# PHADE/ACES:

## A **PH**osphorescent **A**fterglow **DE**tector/

## **A C**hameleon **E**xperimental **S**earch

## A PAC44 Proposal

James R Boyce
*The College of William & Mary*
For the PHADE/ACES Team
June 5, 2016

**Abstract**

Few earth bound laboratory experiments have been conducted with the aim of detecting Dark Energy interactions with Standard Matter. One experiment was conducted by the CHASE Group at Fermilab but found no evidence of predicted interactions. This proposal seeks to repeat the experiment focusing on three key improvements: 1) Photo-Luminescent background elimination thus covering the decays occurring during the first 120 seconds of afterglow 2) Optimization of timing window, collecting data for only 90% of chameleon decays during timing window, and 3) Improving detection solid angle by four orders of magnitude. With these improvements, we can explore the coupling constant range $10^{12} \leq \beta\gamma \leq 10^{17}$. PHADE/ACES **requires no beam time,** is assembled with equipment not in use, and has a very small budget. And yet the possibility of significant discovery exits.

## 1. Introduction

Cosmological observations show that our universe is expanding at a rate that cannot be explained by presently known physics. Invoking the concept of Dark Energy, one theory accounting for this expansion and without violating known physics, suggest observable evidence of Dark Energy is possible in earth bound laboratories via coupling of photons with magnetic field. This coupling is mediated by a Dark Energy scalar field and results in a particle with an effective mass that depends on its local environment, earning the name “chameleon.” This characteristic means that when chameleons are created inside a vacuum chamber they cannot escape the chamber. They can, however, return to photons by the same coupling mechanism. The production of chameleons and their subsequent decay forms the basis of the proposed experiment: to discover, detect and measure the after-glow of chameleons.

The afterglow experimental technique we propose is to shine a laser beam through a vacuum chamber inside a strong magnetic field. According to some theoretical models, a dark energy scalar field mediates the coupling of laser photons with the magnetic field thus generating a chameleon "gas" in the vacuum chamber. Once equilibrium is established between chameleon generation and decay, the source laser is turned off. Detectors will then record the resulting after-glow photon flux. ACES incorporates three significant improvements over previous efforts:

1 Elimination of Photo-Luminescence backgrounds

2 Optimizing Timing Windows

3 Improving Detection Solid Angles.

## 1.1 Relevant Formalism

The probability per photon for chameleon generation, and vice versa, can be shown to be: [1]

$$|P_{\gamma\longleftrightarrow\phi} = \frac{4\beta_\gamma^2 B^2 \omega^2}{{M_{Pl}}^2 {m_{eff}}^4} sin^2\left(\frac{{m_{eff}}^2 L}{4\omega}\right) = \left(\frac{\beta_\gamma BL}{2M_{Pl}}\right)^2$$

where $\beta_\gamma$ is the coupling constant, B is the magnetic field strength, L is the length of the magnetic field, $M_{Pl}$ is the Plank mass. (The last equality comes from expanding the $\sin^2$ term.) Detection of a photon from a chameleon decay involves converting a photon to a chameleon, followed by chameleon converting back to a photon. Thus afterglow detection goes as $(BL)^4$. Small changes in the magnetic field has a large effect in the detection of afterglow photons from chameleon decay.

## 1.2 Photo-luminescent Background

An unexpected large, decaying, count rate was seen by CHASE when their data acquisition began. These photons were independent of the magnetic field B, and therefore could not be due to chameleons. CHASE speculated that this "orange glow" background was due to temperature dependent luminescence induced by the source laser on residual vacuum grease left over from the original construction of the Tevatron dipole. This temperature dependent photo-luminescence, best explained by Jablonski Diagrams, [2] was experimentally demonstrated by Cooke and Bennett using a UV light source onto Apiezon-L vacuum grease and over a temperature range from ambient down to $8^{o}$K. [3] Recently, measurements at Jefferson Lab have extended the range to $2^{o}$K. [4] Basically, energetic photons can excite molecular electrons from the ground state to a higher state which, when returning to the ground state, can encounter a forbidden transition. At normal ambient temperature, the electron can bypass the forbidden transition via vibrational, rotational, or other non-radiative levels. However, if the molecule is cooled, the available, non radiating transition paths are fewer and fewer, forcing the electron to radiatively return to the ground state. This is the reason for the large background in CHASE's data. At $4^{o}$K the green laser light induced orange luminescence in the residual vacuum grease in the Tevatron dipole's vacuum chamber. The relevance to the proposed ACES effort is significant. ACES will operate with a very clean vacuum chamber at room temperature and thus would not have to contend with such photoluminescence phenomena.

### 1.3 Half-lives and Timing Windows

The relationship between chameleon decay constant and coupling constant is shown to be: [1]

$$\Gamma_{dec} = 9 \times 10^{-5} \times \left(\beta_\gamma / 10^{12}\right)^2$$

The afterglow photon flux will have the decay form:

$$F(t) = F(0) \times e^{-\Gamma_{dec} t}$$

which, in terms of half-life, is:

$$t_{1/2} = \frac{ln\,(0.5)}{(-\Gamma_{dec})} = \frac{7.7 \times 10^{27}}{\beta_\gamma^2}$$

Within four half-lives, more than 90% of chameleons in the chamber when the laser is turned off, will have decayed. Therefore useful data collection should occur only during the first 4 half-lives. A timing window longer than that, not only is a waste of time, it accumulates unnecessary background.

Since we don't know the value of $\beta\gamma$, a prudent search strategy is needed. Qualitatively, small coupling constant values will result in weak coupling and long half-lives. Large values result in strong coupling and short half lives that could completely decay away between the time the laser is shut off and the detectors start recording. A timing window that would not be too long or too short, should be used for the initial search. For example, assuming the coupling constant is on the order of $10^{14}$, the half-life would be in seconds, not hours nor microseconds. Thus an initial timing window for ACES would be 4 seconds. If afterglow is detected, the timing window can be shortened to 1 or 0.5 seconds in order to measure the half-life. ACES equipment can explore the range:

$$10^{13} \leq \beta_\gamma \leq 10^{17}$$

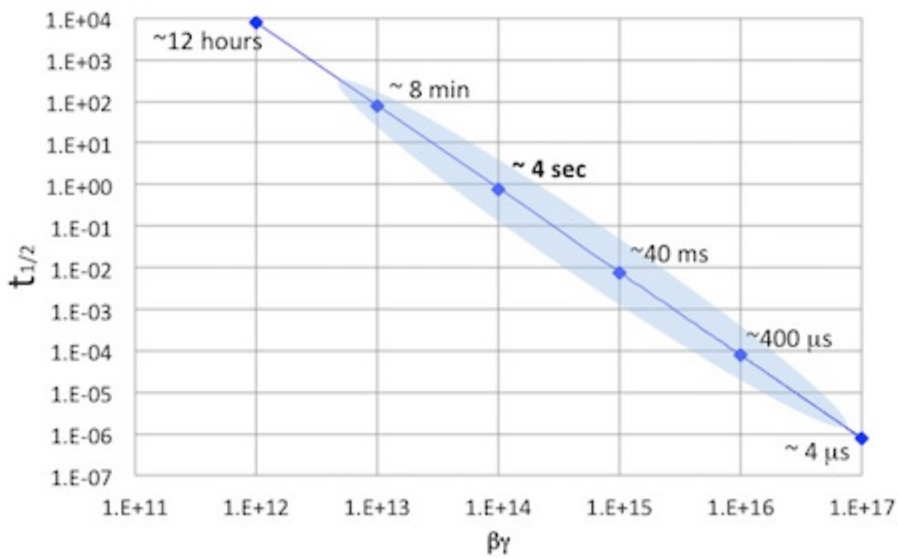


**Figure 1:** Half life vs. coupling constant. The shaded region indicates the search range for ACES. For example, if $\beta\gamma = 10^{14}$, 90% of the chameleon population at t=0 , would have decayed in 4 seconds. Thus the detection timing window ACES would be 4 seconds. Note the timing window for $\beta\gamma = 10^{12}$, the focus of CHASE, would be about 12 hours.

## 1.4 Detection Solid Angle

Soon after chameleons are generated, their motion becomes isotropic due to scattering off residual gas in the chamber and imperfections in the surface of the chamber walls. Consequently photons from decaying chameleons will also be isotropic. The CHASE experiment was such that only photons traveling along the vacuum chamber axis were counted by the detecting PMT. The detection solid angle for CHASE was on the order of $10^{-4}$ sr. [1]

The ACES system incorporates a glass tube lining the vacuum chamber wall which acts as an optical fiber capturing photons and redirecting them towards the detector. The resulting solid angle for detection is on the order of π. An additional benefit of the glass tube liner is the separation of afterglow photons from chameleons, since, by their very nature, chameleons cannot enter the solid material, but photons can.

## 2. PHADE/ACES Configuration

Depicted in Figure 2, is the basic configuration of the PHADE/ACES System. Source photons are from a commercial table-top laser connected to a vacuum chamber. Part of the chamber is inside the dipole that provides the coupling magnetic field. A shutter between the laser and the vacuum system window will be open for source photons and closed for afterglow acquisition. Shutters in front of DET/cameras will be closed during laser ON and open during afterglow acquisition.

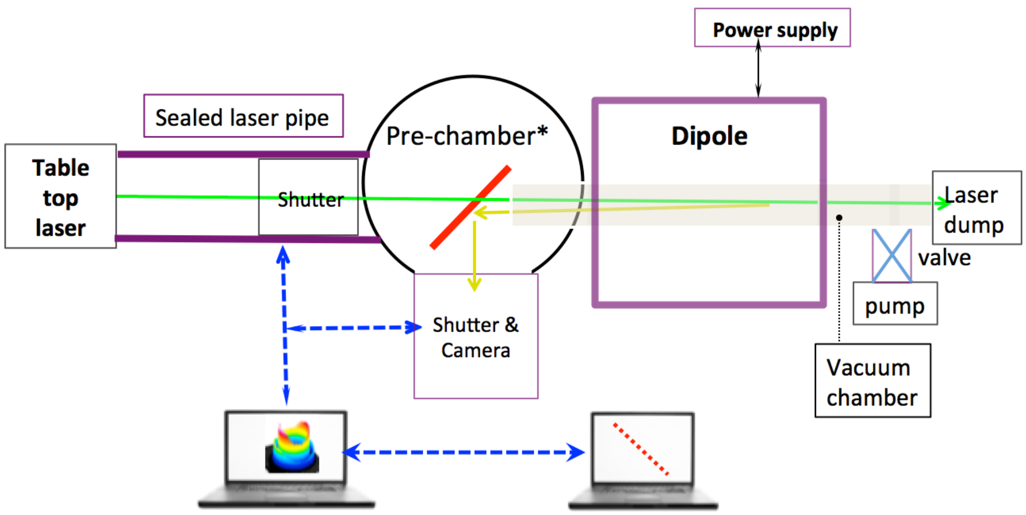


Figure 2: PHADE/ACES Configuration. Source photons, shown in green, pass through a window into the pre-chamber, through a hole in a mirror (red), and into the dipole field (maroon) where chameleons are generated. The photon beam is absorbed in a dump. Chameleons, trapped in the vacuum chamber, bouncing around, rapidly become isotropic, decaying back into photons when their motion takes them through the magnetic field. Decay photons captured by the glass sleeve are directed to the camera.

## 3. ACES-CHASE Comparison

The fact that detection of chameleon decay goes as $(BL)^4$ tends to dismiss discussions of the possibility for meaningful results with the JLab system.

However, the three enhancements ACES uses shows otherwise  as illustrated in Table 1.   Assuming the afterglow of CHASE at t=0 to be approximately $F(t=0) = 10^{8}$ /sec, for $\beta_\gamma = 10^{14}$, ACES should yield a count rate on the order of $10^{9}$ /sec. (24*1E+8). Key to this approach is lining the vacuum chamber with the glass tube. Note the bonus feature: the glass liner will separate afterglow photons from chameleons.

**Table 1:** ACES/CHASE comparison for $\beta\gamma = 10^{14}$

| Parameter | CHASE | ACES |
|---|---|---|
| B (T) | 1.7 | 1.7 |
| L (m) | 6 | 1 |
| $(BL)^4$ | 1.10E+04 | 8.40E+00 |
| $\Omega$ | 1.00E-04 | 3.10E+00 |
| $(BL)^4\,\Omega$ | 1.10E+00 | 2.60E+01 |
| **ACES / CHASE** | **24** | |
| If at t = 0, | CHASE | ACES |
| chameleon population is: | 1.0E+08 | 2.4E+09 |
| Then detectable afterglow is: | 1.0E+03 | 6.0E+08 |

# 4. Experimental Procedures (requiring zero beam time)

The modified afterglow measurement technique ACES proposes consists of the following steps:

## *4.1 Set-up.*

- Acquire all components: vacuum system, optical system, detector/camera system, data acquisition/storage, and magnet system.
- Obtain safety training certification of anyone working with the system, including readiness operations documentation.
- Assemble and test each system, ensure light-tight-ness of configuration..

## *4.2 Commissioning.*

Commission full system without magnetic field but with selected timing windows using phosphorescent target.

## *4.3 PHADE measurements*

Conduct PHADE procedures using low power laser pen pointers to determine optimum glass liner.

## *4.4 Incorporate table-top laser, dipole, and power supply.*

Install table-top laser, dipole, power supply, and certify system is safe.

## *4.5 ACES measurements – backgrounds.*

With B-field = 0, shine table-top laser beam through vacuum chamber lined with glass tube exposing the system to a set time, e.g., 10 seconds. Shut off source laser and acquire a set of sequential images covering wide range of timing window shown in Figure 1.

## *4.6 ACES measurements – chameleon search.*

With B- field = 1.7 Tesla, acquire a full set of timing window data matching data in step 4.5.

### *4.7 Analysis*

Compare results of step 4.5 with with step 4.6. For any timing window showing significant difference between B=0 and B=1.7 T, repeat the measurements.

### *4.8 Follow-on measurements.*

If significant afterglow is found, measure the half life and thus obtain the coupling constant value.

### *4.9 Results Report.*

Prepare final report and submit for peer review. This will include, for example, the region of parameter space explored. Figure 3 shows the parameter space explored by various experiments.

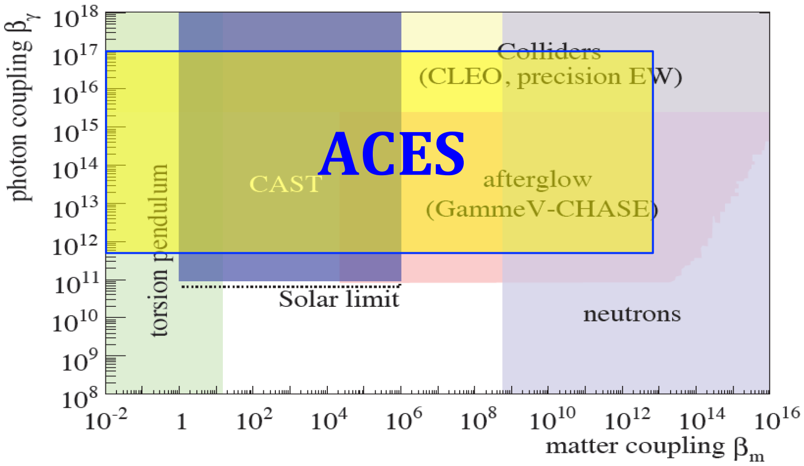


**Figure 3: Parameter space explored by various experiments. ACES, in yellow, overlaps many.**

## 5. Expected results

There are three likely outcomes. The first is that, for whatever reason, insufficient data is collected to draw any conclusion. The second is that no evidence of chameleons is found, but due to the parameter space overlap with other experiments, we confirm that chameleons, if they exist at all, cannot be generated under these conditions. This is a valid result. The third possibility, of course, is that repeatable evidence for chameleon afterglow is measured.

# 6. Budgets & Schedules

## 6.1 Equipment and Labor

The proposed PHADE/ACES budget (equipment & labor) is summarized in the following table. Equipment needed is in two categories: JLab equipment (currently not in use) and new items (purchased by CW&M). Staffing and level of effort are also shown.

**Table 2: PHADE/ACES Equipment & Labor Budget requirements. This proposal requests funding for JLab staff indicated by an asterisk in the third column.**

| JLab equipment | New equipment (CWM) | Staffing (Level of effort %) |
|---|---|---|
| PIXIS Camera | breadboard (18" x 24") | James R Boyce, CWM, (100%) |
| vacuum pump & valve | shutter & controller | Dennis Manos , CWM, (1%) |
| Table-top Laser | mirror w/ hole | Brianna Thorpe, ASU, (20%) |
| Pre-Chamber | LightField (Camera Software) | Andrei Afanasev, GWU & JLab, (5%) |
| LIPSS Dipole | Viewports (2) | *Mahlon Long, JLab, (10%) |
| Dipole Power Supply | Glass tubes | *Carl Zorn, JLab, (3%) |
| DG535 Dual pulse generator | CF flange vacuum chamber | *George Biallas, JLab, (2%) |
| | 64=bit PC | *Jim Coleman, JLab, (1%) |
| | Power meter (Laser dump) | *Electricians, JLab, (0.5%) |
| | | *Vacuum Tech, JLab, (0.5%) |

## 6.2 Schedule

PHADE is expected to be completed on two months. That is, by the end of July, 2016.
ACES could be completed by in the following two months. The more likely scenario is six months after PHADE.

# 7. Summary

The case has been made for conducting a two part investigation: PHADE and ACES. Both parts will use an afterglow technique similar to the CHASE effort at Fermilab. PHADE will show that a glass liner in the vacuum tube will dramatically increase the solid angle for detection of afterglow photons. Two additional improvements: elimination of photoluminescence background, and choosing efficient timing windows will be used by ACES to search for chameleon manifestations of Dark Energy. The parameter space explored by ACES will cover several orders of magnitude and will overlap regions examined by other experiments. Requiring no beam time and only equipment not in use, this effort has the potential for significant, high value discoveries, with very little cost.

The PHADE/ACES Team requests concurrence and approval by PAC44.

# 8. References

[1] A. S. Chou et al., “A Search for chameleon particles using a photon regeneration technique,” Phys.Rev.Lett., vol. 102, p. 030402, 2009. ( See Appendix A.)

[2] H. H. Jaffe and A. L. Miller, “”the fates of electronic excitation energy”,” J. Chem. Educ., vol. 43, p. 469, 1966.

[3] D. Cooke and B.L.Bennette, “Long-lived luminescence from commonly used apiezon compounds,” Journal of Luminescence, vol. 65, pp. 83–288, 1996.

[4] J. R. Boyce, “Phile: A photon induced luminescence experiment.” Tech Note in progress, 2015.

[5] A. Upadhye, J. H. Steffen, and A. S. Chou, “Designing dark energy afterglow experiments,” Phys.Rev., vol. D86, p. 035006, 2012.

# Search for Chameleon Particles Using a Photon-Regeneration Technique

A. S. Chou,[1] W. Wester,[2] A. Baumbaugh,[2] H. R. Gustafson,[3] Y. Irizarry-Valle,[2] P. O. Mazur,[2] J. H. Steffen,[2] R. Tomlin,[2] A. Upadhye,[4] A. Weltman,[5,6] X. Yang,[2] and J. Yoo[2]

[1]*Center for Cosmology and Particle Physics, New York University, 4 Washington Place, New York, New York 10003, USA*
[2]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA*
[3]*Department of Physics, University of Michigan, 450 Church Street, Ann Arbor, Michigan 48109, USA*
[4]*Kavli Institute for Cosmological Physics, University of Chicago, Illinois 60637, USA*
[5]*Department of Applied Mathematics and Theoretical Physics, Cambridge CB2 0WA, United Kingdom*
[6]*Cosmology and Gravity Group, University of Cape Town, Rondebosch, Private Bag, 7700 South Africa*
(Received 1 August 2008; published 22 January 2009)

We report the first results from the GammeV search for chameleon particles, which may be created via photon-photon interactions within a strong magnetic field. Chameleons are hypothesized scalar fields that could explain the dark energy problem. We implement a novel technique to create and trap the reflective particles within a jar and to detect them later via their afterglow as they slowly convert back into photons. These measurements provide the first experimental constraints on the couplings of chameleons to photons.

DOI: 10.1103/PhysRevLett.102.030402 PACS numbers: 12.20.Fv, 14.70.Bh, 14.80.Mz, 95.36.+x

*Introduction.*—Recent cosmological observations have demonstrated with increasing significance the existence of cosmic acceleration, usually attributed to a negative pressure substance known as ‘‘dark energy’’ [1–3]. A major effort is under way to discover the properties of dark energy, including its couplings to standard model fields.

Perhaps the greatest obstacle to solving this problem lies in the techniques used to probe dark energy. Specifically, our inference of the properties of dark energy have so far come only from observational cosmology data. While the results so far are striking, these techniques are limited in that there are very few, if any, techniques available to separate between different theoretical models of dark energy. This is compounded by the extraordinary difficulty in measuring with enough precision the equation of state parameter $w$, and its variation in time.

In this Letter, we will illustrate for the first time how dark energy models may be tested in the laboratory. Unless protected by a symmetry, the dark energy particle should be coupled to all other forms of matter by quantum corrections. Such couplings can lead to equivalence principle violations [4], fifth forces [5], variations in standard model parameters such as the fine structure constant, and unexpected interactions between known particles. The chameleon mechanism [6,7], by which a matter coupling and a nonlinear self-interaction conspire to give a field an environment-dependent effective mass, resolves these issues, while providing a candidate for dark energy. Crucially, chameleon fields can have small masses on cosmological scales, while acquiring large masses locally in order to evade fifth force searches [6–11] while also causing the accelerated expansion observed today. Chameleon dark energy is perhaps most compelling because the very nature of chameleon interactions, if they exist, makes it possible for us to observe them and measure their properties in a diverse array of laboratory tests and space tests of gravity [6,7,12].

Chameleons can couple strongly to all matter particles with no violations of known physics. Chameleons may also couple to photons via $\phi F^2$ type terms where $F_{\mu\nu}$ is the electromagnetic field strength tensor. Such a coupling allows photon-chameleon oscillations in the presence of an external magnetic field. The chameleon mechanism ensures that a chameleon with large couplings to matter will become massive inside typical laboratory materials. A chameleon may be trapped inside a ‘‘jar’’ if its total energy is less than its effective mass within the material of the walls of the jar. In this case, the walls reflect the incoming chameleons. Chameleons produced from photon oscillations in an optically transparent jar can then be confined until they regenerate photons, which emerge as an afterglow once the original photon source is turned off [13–15]. The GammeV experiment in its second incarnation is designed to search for such an afterglow and to measure or constrain the possible coupling of meV mass chameleons to photons. Probing this low scale in a way complementary to astrophysics may be the key to understanding the (meV)$^4$ dark energy density.

*Chameleon phenomenology.*—A chameleon scalar field $\phi$ coupled to matter and photons has an action of the form [8]

$$S = \int d^4x \Big[ -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{e^{\phi/M_\gamma}}{4}F^{\mu\nu}F_{\mu\nu} + \mathcal{L}_m(e^{2\phi/M_m}g_{\mu\nu}, \psi^i_m)\Big] \quad (1)$$

where $g_{\mu\nu}$ is the metric, $V(\phi)$ is the chameleon potential, and $\mathcal{L}_m$ is the Lagrangian for matter.

 

For simplicity, we consider a universal coupling to matter $\beta_m = M_{\rm Pl}/M_m$, where $M_{\rm Pl} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass and $M_m$ is the mass scale associated with the coupling descending from the theory. Theories with large extra dimensions allow matter couplings $\beta_m$ much stronger than gravity, while a rough upper bound of $\beta_m \lesssim 10^{16}$ is obtained from particle colliders [16,17], corresponding to $M_m > 100$ GeV. We allow for a different coupling to electromagnetism, $\beta_\gamma = M_{\rm Pl}/M_\gamma$, through the electromagnetic field strength tensor $F_{\mu\nu}$. This term resembles the dilaton-photon coupling $\sim e^{-2\phi}F^2$ in string theory.

The nontrivial couplings to matter and the electromagnetic field induce an effective potential

$$V_{\rm eff}(\phi, \vec{x}) = V(\phi) + e^{\beta_m \phi/M_{\rm Pl}} \rho_m(\vec{x}) + e^{\beta_\gamma \phi/M_{\rm Pl}} \rho_\gamma(\vec{x}), \tag{2}$$

where we have defined the effective electromagnetic field density $\rho_\gamma = \frac{1}{2}(|\vec{B}^2| - |\vec{E}|^2)$ (for scalars) or $\rho_\gamma = \vec{E} \cdot \vec{B}$ (for pseudoscalars) rather than the energy density. The expectation value $\langle\phi\rangle$, the minimum of $V_{\rm eff}$, and thus the effective mass of the chameleon ($m_{\rm eff} \equiv \sqrt{d^2 V_{\rm eff}/d\phi^2}$), depends on the density of both background matter and electromagnetic fields. This dependence is crucial; the afterglow phenomenon requires that the particles have large mass in the walls of the jar (to ensure containment) but that they remain sufficiently light inside the jar to allow coherent, constructive chameleon-photon oscillations over the dimensions of the jar. For a large range of potentials, the effective mass scales with ambient density as $m_{\rm eff}(\rho) \propto \rho^\alpha$, for $\alpha$ of order unity. For example, with power law models $V(\phi) \propto \phi^n$ with $n > 2$, or chameleon dark energy models [8], $V(\phi) = \Lambda^4 \exp(\Lambda^n/\phi^n)$ with $\Lambda = 2.3$ meV and $n > 0$, we find $0 < \alpha < 1$. Here, $n$ is allowed to be any real number. As discussed below, our limits on $\beta_\gamma$ will only be valid for models in which the predicted density scaling is strong enough that both the coherence condition and the containment condition can be satisfied.

*GammeV apparatus.*—The GammeV apparatus, described in [18] and shown in Fig. 1, consists of a long stainless steel cylindrical vacuum chamber inserted into the bore of a $B = 5$ T, $L = 6$ m Tevatron dipole magnet. The entrance and exit of the chamber are sealed with BK7 glass vacuum windows. A 20 Hz pulsed Nd:YAG laser emits $\omega = 2.33$ eV photons into the chamber at a rate of $F_\gamma \sim 10^{19}$ photons/ sec. The 1 cm$^{-1}$ linewidth of the laser is sufficiently large to span the discrete energy levels of the trapped chameleons.

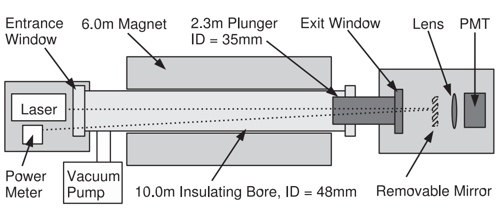


FIG. 1. The GammeV apparatus.

Interactions with the magnetic field cause each photon to oscillate into a superposition of photon and chameleon states. This superposition can be measured through collisions with the windows; chameleons bounce, while photons pass through. In order to populate the jar with chameleons, the laser is operated continuously for $\tau_{\rm pr} \approx 5$ h. After emerging through the exit window of the chamber, the beam is reflected back through the chamber in order to increase the chameleon production rate and facilitate monitoring of the laser power.

During the afterglow phase of the experiment, the laser is turned off and a low noise photomultiplier tube (PMT) placed at the exit window is uncovered. Chameleons interacting with the magnetic field convert back into photons, some of which escape to be detected by the PMT. Data are taken in two separate runs, with the laser polarization either aligned with or perpendicular to the magnetic field, to search for pseudoscalar as well as scalar chameleons.

Throughout the production and afterglow phases, a pressure $P_{\rm chamber} \approx 10^{-7}$ Torr is maintained inside the vacuum chamber using a turbomolecular pump connected to a roughing pump. Because the low-mass chameleons are highly relativistic inside the chamber, the turbo pump simply acts as extra volume (0.026 m$^3$) for the chameleons. The positive displacement roughing pump is however the weakest "wall" of the chamber, and chameleons must be able to reflect on the higher pressure $P_{\rm pump} = 1.9 \times 10^{-3}$ Torr residual gas at the intake of the roughing pump. The position-dependent $m_{\rm eff}$ acts as a classical potential for the chameleon particle. A semiclassical tunneling calculation indicates that chameleons will be confined in the chamber over the duration of the data runs ($10^{13}$ reflections) if $(m_{\rm eff} - \omega) > 10^{-6}$ eV at all boundaries of the apparatus. Also, our experiment is only sensitive to models in which $m_{\rm eff}$ is sufficiently small in the regions away from the walls to allow coherent oscillations: $m_{\rm eff} \ll \sqrt{4\pi\omega/L} = 9.8 \times 10^{-4}$ eV. If $m_{\rm eff}$ is dominated by interactions with the residual gas rather than by interactions with the magnetic energy density, then defining $m_{\rm eff} \equiv m_0(P/P_{\rm pump})^\alpha$, our constraints on $\beta_\gamma$ are valid for $\omega < m_0 < \sqrt{4\pi\omega/L}(P_{\rm pump}/P_{\rm chamber})^\alpha$ and hence $\alpha \gtrsim 0.8$ which saturates these inequalities. Since in our apparatus, $\rho_m \approx \rho_\gamma \approx 2 \times 10^{-13}$g/cm$^3$, the experiment is mainly sensitive to models in which $\beta_m \gg \beta_\gamma$ which in addition predict large density scaling $\alpha$.

*Expected signal.*—In terms of the coupling $\beta_\gamma$, and $m_{\rm eff}$ in the chamber, the chameleon production probability [19–21] per photon is

$$\mathcal{P}_{\rm pr} = \frac{4\beta_\gamma^2 B^2 \omega^2}{M_{\rm Pl}^2 m_{\rm eff}^4} \sin^2\left(\frac{m_{\rm eff}^2 L}{4\omega}\right). \tag{3}$$

A particle that has just reflected from one of the chamber windows is in a pure chameleon state. Repeated bounces

TABLE I. Summary of data for both configurations.

| Configuration | Fill Time (s) | # photons | Vacuum (Torr) | Observation (s) | Offset (s) | Mean Rate (Hz) | Excluded (low $m_{\rm eff}$) |
|---|---|---|---|---|---|---|---|
| Pseudoscalar | 18 324 | 2.39e23 | 2e-7 | 3602 | 319 | 123 | $6.2\text{e}11 < \beta_\gamma < 1.0\text{e}13$ |
| Scalar | 19 128 | 2.60e23 | 1e-7 | 3616 | 1006 | 101 | $5.0\text{e}11 < \beta_\gamma < 6.4\text{e}12$ |

off of imperfectly aligned windows and the chamber walls cause chameleon momenta to become isotropic. As a chameleon passes through the magnetic field region, it oscillates between the photon and chameleon states. In the small mixing angle limit, the photon amplitude $\vec{\Psi}_\gamma$ due to this oscillation is given by

$$\left(-\frac{\partial^2}{\partial t^2} - k^2\right)\vec{\Psi}_\gamma = \frac{k\beta_\gamma B}{M_{\rm Pl}}\hat{k}\times(\hat{x}\times\hat{k})\Psi_\phi, \qquad (4)$$

where $\Psi_\phi \approx 1$ is the chameleon amplitude, $k \approx \omega$ is the momentum, and $\hat{k}$ and $\hat{x}$ are unit vectors in the direction of the particle momentum and the magnetic field, respectively. The chameleon decay rate corresponding to a particular direction $(\theta, \varphi)$ is $[|\vec{\Psi}_\gamma(\theta,\varphi)|^2 + \mathcal{P}_{\rm abs}(\theta,\varphi)]/\Delta t(\theta)$ evaluated at the exit window, where $\theta$ is the direction with respect to the cylinder axis, $\mathcal{P}_{\rm abs}$ is the total probability of photon absorption in the chamber walls, and $\Delta t(\theta) = \ell_{\rm tot}/\cos(\theta)$ is the time required to traverse the $\ell_{\rm tot} \approx$ 12.3 m chamber. We model a bounce from the chamber wall as a partial measurement in which the photon amplitude is attenuated by a factor of $f_{\rm ref}^{1/2}$, where $f_{\rm ref}$ is the reflectivity. The mean decay rate $\Gamma_{\rm dec}$ per chameleon is found by averaging over $\theta$ and $\varphi$. Although the cylinder walls are not polished, a low absorptivity $1 - f_{\rm ref} = 0.1$ is assumed in order to overpredict the coherent build up of photon amplitude over multiple bounces. As described below, this overprediction of the decay rate results in a more conservative limit on the coupling constant. We obtain $\Gamma_{\rm dec} = 9.0\times 10^{-5}(\beta_\gamma/10^{12})^2$ Hz.

While the laser is on, new chameleons are produced at the rate of $F_\gamma\mathcal{P}_{\rm pr}$ and decay at the rate of $N_\phi\Gamma_{\rm dec}$. After a time $\tau_{\rm pr}$ the laser is turned off, and the chamber contains $N_\phi^{(\rm max)} = F_\gamma\mathcal{P}_{\rm pr}\Gamma_{\rm dec}^{-1}(1 - e^{-\Gamma_{\rm dec}\tau_{\rm pr}})$ chameleon particles. For our apparatus, this saturates at $3.6\times 10^{12}$ for $\beta_\gamma \gtrsim 10^{12}$ and small $m_{\rm eff}$. The contribution to the afterglow photon rate from nonbouncing chameleon trajectories is

$$F_{\rm aft}(t) = \frac{\epsilon_{\rm det} f_{\rm vol} f_{\rm esc} F_\gamma \mathcal{P}_{\rm pr}^2 c}{\ell_{\rm tot}\Gamma_{\rm dec}}(1 - e^{-\Gamma_{\rm dec}\tau_{\rm pr}})e^{-\Gamma_{\rm dec}t}, \qquad (5)$$

for $t \geq 0$, where $t = 0$ is the time at which the laser is turned off. The detector efficiency $\epsilon_{\rm det}$ contains the 0.92 optical transport efficiency, as well as the 0.387 quantum efficiency and 0.7 collection efficiency of the PMT. Because chameleons in the turbo pump region do not regenerate photons, we consider only the chameleons in the cylindrical chamber, which represents a volume fraction $f_{\rm vol} = 0.40$ of the total population.

In order to set conservative, model-independent limits, we consider only the afterglow from the fraction $f_{\rm esc} = 5.3\times 10^{-7}$ of chameleons which travel the entire distance $\ell_{\rm tot}$ from entrance to exit windows without colliding with the chamber walls, and are focussed by a 2 in. lens onto the PMT. While many chameleons that bounce from the walls may also produce photons which reach the detector (indeed, most of the photons that can reach the detector are on bouncing trajectories), such collisions result in a model-dependent chameleon-photon phase shift [22] which can affect the coherence of the oscillation on bouncing trajectories. Figure 2 shows the prediction for the minimum afterglow signal consisting of only the direct light, and attenuated by the fastest possible decay rate $\Gamma_{\rm dec}$ in Eq. (5). This afterglow rate is plotted for several values of the photon-chameleon coupling $\beta_\gamma$. Nonobservation of this underpredicted rate sets the most conservative limits.

*Results.*—After turning the laser off, we collect afterglow data for 1 h on the PMT cathode. Table I shows relevant data for both of the data runs including: the total integration time during the filling stage, the total number of photons which passed through the chamber, a limit on the vacuum quality (which can affect the chameleon mass and hence the coherence length of the oscillations), the length of the afterglow observation run, the time gap between filling the chamber and observing the afterglow, the mean observed trigger rate, and the limits on $\beta_\gamma$ for coherent oscillations.

In order to minimize the effects of systematic uncertainties due to fluctuations in the dark rate, we compare the expected afterglow signal averaged over the entire obser-

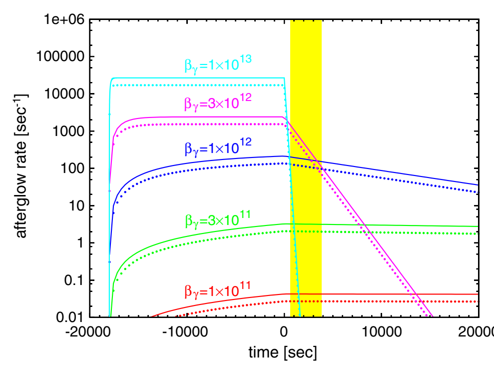


FIG. 2 (color online). Expected afterglow rate for various values of $\beta_\gamma$. The solid curves are for chameleons with masses of $10^{-4}$ eV while the dotted curves are for $5\times 10^{-4}$ eV chameleons. Our observation time window for pseudoscalar chameleons is shown shaded in yellow; the corresponding time window for scalar chameleons is shifted to the right by about 700 sec.

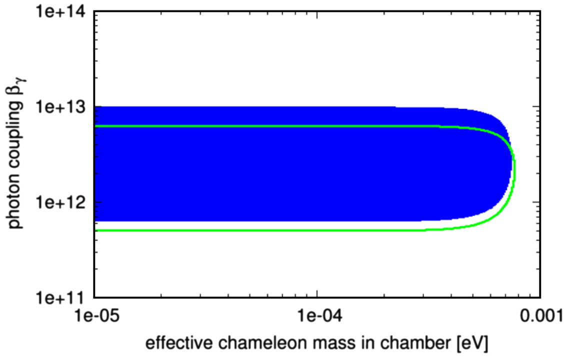


FIG. 3 (color online). Region excluded by GammeV to $3\sigma$ for pseudoscalar particles (solid blue region) and for scalar particles (region between green lines).

vation time to the mean signal observed by the PMT. The dominant uncertainty in our measurements of the afterglow rate is the systematic uncertainty in the PMT dark rate. We estimate this quantity, using data from [18], by averaging the count rate in each of the 55 nonoverlapping samples approximately 1 h in length. The dark rate, computed by averaging the sample means, is 115 Hz, with a standard deviation of 12.0 Hz. No excess is seen in the chameleon data runs over this mean dark rate and all measured rates are well below the ~600 Hz maximum throughput of our data acquisition system. The systematic variation in the dark rate is much larger than the statistical uncertainty in the individual sample means. Thus our $3\sigma$ upper bound on the mean afterglow rate is 36 Hz above the mean of the data rate for each run, after the 115 Hz average dark rate has been subtracted.

For each $m_{\rm eff}$ and $\beta_\gamma$ we use (5) to compute the total number of excess photons predicted within the observation time window. Figure 3 shows the regions excluded by GammeV in the $(m_{\rm eff}, \beta_\gamma)$ parameter space for scalar and pseudoscalar chameleon particles. At $m_{\rm eff}$ near $\sqrt{4\pi\omega/L} = 9.8 \times 10^{-4}$ eV, our exclusion region is limited by destructive interference in chameleon production. At higher $m_{\rm eff}$, a larger $\beta_\gamma$ is needed to produce an equivalent nonbouncing minimum signal rate. However, for $\beta_\gamma \gtrsim 10^{13}$ our sensitivity diminishes because, as shown in Fig. 2, the chameleon decay time $\Gamma_{\rm dec}^{-1}$ in GammeV could be less than the few hundred seconds required to switch on the PMT. Our constraints could be extended to higher $\beta_\gamma$ by more quickly switching on our detector, by reducing the magnetic field strength, and/or by making the chamber walls less reflective to reduce $\Gamma_{\rm dec}$. Finally, at low $\beta_\gamma$ we are limited by our uncertainty in the PMT dark rate. At low $\Gamma_{\rm dec}$, Eq. (5) reduces to a constant rate $F_{\rm aft} \approx \epsilon_{\rm det} f_{\rm vol} f_{\rm esc} F_\gamma \mathcal{P}_{\rm pr}^2 c/\ell_{\rm tot}$, which, for $\beta_\gamma \lesssim 5 \times 10^{11}$, is below our detection threshold. In summary, GammeV has carried out the first search for chameleon afterglow, a unique signature of photon-coupled chameleons. Figure 3 presents conservative constraints in a model-independent manner, over a restricted range of chameleon models. Improvements to this experimental setup have the potential to open up the chameleon parameter space to testability. Hopefully, this work will inspire others to consider alternative ways to test for dark energy—in high and even low energy experiments.

We thank the staff of the Fermilab Magnet Test Facility of the Fermilab Technical Division, and the technical staff of the Fermilab Particle Physics Division, who aided in the design and construction of the apparatus. We are grateful to S. Gubser and W. Hu for many informative discussions. J. S. thanks the Brinson Foundation for their generous support. This work is supported by the U.S. Department of Energy under Contract No. DE-AC02-07CH11359. A. C. is supported by NSF-PHY-0401232.

[1] J. Frieman, M. Turner, and D. Huterer, arXiv:0803.0982.
[2] R. R. Caldwell, R. Dave, and P. Steinhardt, Phys. Rev. Lett. **80**, 1582 (1998).
[3] B. Ratra and P. J. E. Peebles, Phys. Rev. D **37**, 3406 (1988).
[4] C. Will, *Theory and Experiment in Gravitational Physics* (Basic Books/Perseus Group, New York, 1993).
[5] E. Fischbach and C. Talmadge, *The Search for Non-Newtonian Gravity* (Springer-Verlag, New York, 1999).
[6] J. Khoury and A. Weltman, Phys. Rev. Lett. **93**, 171104 (2004).
[7] J. Khoury and A. Weltman, Phys. Rev. D **69**, 044026 (2004).
[8] P. Brax *et al.*, Phys. Rev. D **70**, 123518 (2004).
[9] S. S. Gubser and J. Khoury, Phys. Rev. D **70**, 104001 (2004).
[10] A. Upadhye, S. S. Gubser, and J. Khoury, Phys. Rev. D **74**, 104024 (2006).
[11] E. G. Adelberger *et al.*, Phys. Rev. Lett. **98**, 131104 (2007).
[12] S. Baessler *et al.*, Phys. Rev. Lett. **83**, 3585 (1999).
[13] The "particle trapped in a jar" technique was developed as part of the GammeV experiment, and independently realized in [14,15].
[14] M. Ahlers *et al.*, Phys. Rev. D **77**, 015018 (2008).
[15] H. Gies, D. F. Mota, and D. J. Shaw, Phys. Rev. D **77**, 025016 (2008).
[16] D. F. Mota and D. J. Shaw, Phys. Rev. D **75**, 063501 (2007).
[17] D. F. Mota and D. J. Shaw, Phys. Rev. Lett. **97**, 151102 (2006).
[18] A. S. Chou *et al.* [GammeV (T-969) Collaboration], Phys. Rev. Lett. **100**, 080402 (2008).
[19] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983); **52**, 695(E) (1984).
[20] P. Sikivie, Phys. Rev. D **32**, 2988 (1985); **36**, 974(E) (1987).
[21] G. Raffelt and L. Stodolsky, Phys. Rev. D **37**, 1237 (1988).
[22] P. Brax *et al.*, Phys. Rev. D **76**, 085010 (2007).

# James R. Boyce

| Professional preparation: | Major or position | Degree | Advisors |
|---|---|---|---|
| Florida State University | Physics and Mathematics | B.S. - 1964 | |
| Florida State University | Physics | M.S. – 1966 | Neil Fletcher |
| Duke University | Physics | Ph.D. – 1972 | Henry Newson |
| Duke University | Postdoc Research Associate | 1972 – 1974 | Ed Bilpuch |
| Computer Science Corp. | Atmospheric research | 1974 – 1975 | |
| Cornell University | Postdoc Research Associate | 1975 – 1978 | David C. Clarke |

RESEARCH AND MANAGEMENT APPOINTMENTS:

***Visiting Materials Scientist***...(70%)….The College of William and Mary……......……..2012-present
***Visiting Scientist….***(30%)...................Laboratory for Nuclear Science, M.I.T.................2012-present
***FEL physicist***....Thomas Jefferson National Accelerator Facility (Jefferson Lab.)……..…1996-2012
***Jefferson Lab Technology Transfer Manager***.............…Jefferson Lab..……..…..………..1996-2012
***Staff Scientist III and Accelerator Division Advisor***……Jefferson Lab………......……….1987-1996
***Staff Scientist III***…………Schlumberger-Doll Research……..……………...........……..1978-1987

PUBLICATIONS

1. A Afanasev, OK Baker, KB Beard, G Biallas, J Boyce, M Minarni, R Ramdon, M Shinn, P Slocum, *Experimental limit on optical-photon coupling to light neutral scalar bosons* Phys. Rev. Lett., 101 (12), 120401. (Number of citations: 102)
2. JR Boyce*. An overview of dark matter experiments at Jefferson Lab* Journal of Physics: Conference Series 384:012008, 2012.
3. JR Boyce. *The DarkLight experiment-a status report* Frascati Physics Series 56 (2012) Frascati Phys. Ser., 56:48–59, 2012.
4. S Abrahamyan, Z Ahmed, K Allada, D Anez, T Averett, A Barbieri, K Bartlett, J Beacham, J Bono, JR Boyce, P Brindza, A Camsonne, K Cranmer, MM Dalton, CW de Jager, J Donaghy, R Essig, C Field, E Folts, A Gasparian, N Goeckner-Wald, J Gomez, M Graham, J-O Hansen, DW Higinbotham, T Holmstrom, J Huang, S Iqbal, J Jaros, E Jensen, A Kelleher, M Khandaker, JJ LeRose, R Lindgren, N Liyanage, E Long, J Mammei, P Markowitz, T Maruyama, V Maxwell, S Mayilyan, J McDonald, R Michaels, K Moffeit, V Nelyubin, A Odian, M Oriunno, R Partridge, M Paolone, E Piasetzky, I Pomerantz, Y Qiang, S Riordan, Y Roblin, B Sawatzky, P Schuster, J Segal, L Selvy, A Shahinyan, R Subedi, V Sulkosky, S Stepanyan, N Toro, D Walz, B Wojtsekhowski, J *Zhang Search for a new gauge boson in electron-nucleus fixed-target scattering by the APEX experiment* Physical review letters 107 (19), 191804. (Number of citations: 157)
5. C Tschalaer, R Alarcon, S Balascuta, SV Benson, W Bertozzi, JR Boyce, R Cowan, D Douglas, P Evtushenko, P Fisher, E Ihloff, N Kalantarians, A Kelleher, R Legg, RG Milner, GR Neil, L Ou, B Schmookler, C Tennant, GP Williams, S Zhang, *Transmission of High-Power Electron Beams Through Millimeter Apertures* Phys. Rev. Lett. RL 111, 164801 (2013).
6. JR Boyce, USPTO Patent No. 4,587,423: May 6, 1986. "*Method for Gravel Pack Evaluation*."
7. James R Boyce, USPTO No. 7,885,385 B1: Feb. 8, 2011. "*Tunable X-Ray Source*."
8. JR Boyce, *Thomson scattering in the Jefferson Lab infrared FEL* (Book Chapter in Femtosecond Beam Science, edited by Mitsuru Uesaka, 2005, Imperial College Press, pp. 193-201).
9. JR Boyce, G King, W Diamond, AJ Becker, J Doucet, RL Bramblett*. An electron linac as an x-ray source for measuring geological density* Nuclear Instruments and Methods in Physics Research. Volume 242, Issue 3, 15 January 1986, pages 507–510.
10. JR Boyce, TD Hayward, R Bass, HW Newson, EG Bilpuch, FO Purser, HW Schmitt, *Absolute cross sections for proton-induced fission of the uranium isotopes*. Physical Review C 10 (1), 231.

SYNERGISTIC ACTIVITIES:

1. As Team Leader, Received Vice-President Al Gore's "Hammer Award" for "helping build a government that works better and costs less." March 26 1997.
2. Active participant in DOE's Technology Transfer Working Group (TTWG). Author of the acronym for the new program complimenting CRADAs, and Work for Others. (WFOs:) "Agreement Commercializing Technology," or "ACT." 2012.
3. As Tech Transfer Manager for JLab, managed Intellectual Property program, assisted small businesses negotiate Cooperative Research and Development Agreements (CRADAs) with JLab, and met and exceeded contractual metrics for Tech Transfer from 1996-2012.
4. Member of Bard of Directors of regional economic organizations: Hampton Roads Research Partnership (HRRP membership: basic research universities, JLab, NASA, NIA), Hampton Roads Technology Council (HRTC membership: regional Tech. companies, JLab, NASA, NIA), and regional Economic Development Associations. (1997-2010).
5. Accelerator Readiness Review Team Leader organizing phased and tailored process ensuring successful commissioning and operations of new national Laboratory for nuclear physics (CEBAF – the Continuous Electron Beam Accelerator Facility, re-named the Thomas Jefferson National Accelerator Facility, nicknamed Jefferson Lab or JLab.) (1990-1993).

COLLABORATORS AND OTHER AFFILIATIONS (Note: since ACES PI is a member of these three collaborations, in order to avoid conflict of interest or the appearance thereof, members should not be asked to review this ACES proposal.)
**DarkLight Collaboration:** C Tschalaer, R Alarcon, S Balascuta, SV Benson, W Bertozzi, JR Boyce, R Cowan, D Douglas, P Evtushenko, P Fisher, E Ihloff, N Kalantarians, A Kelleher, R Legg, RG Milner, GR Neil, L Ou, B Schmookler, C Tennant, GP Williams, S Zhang,
**APEX Collaboration:** S Abrahamyan, Z Ahmed, K Allada, D Anez, T Averett, A Barbieri, K Bartlett, J Beacham, J Bono, P Brindza, A Camsonne, K Cranmer, MM Dalton, CW de Jager, J Donaghy, R Essig, C Field, E Folts, A Gasparian, N Goeckner-Wald, J Gomez, M Graham, J-O Hansen, DW Higinbotham, T Holmstrom, J Huang, S Iqbal, J Jaros, E Jensen, A Kelleher, M Khandaker, JJ LeRose, R Lindgren, N Liyanage, E Long, J Mammei, P Markowitz, T Maruyama, V Maxwell, S Mayilyan, J McDonald, R Michaels, K Moffeit, V Nelyubin, A Odian, M Oriunno, R Partridge, M Paolone, E Piasetzky, I Pomerantz, Y Qiang, S Riordan, Y Roblin, B Sawatzky, P Schuster, J Segal, L Selvy, A Shahinyan, R Subedi, V Sulkosky, S Stepanyan, N Toro, D Walz, B Wojtsekhowski, J Zhang.
**LIPSS Collaboration:** A Afanasev, OK Baker, KB Beard, G Biallas, M Minarni, R Ramdon, M Shinn, P Slocum.

**Groups competing with ACES:** (Note: Since these are competitors of ACES, They should not be asked to review or comment on this ACES proposal.)
**GammeV and CHASE:** AS Chou, WC Wester, A Baumbaugh, HR Gustafson, Y Irizarry-Valle, PO Mazur, JH Steffen, R Tomlin, A Upadhye, A Weltman, X Yang, and J Yoo.

**Graduate Advisors and Postdoctoral Sponsors:** Although such Graduate Advisors and Postdoctoral Sponsors are anticipated, none have been identified as yet.

**Students:** The ACES PI has mentored the following undergraduate students: Taylor Robinson, Jon Evans, Jennifer Callan, Joe Amman, and Allison Schue.

**AFFILIATIONS/MEMBERSHIPS:** American Physical Society, Sigma Xi, American Institute of Physics (AIP) Corporate Associates Advisory Committee (CAAC). Board of Directors: HRRP (Hampton Roads Research Partnership), HRTC (Hampton Roads Technology Council), HREDA (Hampton Roads Economic Development Association).