Modal Structure Analysis of a 2μm Laser System for Use in Atomic PNC Experiments

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August 18, 1999

Continued progress on Atomic PNC experiments with trapped Ba^+ ions at the University of Washington hinges upon the ability to directly induce the violating transition in these ions. A 2.05μm laser system has been acquired from NASA for this purpose. Successful utilization of this system requires the laser to be locked to a specific modal line as to prevent drifting of the laser frequency output. This can be acquired through the implementation of active feedback frequency stabilization. The generation of an error signal for this process demands the laser to possess a well defined modal structure. The modal structure of the laser had previously been observed through a Fabry-Perot cavity but exhibited unsymmetric and spurious unwanted mode lines. This undesirable modal structure was hypothesized to be the result of optical feedback and a lack of optical mode matching precision. Thorough investigation produced evidence of a modal coupling dependence on optical feedback to the laser. An optical isolator was constructed to remedy this problem. A series of calculations were also performed to develop the correct mode matching lens geometry. The results and conclusions of these procedures are discussed.

1. Background

Parity Violation manifests itself in physical processes that prefer one "handedness" over the other. In the Ba^+ experiment, PNC exposes itself in the exchange of a Z_0 boson between the nucleus and an electron in the Electroweak interaction. A Feynman Diagram of this interaction is provided in Figure 1. The violation occurs in the Z_0's preference to interact with "left handed" electrons. A left handed electron is defined to possess normalized spin and momentum vectors such that $\sigma \cdot p$ =-1.

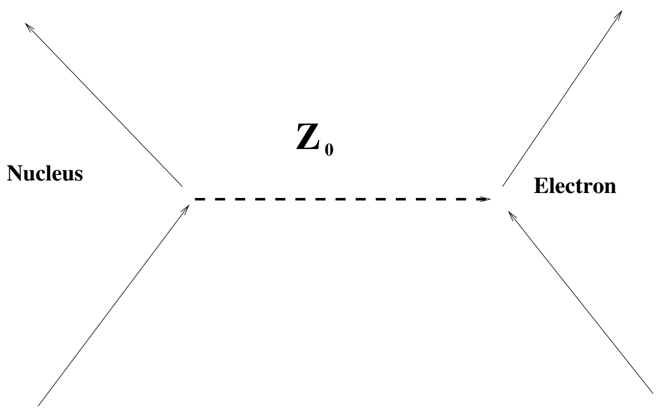


Fig. 1. Feynman Diagram for Z_0 boson exchange

PNC has been observed only in the weak interaction. This exclusive property provides physicists with a tool for probing weak energy scales in search of new phenomena. Thus, parity violation is crucial in the investigation of processes concealed by the dominating electromagnetic and strong forces.

2. The Barium Ion Experiment

The parity violating transition in Ba^+ is the decay of a metastable D state to a mixed ground state of S and P states possessing opposite parity. An energy level diagram for Ba^+ is provided in Figure 2. As one can see from the energy level diagram, this decay can be reversed by the absorption of 2.05 μm light. Currently, the violating transition is indirectly induced by "shelving" the electron into the metastable D state through the implementation of two diode lasers, one at 649nm and another at 498nm. The addition of the 2.05 μm laser to the setup would provide a method of determining whether the violating transition is taking place.

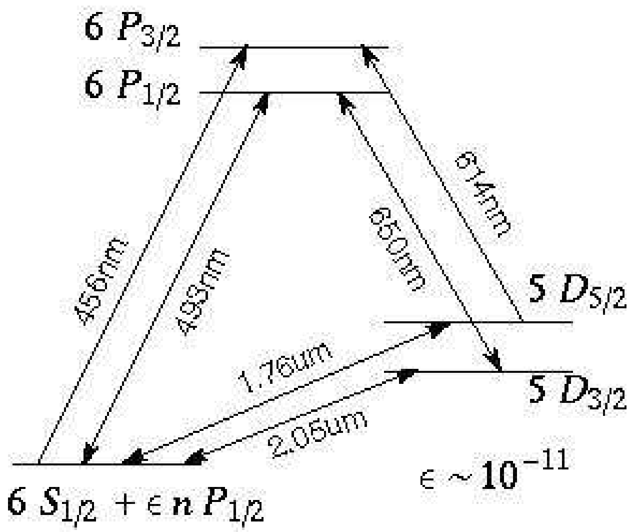


Fig. 2. Energy Level Diagram for Ba^+

3. Implementation of the 2μm Laser

The 2μm laser system consists of a solid state laser pumped by a fiber-optically coupled diode laser. The laser will be used to test the occurrence of the violating transition by attempting to induce the transition itself. This requires the laser to have an extremely stable frequency output. As expected, the laser acquired from NASA does not inherently possess this virtue, as the laser output frequency currently displays a pronounced drift.

The elimination of this frequency drift can be attained in a number of ways. In this experiment, active feedback frequency stabilization will be used to lock the frequency of the laser. This technique requires the generation of an error signal that can monitor the deviance of the laser output from the desired frequency. This error signal can be acquired by taking the "derivative" of a modal peak. This "derivative" increases as the frequency moves away from the top of the peak and registers zero at the top of the peak. Thus, if one can minimize the absolute value of this error signal, one can lock to the top of the specific modal peak. A lock box has been constructed that will minimize this error signal by actively adjusting the frequency of the laser through current modulation. The pumping diode laser has a frequency dependence on current, rendering the alteration of the output from the solid state laser possible. But this entire procedure hinges upon the ability to generate an error signal, which in turn requires the attainment of easily resolved modal peaks.

A. Modal Structure of the Laser

The Fabry-Perot cavity which the modes are observed through consists of a Pyrex tube with a piezo-ceramic tube attached to the end. The sum total length of this cavity is approximately 28cm. Partially reflecting spherical mirrors at both ends of the cavity provide the resonating effect required from the cavity. The laser will resonate in the cavity in a fashion analogous to sound waves in air columns. Certain periodically spaced cavity lengths will produce modes in the laser. The modes are observed by placing an oscillating voltage across the piezo which will in turn oscillate the length of the piezo and the cavity. The intensity of the beam is measured with a photodiode detector and is observed on an oscilloscope against the voltage across the piezo (which is proportional to the length of the cavity).

The frequency separation between consecutive modes is given by,

$$F.S.R = \frac{c}{2L} \tag{1}$$

where c is the speed of light and L is the length of the cavity at equilibrium. This expression can be used to derive a similar relationship for the wavelength spacing between consecutive modes. This relationship is given by,

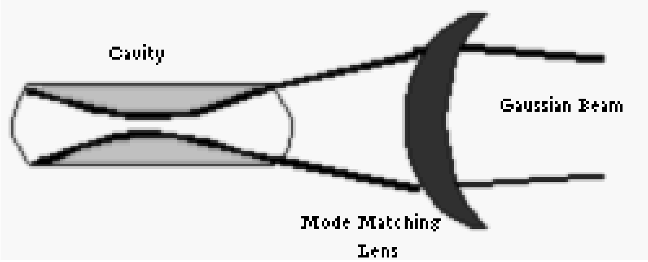
$$\Delta\lambda = \frac{\lambda^2}{2L} \tag{2}$$

where λ is the wavelength of the laser. This spacing corresponds to the alterations in length the cavity must make to create successive modes. The goal is to sweep the voltage across the piezo such that the cavity changes length enough to observe only two modal lines.

B. Mode Matching Optics

The Gaussian profile of the laser beam demands the implementation of mode matching optics prior to its entrance into the cavity. Gaussian beams diverge as they propagate, thus they cannot be treated as simple rays. An improperly shaped beam resonating in the cavity will induce spurious mode lines. This is because the unmatched components of the beams will be creating "extra" cavities in the system. The beam shape must be manipulated such that upon entrance into the cavity, its radius of curvature matches that of the partially reflecting lens and its waist is located at the center of the cavity. This setup is illustrated in Figure 3. To accomplish this beam manipulation, a lens of specific focal length must be placed a certain distance from the edge of the cavity. These parameters are calculated utilizing a method which combines ray matrices with the Gaussian properties of the beam. Ray matrices allow one to calculate optical geometries by utilizing translation and component matrices for the beam. An expression for the propagation of the beam through the cavity was derived using this method. This derivation came from simply multiplying each propagation matrix times the next optical component matrix. By iterating this matrix expression for a large number of "periods", one could numerically solve for the correct parameters that would allow for the modes to develop correctly.

Fig. 3. Two Dimensional Description of Mode Matching Geometry



C. Optical Feedback

Feedback to the laser is exceedingly detrimental to the progress of modal structure analysis. The laser experiences a more pronounced frequency drift and the structure of the modes is hampered when feedback is allowed back to the laser. At this point, optical feedback is the greatest stumbling block on the path to progress.

Lasers operate by creating a standing wave in a "lasing" cavity. This cavity is where the amplification of light takes place. Feedback to the laser creates extra cavities in the lasing setup. These extra cavities result in a shift of the aforementioned standing wave. This effect alters the frequency of the laser by small, yet substantial magnitudes.

At this point there are two definitive sources of evidence for optical feedback in the system.

1. The Razorblade Test

If the beam is partially blocked with a sharp edge, such as a razorblade, the modal peaks on the display should simply reduce in amplitude from a loss of power to the cavity. However, it has been observed that not only do the peaks reduce, but they display a *shift*. By blocking off part of beam the feedback to the laser is being reduced as well. If the peaks shift position, then the frequency of the laser is being altered. This observation purports a definite frequency dependence on feedback to the laser.

2. The "Twin Peaks" Test

Certain modes of the laser appear to have a "cloning" effect in which two peaks of identical nature are observed. This was first hypothesized to be the result of a hysteresis effect in the piezo, but further investigation has revealed that the twin peaks are a result of optical feedback. If the frequency of the cavity dither is increased, the peaks move closer together. Our hypothesis states this is the due to a shortening in the interaction time between the laser and the cavity, and thus the feedback is taken out of effect. Expelling the feedback in this manner brings the peaks closer together, into the one "true" peak. A rigorous explanation of this phenomenon has not been explored thus far, so these conclusions are certainly suspect to scrutiny.

As a result of this evidence for optical feedback in the system, a number of solutions to this problem were presented.

3. Attenuation of Beam

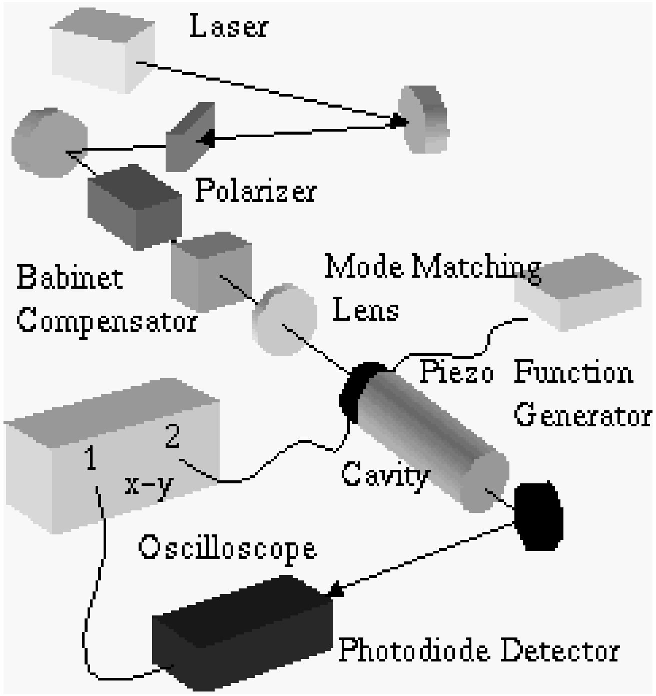
Suggestions were made along the lines of merely reducing the feedback until the effect was negligible. The most obvious of these was the attenuation of the beam before it entered the cavity. This was desirable because when the laser is implemented in the setup, most of the beam will be sent off to the experiment, while only a small fraction of it will go into the lock setup. However, the beam was attenuated until the peaks were barely resolved from noise in the system, and yet the feedback lingered. This essentially threw out another option in which the optical path length between the laser and the cavity would be increased. This would be implemented so the feedback (Gaussian) beam diverged enough so that only a small fraction of the feedback beam was introduced back into the laser.

These findings led to our acknowledgement of this laser's extreme sensitivity to feedback. Sensitivity of this magnitude rendered complete expulsion of the feedback beam as the only viable solution to the problem.

D. Optical Isolation

Optical isolation involves the use of polarized characteristics of the beam to nearly eliminate all feedback to the laser. The optical isolator configuration for our setup is displayed in Figure 4.

Fig. 4. Setup for Optical Isolator in Conjunction with Fabry-Perot Cavity



We discovered the laser output was strongly linearly polarized. Using this knowledge, a linear polarizer was aligned to allow all or most of this output beam through. The light was then sent through a Babinet Compensator which was to be configured to act as a quarter wave plate. This quarter wave plate would convert the linearly polarization to circular. The beam then was incident upon the cavity, which is where it partially reflected back towards the laser. This was the feedback beam. Upon reflection, the light made a shift to the opposite circular polarization. This light was then sent back through the quarter wave plate, which converted this circular polarization back to a linear polarization perpendicular to that of the incoming beam. Therefore, when this beam hit the polarizer on its way back to the laser, the polarizer would not let any of the light through. The feedback beam would be completely extinguished.

This process did not work quite as neatly as it may sound. Polarizing components are extremely sensitive to wavelength. The components used in this setup were not specifically designed for use with 2μm light. This setup was to be used as a "test" for observing the effects extinguishing the feedback would have on the mode structure. While my investigations led me to believe the input polarizer was working correctly, I firmly believe the Babinet Compensator was not, *and will not* function as a quarter waveplate at the desired wavelength. This conclusion comes after a great deal of testing the compensator's effect on the beam. This test involved simply placing another linear polarizer after the compensator. If the compensator was acting as a quarter waveplate, the intensity of the light would not change if the polarizer is rotated. This is because the polarizer will be selecting out different linear components of the beam, which in circular polarization all have the same magnitude. Between myself and a number of others in the lab, a great deal of time was spent searching for this configuration of the compensator. Our investigations proved futile, as a correct configuration was not observed. To notice any effects from optical isolation in a reasonable amount of time, polarizing components designed for the correct wavelength must be purchased.

4. Conclusions

Without the successful implementation of an optical isolator, the mode structure could not be improved significantly over the course of the summer. A number of methods were attempted and valuable lessons were learned from their failure. Future improvements on the mode structure will hinge upon the developement of a successful optically isolating system. This summer's exploration on this subject may point to a commercially purchased isolator as the most efficient and viable solution to this problem. In experimental physics, learning from one's failures or mistakes is a key to the success of a project.

5. Acknowledgments

I would like to thank Dr. Norval Fortson, Mike Schacht, Dr. Alex Cronin, and Timo Koerber for the time they spent with me, and for the valuable lessons in experimental physics they have passed on to me this summer. This paper has been written nearly in its entirety based on converstations with them. I wish Norval and Timo good luck in their future endeavors with this project.