT. The use of sources such as these allows table-top experiments, but the number of atoms available with this technique is still somewhat limited.

3.3 *Delivery to the Trap*

Different methods are used to transport the atoms from the target to the trapping region. The extraction of the radioactive atoms from the target or source can be in the form of a neutral atomic beam [30] or as ions [29, 33, 71]. The simplest is to form an atomic beam directly at the target. Figure 4 shows the target system used at Berkeley. Because the pressure in the target is lower than in most atomic beam sources, high aspect ratio($l/d = 25$) exit tubes can provide the initial collimation, and then transverse laser beams cool the lateral motion from the central core of the beam. A few percent of the emitted atoms reach the trapping region about 2 meters away from the target.

An alternative to forming an atomic beam directly at the target is to ionize the atoms for efficient transport from the target region to the trapping region, and then neutralize the atoms and form an atomic beam much nearer to the trapping region. This can allow for excellent isolation of the vacuum system of the accelerator from the very high vacuum requirements of the trap (10^{-10} Torr for $\approx$ 100 sec lifetime), and for operation of the trap in a much reduced radiation environment. The manipulation of alkali atoms is easier than for most other atoms because metals exist with work functions both greater than and less than the ionization potential of the alkalis. This allows for surface ionization from such metals as Au, W and Ta, and surface neutralization from Y or Hf. The 'recycling collimator' [68] and the 'orthotropic oven' [69] use these properties to collimate atomic beams of alkalis.

The approach followed by the Stony Brook group lets the radioactive atoms leave the Au target as ions. The ions accelerate and focus through a series of Einzel lenses and land into a neutralizing surface of yttrium at the entrance of the glass cell (see Fig. 7). The surfaces of both target

(Au) and neutralizer (Y) are hot, the first very close to its melting point in order to accelerate the diffusion to the surface. The second at about 1000 K to also enhance the emission of neutral atoms. The vacuum requirements of the MOT do not permit more traditional methods of neutralization such as a Cs vapor cell.

4 RESULTS

There are only preliminary results in this very new field. Most groups have concentrated their efforts in developing efficient methods to trap the radioactive alkali atoms from a target or from a source. Some measurements are beginning to take shape and they hint at the great potential of physics with cold radioactive samples of atoms.

4.1 *Na*

The Berkeley group trapped radioactive ^{21}Na atoms in a MOT [30] at the LBNL 88" Cyclotron. ^{21}Na decays by positron emission to its mirror, ^{21}Ne, with a 22.5 sec halflife. This mirror beta decay of ^{21}Na is an interesting 'laboratory' for studying the fundamental weak interaction. An accurate measurement of the beta asymmetry can be used in a precision test for the $V - A$ structure of the weak interaction. ^{21}Na has a similar hyperfine structure to the stable isotope ^{23}Na allowing for developing the trapping techniques with the stable isotope. They enhanced the brightness of the atomic beam with additional transverse laser cooling before the atoms enter the 1.2 m Zeeman slower (see Fig. 4). To maximize the trap loading efficiency they have added a set of extraction coils at the end of the solenoid. They have reported a capture efficiency of 20% of all atoms in the slowed atomic beam, and a ratio of trap loading rate to target production rate of the order of 10^{-5}. The lifetime of the isotope is short and requires moderately fast extraction of the activity from the oven-target. In their original experiment the dwell time for ^{21}Na in their oven-target was 40 sec. They achieved a mean lifetime of the trap of 6.3 sec.

They have recently observed 40,000 trapped ^{21}Na atoms in their experiment [70], as a result of an improved target which uses multiple thin layers of CaO that permit rapid escape, as well as better collimation of the atomic beam from the target. They are currently refining a technique to measure the 1.9 GHz ground state hyperfine splitting of ^{21}Na. Using a pulsed trap-pump-probe scheme, they anticipate a precision bet-

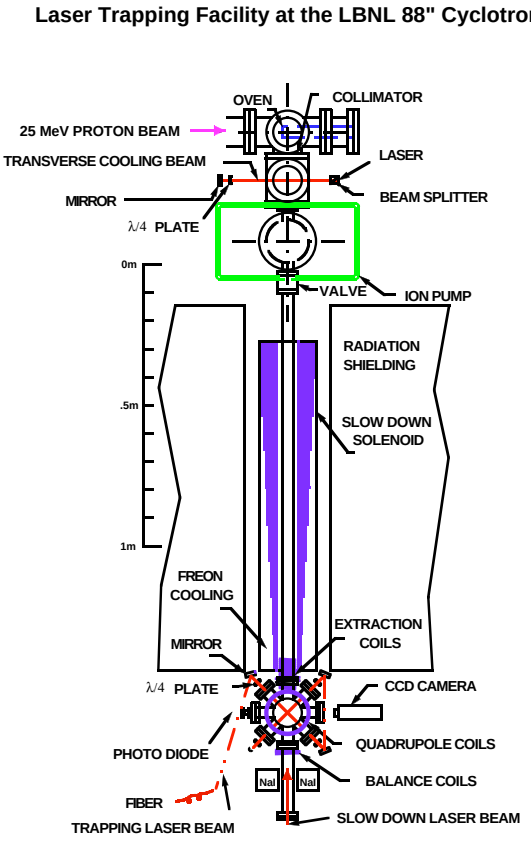

Figure 4: Trapping facility for Na at Berkeley.

ter than 100 Hz with the current trap sizes and based on studies using stable ^{23}Na. In a very important development they have observed the β^+ from the trapped atoms using an in-vacuum plastic scintillator, and also the β and γ backgrounds present in their trapping chamber. These measurements will guide several planned improvements to the apparatus to achieve larger traps and cleaner β signals. They estimate that 100,000 trapped ^{21}Na atoms will be necessary for a 1% measurement of the parity violating beta decay asymmetry parameter, which would probe for possible right-handed charged electroweak currents.

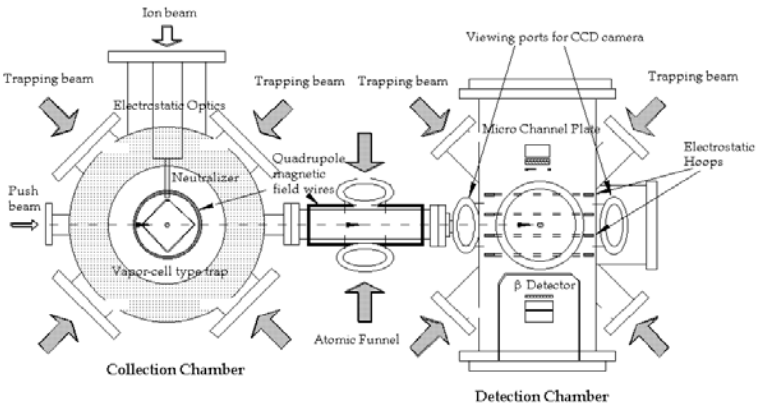

Figure 5: TRIUMF apparatus

4.2 *K*

^{37,38}K

The TISOL (Triumf Isotope Separator On-Line) facility at TRIUMF produces intense mass separated beams of all of the alkali atoms, including francium. TISOL essentially creates the desired radioactive isotopes by bombarding a suitable target with energetic protons from TRIUMF's cyclotron. They have trapped two radioactive potasium isotopes. They have used beams of about 10^7 ^{37}K and ^{38m}K ions/s which are stopped in a heated neutralizer, trapping about 6000 neutral atoms in a vapor-cell type MOT. They have recently achieved the transfer of trapped atoms from this collection trap into a second MOT (see Fig. 5). Their collection vapor-cell trap is now a hollow quartz Dryfilm-lined cube inside a stainless steel vacuum vessel. This allows for moving the neutralizer much closer to the trap volume. The second MOT provides a backing-free, localized source of atoms for the coincident detection of Ar-recoils and positrons which allows determination of the neutrino momenta. They have captured and moved to the second trap both 0.925 s isomeric ^{38m}K and 1.226 s ^{37}K. They have seen coincidences between Ar recoiling nuclei and β^+. They have measured the charge state distribution of Ar recoils, and shown that the coincidences are clean enough to proceed with experiments.

For efficient detection of the low-energy recoils, they accelerate them into a microchannel plate (MCP). They have applied a uniform electric field to the entire region, and accelerate the $Ar^{1+,2+,3+}$ into the MCP

to improve the efficiency of capture, and to subtend a larger angular range in the recoil distribution (all angles for Ar^{2+} and higher). The efficiency of detection depends on the final state charge distribution of the Ar daughter products, which they have measured. The β^+ detector is a double-sided silicon strip detector with 1mm position sensitivity backed by a stack of 2.5mm-thick Si(Li) detectors. They have sufficient statistics for a 5% determintion of the angular correlation coefficient a in ^{37}K, which can be predicted well enough to explore their systematic errors at this level. The have also demonstrated that it is possible to detect the shake-off electrons (in coincidence with the β^+) by changing the sign of the electric field. This could lead to clean detection of recoils in coincidence with the shake-off electrons, and simultaneous determination of the β^+ asymmetry A and the recoil asymmetry (related to A+B, where B is the ν asymmetry) from polarized ^{37}K. Deviations of the observable A/B from standard model predictions has linear sensitivity to the mixing angle ζ between right- and left-handed sectors.

Their active program of trapping radioactive atoms plans to eventually use the more intense beams from the ISAC facility which is under construction.

^{39,40,41}K

The Wisconsin group [72] has also developed a program to study radioactive ^{37}K and ^{38}K for measurements of the asymmetry parameter in β decay. The early work of the group has included the development of a vortex-force trap, measuring collisions in ^{85}Rb atoms, and creating a spin-polarized trap. They have trapped stable ^{39,40,41}K and are currently readying their apparatus for on-line trapping of radioactive isotopes using the 12 MeV tandem accelerator (see Fig. 6). They have an accumulating trap tested off line of the kind that has one opening for sending a cold beam into a second trap [31]. They hope to trap radioactive ^{37}K and ^{38}K and begin measurements of the asymmetry parameters in weak decay processes.

4.3 *Rb*

^{79}Rb

The Stony Brook effort started with the trapping of radioactive ^{79}Rb atoms produced in the Stony Brook Tandem accelerator [29]. Rb has stable isotopes and the whole system could be tested before injecting radioactive atoms. Rb has very similar chemical properties to Fr, our atom of interest, and it helped in the design and construction of the present apparatus. The apparatus with separate target, ion transport system,

Figure 6: Apparatus to load radioactive atoms in Wisconsin

neutralizer and glass cell produced very succesful results, and has been adopted by most groups in the field. From the known isotope shift of the radioactive atoms, the lasers could be shifted by a fixed amount from stable frequency references. The half-life of ^{79}Rb is 23 min and we produced it in a thin vanadium target with a ^{31}P beam. The reaction products were impanted into a Au catcher heated to close to its melting point to enhance the diffusion of the reaction products to the surface. The rubidium surface-ionized on exit and after transport through electrostatic lenses, landed in a cold Y neutralizer. We irradiated the target for three lifetimes accumulating activity in the neutralizer. We then isolated the MOT neutralizer region from the target production to improve the vaccum. We heated the Y neutralizer injecting the accumulated radioactive atoms into the dryfilm coated glass bulb. The beam of ^{79}Rb

lasted about 300 sec and we trapped about 80 Rb atoms. The $1/e$ fill time of the trap was 25 sec. We illuminated the volume of the glass cell (10 cm diameter) through six 5 cm diameter windows. The overall efficiency of the process from production to trapping was about 1×10^{-5}. We used lock-in detection of the fluorescence from the trapped atoms, through the modulation of the repumper laser frequency. We had to reject the background from laser light scattered from the glass cell. This experiment and all the development of the apparatus prepared us for the production and trapping of Fr.

^{82}Rb

The Los Alamos group [73] has a coupled magneto-optical trap (MOT) - mass separator system for trapping radioactive isotopes. A radioactive ^{82}Sr(25.0 days) source is heated to evolve the daughter ^{8}2Rb(1.25 min) activity. The Rb is surface ionized, accelerated, and mass separated. The mass separated beam is focused through a 6 mm diameter opening of the 75 mm cubic dryfilm-coated trapping cell and implanted into a 5 mm diameter yttrium foil which is then inductively heated to release the neutral atoms. The laser beams are also 75mm in diameter for efficient trapping. They have observed a large trapped cloud (20 mm in diameter) of implanted stable ^{85}Rb in early testing, and plan to trap 10^6 ^{82}Rb(1.25 min) atoms. Their goal is to pursue the beta-spin correlation function of ^{82}Rb for precision tests of the electroweak model. They intend to use a TOP trap to measure the beta-spin correlation as a continuous function in both energy and angle of the emitted beta particles relative to the polarized nucleus.

4.4 *Fr*

^{209,210,211}Fr

At Stony Brook we have concentrated our efforts on Fr. The availability of francium has made possible a number of measurements of its atomic structure and properties. There is strong interest in Fr because it is the heaviest 'simple' atom. It is an alkali with a single S electron outside a radon core. Fr is an excellent candidate for atomic parity nonconservation measurements. The prediction of the atomic PNC effect for Fr is eighteen times larger than in Cs [74]. The enhancement comes from the larger number of nucleons and the increased density of the electron at the nucleus from the high Z and from relativistic effects. The availability of different isotopes may overcome some of the difficulties with the extraction of the weak charge from a PNC measurement.

We initially trapped about 1000 ^{210}Fr atoms in a magneto-optical

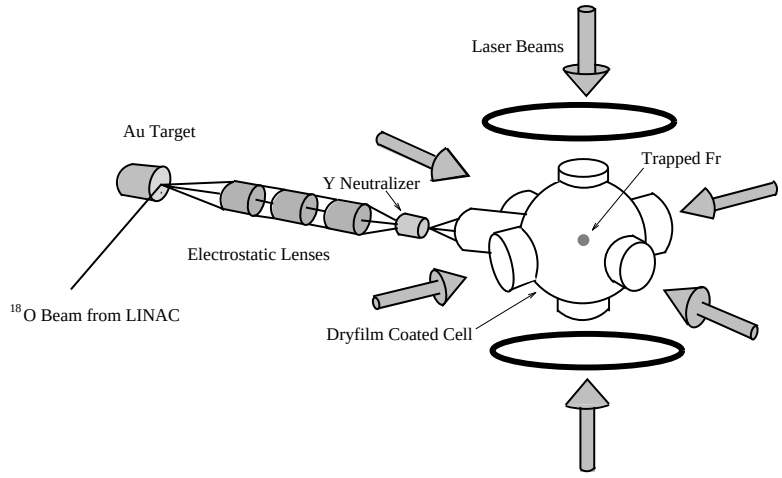

Figure 7: Stony Brook apparatus

trap [33]. The apparatus separates the production and the trapping, transporting the radioactive atoms as ions to the entrance of the MOT where they neutralize on a hot Y surface (see Fig. 7). The system works on-line with the accelerator and improvements in the differential pumping give a trap $1/e$ lifetime close to 30 sec. The Au target and ion transport system can deliver $10^6/sec$ ^{210}Fr ions to the neutralizer. We can not measure a dwell time on the neutralizer once it is hot. Improvements in the system have increased the number of trapped atoms by about an order of magnitude and we can observe images of the fluorescence as that of Fig. 1 while we perform other experiments. Our overall efficiency from target to trap has increased to about 0.1%.

Our studies of Fr focus on the atomic properties that are necessary input for future work on weak interactions. The energy level structure of Fr is only partially known. The first two excited S states had not been observed prior to our work. The 8S state is a possible level to use for a parity non-conservation measurement.

We observed the 9S level by two-photon excitation of the atoms confined and cooled in a magneto-optical trap. For the first step we used the resonant intermediate level $7P_{3/2}$, the upper state of the trapping transition. An infrared diode laser at 851 nm provided the excitation necessary to reach the $9S_{1/2}$ [75]. We identified the transition both from detecting the 430 nm blue fluorescence in the decay path $9S \rightarrow$

$8P \rightarrow 7S$, and from the decrease in the trap flurorescence when atoms excited to the 9S are removed from the cycling transition. The *ab initio* calculations by Dzuba *et al.* [74] provided an overall guide to the search of the 9S level, but semi-empirical quantum defect calculations narrowed significantly the region of search. We have been using a similar two-photon excitation technique to study the 8S level.

We have extended the knowledge of the francium atom beyond its energy level structure. We have measured the lifetimes of the $7P_{3/2}$ and $7P_{1/2}$ levels and extracted the dipole matrix elements between these levels and the 7S ground state. We used a time-correlated single photon counting technique for the first measurement of an atomic radiative lifetime in ^{210}Fr [76]. The trapping cycle populates the $7p\ ^2P_{3/2}$ level, and in order to measure its lifetime we rapidly switched off the trapping laser for 500 ns with a repetition rate of 100 kHz. We observed the free decay of the excited state. The detection of an 718 nm fluorescence photon starts a time-to-amplitude converter that stops with a pulse derived from the cycle. A histogram of the data gives the exponential decay of the fluorescence. With this method the statistical uncertainty obtained is less than 1%. The lifetime of 21.02(16) ns gives a value for the reduced transition matrix element between the levels $7s\ ^2S_{1/2} \rightarrow 7p\ ^2P_{3/2}$ of 5.898(22) a_0 atomic units. The results are a precision experimental test of the atomic many-body perturbation theory applied to the heaviest alkali. To study other states, we manipulate the atomic populations by sequential application of laser pulses of different frequency. We have done this to measure the $7p\ ^2P_{1/2}$ level lifetime [77]. The dipole matrix elements between the 7S and 7P levels are a sensitive probe of the wave functions that are important for the parity non-conservation measurement.

We have also trapped ^{209,211}Fr. The production and trapping efficiency are similar to ^{210}Fr. The efforts to understand the atomic structure of Fr are advancing, and the comparisons with theory, critical for the interpretation of any future atomic parity non-conservation measurement, are extremely encouraging. The results already test the most sophisticated many body perturbation theory calculations with the heaviest of the simple atoms, and enhance the confidence in the important Cs calculations.

^{221}Fr

The University of Colorado/Lawrence Berkeley National Laboratory group [35] has trapped ^{221}Fr from a radioactive source. They are interested in atomic parity non-conservation and searches for an electric dipole moment. An orthotropic oven [69], with ^{225}Ac as the source of

^{221}Fr, injected francium atoms into an improved vapor cell magneto-optical trap optimized for a high trap loading rate. The francium oven and the quartz vapor cell were inside a vacuum chamber. The oven was heated to 1323 K and placed very close to the cell. They used the techniques developed by Stephens *et al.* [46] to coat their cell with Dry-film, and to cure the coating by exposure to alkali vapor. They had a constant flux of 2.3×10^3 s^{-1} Fr atoms entering the cell. The overall total efficieny from production to trapping was 0.4%, with more than 30% of the ^{221}Fr atoms entering the cell trapped. They have measured hyperfine structure of the first excited $7P_{1/2}$ and $7P_{3/2}$ levels in ^{221}Fr using laser fluorescence and absolute wavemeter measurements of the $S \rightarrow P$ transitions.

5 CONCLUSIONS AND OUTLOOK

The ability to collect, confine, and cool radioactive atoms has opened up the possibility for a wide variety of experiments. These include precision measurements aimed at probing the very nature of the fundamental interactions. This new capability results from merging the specialized expertise in atomic physics to cool and trap atoms, with the specialized experience in nuclear physics for extracting radioactive atoms rapidly and efficiently from production targets. The development of these new techniques continues a long line of experiments which have further confined atoms and nuclei in smaller and smaller space dimensions, along with cooling them to lower and lower temperatures. The field of radioactive atom trapping is in its infancy, barely more than three years old, with many of the initial experiments still in progress. Future developments are hard to predict, but several possible directions for the field seem likely to be important:

1. Trapping of new species: Radioactive atom trapping so far has been confined to the alkali elements. Most of the stable alkaline earth elements have been trapped, as well as the rare gas elements by use of metastable states. The heaviest of these two columns in the periodic table are Radium and Radon, and both can be copiously produced in isotope separators. These elements both have many radioactive isotopes, with a broad range of decay properties which can be studied with great precision in a trap.

2. Further study of Francium: As the heaviest alkali, francium is the element of choice for tests of parity nonconservation and for

time reversal experiments. The detailed study of the francium atomic system is in progress, but will continue with measurement of more properties such as excited state lifetimes and polarizabilities. These measurements will further test, motivate and refine the many-body calculations of the atomic properties that are necessary for the parity and time reversal experiments.

3. Development of nuclear detection methods: Atomic detection methods have been used almost exclusively to detect trapped atoms since a single atom can scatter millions of photons every second and give a detectable signal. Detection of the nuclear radiations directly from trapped atoms is more difficult for several reasons. Atoms which have been lost from the trap or were never trapped can be attached to the detector surfaces, providing enhanced detection solid angles for undesired events. In addition, the radioactive atom decays only once, with the probability of detection limited by the solid angle and detector efficiency. These problems are being solved, but generally more trapped radioactive atoms are required for nuclear detection experiments than for atomic detection methods.

4. Full reconstruction of β decay events: There are exciting signals showing the β decay of trapped atoms. The full reconstruction of the event, by detecting the electron or positron at the same time as the recoiling ion require careful knowledge of the state of the ion including any effects of shake off. The coincidence signals herald some important developments in this field that can provide new and stringent tests to our understanding of the weak interaction.

5. New Facilities: New facilities for producing radioactive elements are being planned which will provide new and more intense beams, and applications which were once thought impossible may become routine.

It has long been a dream of scientists to be able to have a set of 'tweezers' to be able to pick up an individual atom and hold it still for further study. This dream has been realized, and extended now to atoms with radioactive nuclei. How this new capability will be used to further probe the nature of atoms and nuclei, and where this work will lead is hard to predict, but it is an exciting new development!

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