Photofission of Actinides with Linearly Polarized Photons

Technical Workscope : AFS-2

Overview and Mission Relevance:

This project involves the investigation of nuclear photofission at a fundamental level, with the ultimate goal of developing a new technique to quantify actinides for safeguards and quality control applications. In this proposal, we outline a plan to

1. measure the asymmetric neutron angular distribution resulting from anisotropic fission fragment emission when actinides are actively interrogated by linearly polarized photons
2. evaluate the potential for utilization of this phenomenon in the areas of materials control and accountability.

The method for the production of linearly polarized photons from a bremsstrahlung beam described in this proposal is well established [1] and can be readily implemented as an add on to other systems using bremsstrahlung beams for active interrogation. The fundamental measurements of the neutron angular distributions resulting from the angular dependence of fission fragment emission constitute a new, previously unexplored area of investigation. The expected neutron rate ratios have the potential to enable a quantitative measurement of actinides for safeguards and quality control applications.

Work Scope Description:

It has long been known that the nuclear fragments resulting from photon induced fission of heavy nuclei are emitted anisotropically when measured with respect to the incident photon direction. The first such measurement [2], performed with unpolarized photons in 1956, found an angular distribution given by $a + b\sin^2\theta$, where θ is the polar angle and the ratio a/b was found to depend on the energy of the incident photon, the target, and the type of fission fragment observed. The introduction of linear photon polarization breaks the azimuthal symmetry by imposing a preferred direction in space perpendicular to the incident photon beam. This ϕ asymmetry was observed in 1982 [3] with the measurement of fission fragments from the polarized photofission of thorium. Here, we propose a technique which has the potential to be sensitive to these azimuthal asymmetries, but avoids the technical difficulties associated with directly detecting the short-ranged fission fragments.

For linearly polarized photons and considering only electric dipole (E1) transitions, the photofission of an even-even nucleus ($J^\pi = 0^+$, such as ^{238}U) gives an angular distribution of the fission fragments [3]:

$$W(\theta, \phi) = A_o + A_2(P_2(\cos\theta) + P_\gamma f_2(1,1)\cos 2\phi P_2^2(\cos\theta)) \quad (1)$$

The angular distribution coefficients A_o and A_2 depend on the transition state (J,K), where K is the projection of the total spin J on the symmetry axis of the deformed nucleus. For $J = 1, K = 0$, we have $A_o = 1/2, A_2 = -1/2$ and for $J = 1, K = 1$, we have

$A_o = 1/2, A_2 = 1/4$. $P_2 = \frac{1}{2}(2 - 3\sin 2\theta)$, P_γ is the degree of photon polarization, and $f_2(1,1) = 3\sin 2\theta$. θ is the polar angle with respect to the beam and ϕ is the azimuthal angle ($\phi = 0$ parallel to the electric field vector and $\phi = \pi/2$ perpendicular to $\vec{\mathrm{E}}$).

The calculated angular distributions of the fission fragments are shown in Fig. for fragments emitted parallel and perpendicular to the polarization vector for a photon polarization of 30% and for both K = 0 and K = 1. It can be seen that the asymmetries are large, even for such a low polarization.

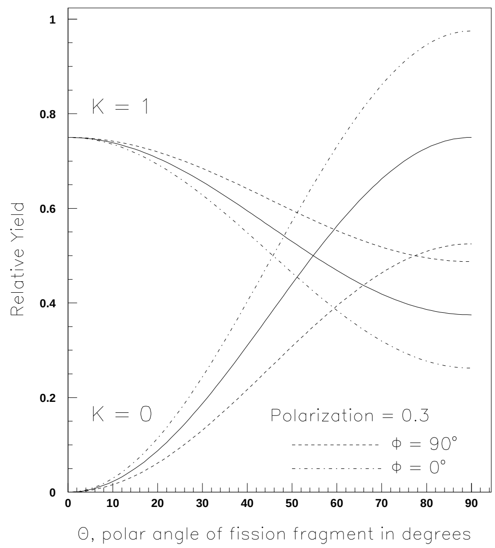

Figure 1: θ distribution of fission fragments with photon beam polarization of 30% for $K = 0, 1$ and $\phi = 0, 90°$. K is the quantum number denoting the projection of the spin of the transition state on the symmetry axis of the deformed fissioning nucleus. Solid lines are for unpolarized photons.

For any target thicker than a few mg/cm^2, of course, the fission fragments are not easily detectable due to their heavy ionization energy loss and resulting short range when traversing the target. The question we wish to address here concerns whether or not the angular asymmetry in the fission fragments is manifest in the angular and energy distributions of the prompt neutrons which they emit, thus providing a possible unique signature for the presence of photofission. Such a technique exploits the unique kinematics of the fission process in conjunction with the relative penetrability of the fission neutrons.

To a very good approximation, the recoiling fission fragments emit neutrons isotropically in their center of mass [5] with a statistical energy distribution. A fully accelerated fission fragment travels with a speed of about 4% of the speed of light. In the center of mass of the fragment, a typical 1 MeV neutron travels with a β of about 4.6% of c. Thus, the neutron energy spectrum measured in the laboratory is a convolution of the "primordial" spectrum which the excited fission fragment emits and the kinematical boost effects due to the fragment recoil.

These effects were examined in a Monte Carlo simulation employing the following assumptions:

- The fission fragment mass distribution was sampled uniformly between $85 < A < 105$ and $130 < A < 150$.
- A fixed amount of total kinetic energy, 175 MeV, is shared between the two fission fragments in a manner consistent with momentum conservation.
- Neutrons are emitted isotropically in the center of mass of the fully accelerated fission fragments with an energy distribution given by:

$$N(E) = \sqrt{E} \exp(-E/0.75) \tag{2}$$

  This reproduces the fission laboratory neutron energy distribution as measured with (n, f).

- The fission fragment angular distribution is sampled in both θ and ϕ as noted previously for either K = 0 or K = 1, and the neutrons were given the appropriate kinematic boost.
- The resulting rate ratio $\frac{N(\theta=\pi/2,\phi=0)}{N(\theta=\pi/2,\phi=\pi/2)}$ is calculated for $P_\gamma = 0.3$. This degree of polarization is commensurate with that attainable using off axis bremsstrahlung, as described below.

For a pure $K = 0$ transition, the resulting ϕ distribution is shown in Fig. . The resulting rate ratio, $\frac{N(\theta=\pi/2,\phi=0)}{N(\theta=\pi/2,\phi=\pi/2)}$ is 1.25, reflecting the angular distribution of the fission fragments as well as the "washing out" effect of the neutrons emitted isotropically in the frame of the fission fragment. This rate ratio is for the case in which there is no cut on the neutron energy. If one imposes the cut $E_n > 2$ MeV in the simulation, the rate ratio rises to 1.37. For the pure $K = 1$ case, the resulting ϕ distribution is also shown in Fig. . The corresponding rate ratio in this case is 0.84 without any neutron energy cut.

The veracity of the above calculations is based on well founded physics, but will need to be confirmed. In the measurements proposed here, fission in actinides will be induced by a bremsstrahlung beam of continuous energy. In practice, fission may proceed via multiple channels, and one cannot directly calculate the expected neutron rate ratios. As such, we propose a complete experimental investigation of the θ and ϕ distributions of the neutron yields for a number of actinides to ascertain the magnitude of the rate ratios and to determine the sensitivity to the presence of fission and the selectivity of the technique to the identity of the target nuclide.

Proposed production of linearly polarized photons

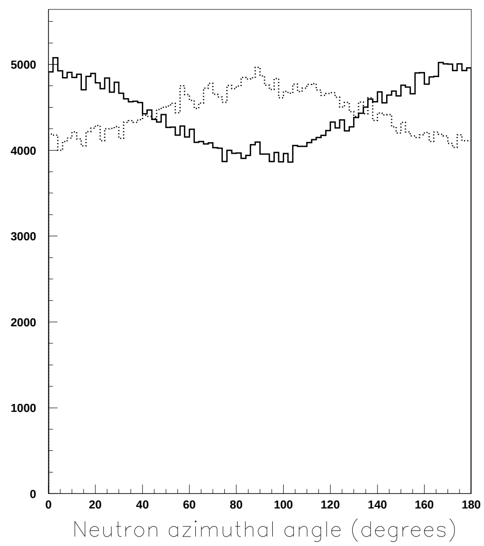

Figure 2: Monte Carlo ϕ distribution of neutrons at $\theta = 90°$. Solid: $K = 0$. Dashed: $K = 1$.

As described in the *Resources and Capabilities* section of this proposal, the experimenters have ready access to a low energy electron linac. The energy of this accelerator is well suited to produce photons in the energy region of the giant dipole resonance of actinides, where the photofission cross section is approximately 1/2 barn. We propose to optimize our existing beamline for the production of linearly polarized bremsstrahlung photons modeled after that constructed by the Geissen group [4]. It is well known that when an electron beam strikes a thin radiator, the resulting bremsstrahlung radiation which lies off axis from the incident beam is polarized as shown in Fig. [4]. If one collimates the photon beam at an angle of $\theta = \frac{m_e c^2}{E_{\text{beam}}}$ where m_e is the rest mass of the electron and E_{beam} is the energy of the incident electron beam, the polarization is maximized. A schematic of the relevant geometry is shown in the Fig. . For such a set up, linear polarizations of the photon beam of around 30% are typical. The rate of the photons as compared to the uncollimated case is decreased by approximately a factor of 20 to 30 due to the photon beam collimation as well as the need for a thin radiator to minimize multiple scattering of the incident electrons. The latter requirement is necessary to preserve the correlation between the angle of the incident electron and the resulting photon so there is a unique relationship between θ and the polarization P_γ.

We propose to optimize our linearly polarized bremsstrahlung beamline and construct a polarimeter to measure its performance. This facility will be used to measure the angular dependence of the photofission neutron yields as a function of the target, the bremsstrahlung endpoint energy, and the neutron energy to evaluate the sensitivity of this technique to the presence of photofission events. A schematic of the proposed experimental setup is shown in Fig. . It consists of a pulsed electron accelerator delivering approximately 14 MeV electrons which are bent 90 degrees in the horizontal plane. In order to change the photon polar-

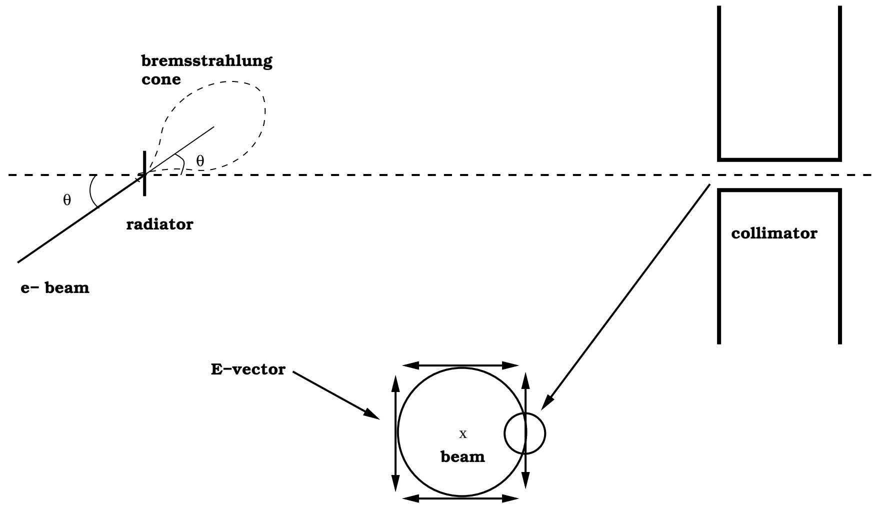

Figure 3: Production of linearly polarized photons by the off axis bremsstrahlung technique. An electron beam strikes a thin ($\sim 10^{-3}$ radiation length) radiator, and a downstream collimator passes photons whose trajectories lie off axis from the incident electron beam. The optimal angle, θ, was chose to be 2° for the proposed experiment to optimize photon intensity and polarization.

ization state, the electrons are then bent up or down in the vertical plane approximately two degrees before they strike a thin (10^{-3} radiation length) bremsstrahlung converter. Approximately 90% of the bremsstrahlung photons propagating down the beamline are contained within a cone having an opening angle three times larger than the characteristic angle ($\theta_c = m_e/E_{\rm beam}$, ignoring multiple scattering effects. A fixed collimator is placed downstream of the bremsstrahlung radiator and is offset in the horizontal plane. This collimator selects bremsstrahlung photons which are off axis from the primary electron beam, and therefore are linearly polarized 45 degrees in a plane with respect to the horizontal, with an orientation depending upon the angle of incidence of the electron beam on the bremsstrahlung radiator. Between the radiator and the collimator, a magnet deflects charged particles in the horizontal plane away from the photon collimator.

The photons exit the vacuum via a thin window at the downstream edge of the collimator on the downstream side of a four foot thick concrete wall. This window serves as a thin converter for a pair spectrometer luminosity monitor which is used for relative normalization of the photon flux in the two polarization states. In addition to the converter, the pair spectrometer consists of a 0.35 T, 20 cm long dipole magnet and two plastic scintillator detectors to measure the electrons and positrons in coincidence. The size of the scintillators will be small in the direction of the dispersive plane of the magnet, thus providing momentum analysis of the electrons and positrons. The yields of the electron-positron pairs will be directly proportional to the photon flux at a photon energy given by the position of the plastic scintillator detectors and the pair spectrometer magnetic field setting, thus providing a relative flux normalization between the two polarizations states. The pair converter thickness, electron and positron detector size and position, and magnetic field setting are chosen to provide electron-positron coincidences for about one out of every ten beam pulses in order to minimize accidental coincidences. Electron-positron timing distributions will be recorded in a time to digital converter (TDC). A schematic of the proposed pair spectrometer is shown in Fig .

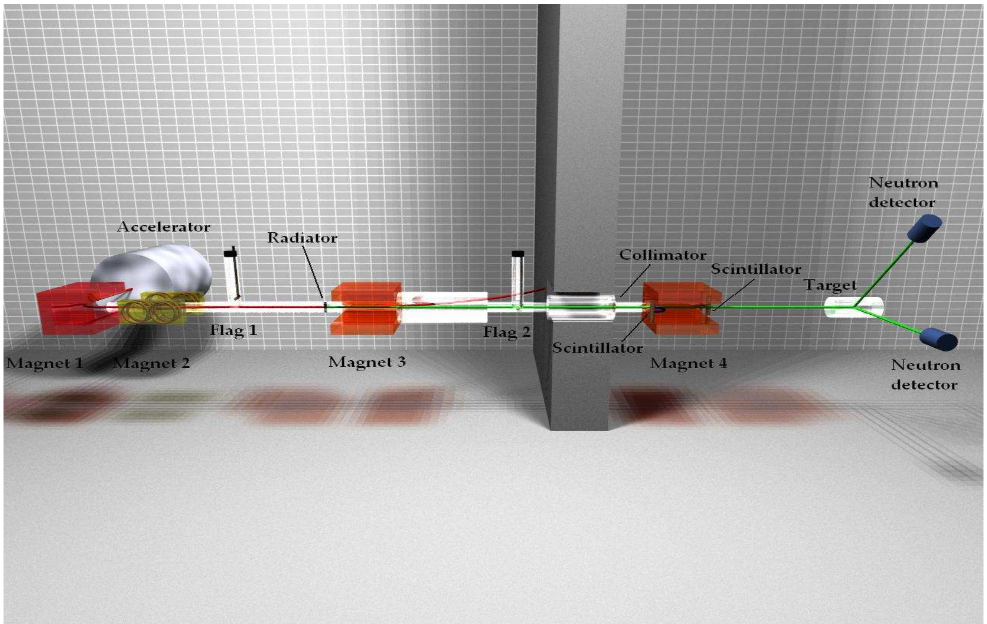

Figure 4: A schematic of the proposed experimental setup. 14 MeV electrons are produced in a linear accelerator (left, back) and bent by a magnet (left, front) 90 degrees in the horizontal plane. They are then bent up or down 2 degrees ($= m_e/E_{\rm beam}$) before impinging on a thin bremsstrahlung radiator. The bremsstrahlung photons then pass through a hole in a wall, consisting of a collimator placed off axis from the electron beam. The photon flux is measured by a pair spectrometer (red magnet to the right of the wall). The resulting polarized photon beam impinges on a target (white), and neutrons are detected at 90 degrees to the beam in plastic scintillator detectors using the time of flight technique.

The physics target will be placed downstream of the pair spectrometer. When polarimetry experiments are being performed, this target will consist either D_2O or H_2O and during production runs will generally be a solid actinide target. Subtracting the measured H_2O neutron rate from the meaured D_2O neutron rate removes the neutron background from Oxygen. A plastic scintillator neutron detector will be placed at an angle of 90 degrees with respect to the beam, at a 45 degree angle from the horizontal plane. This detector will measure the neutron yields as a function of the orientation of the polarization. A second detector will be placed at a 90 degree angle with respect to the beam in the horizontal plane. The purpose of this detector will be to monitor the setup for rate ratio changes unrelated to polarization, and to provide a relative photon flux monitor which is redundant with the pair spectrometer. Neutrons will be identified via the time of flight method, with the start signal coming from the accelerator beam pulse.

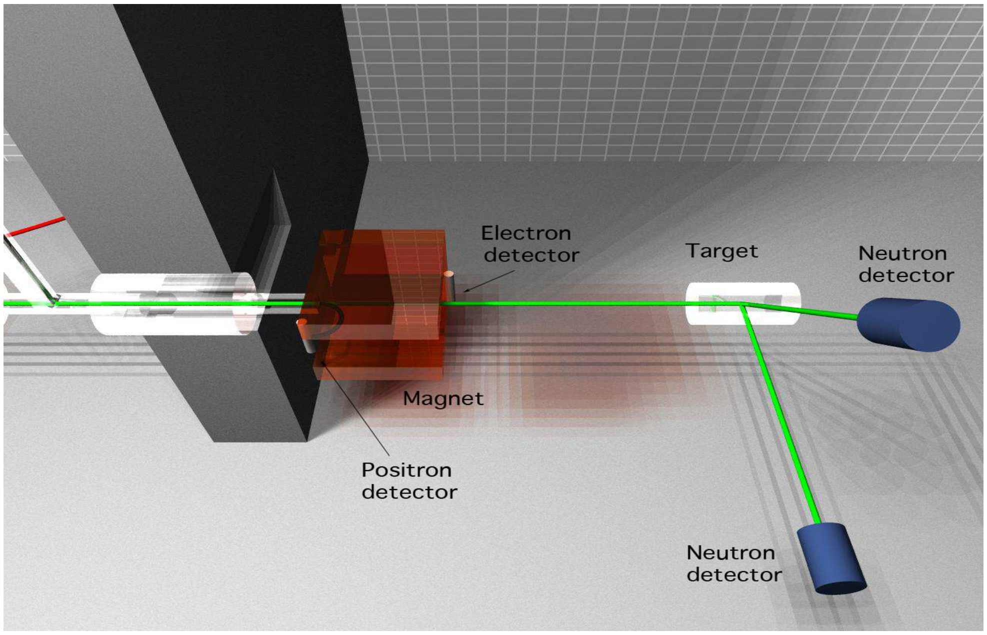

Figure 5: A schematic of the proposed pair spectrometer luminosity monitor (red). Photons entering the experimental hall impinge upon a thin (10^{-3} radiation length) pair converter. Electrons and positrons are momentum analyzed in a magnet, and detected in plastic scintillator detectors. Target (white) and neutron detectors (blue) are also shown.

Milestones

This is a proposed three year project. Key milestones are noted below.

Month	Milestones
12	Acquire and assemble instrumentation: vacuum pipe for electron beam dump, beam dump magnet, exit window/pair converter,radiator, photomultiplier tubes and bases, octal discriminators, 4-fold logic unit.
24	Commission experimental setup, begin measurements.
36	Report on fundamental measurements and provide written technical assessment of potential for applications.

Table 1: Milestones

Timeline and Deliverables

The work plan for this proposed project is as follows:

Month	Deliverable
6	Develop beam diagnostics including two view screens for monitoring the position and angle of the electron beam, and a pair spectrometer photon flux monitor consisting of a converter target, dipole magnet, plastic scintillation detector and associated electronics.
12	Establish beamline for linearly polarized photons. This will consist of the installation of a new vacuum system, a remotely removable bremsstrahlung radiator, coil deflector magnets to deflect the beam up and down two degrees to vary the photon beam polarization, and an off axis photon beam collimator.
20	Verify the production of linearly polarized beam using the high analyzing power of the photodisintegration of the deuteron [6] ($\vec{\gamma} + d \rightarrow n + p$). Here, we will measure the azimuthal dependence of the neutron yields at $\theta_n = 90°$ from deuterated water targets. Backgrounds will be directly measured using an identical setup except with an H_2O target.
24	Measure neutron azimuthal rate ratios for actinides as a function of target, bremsstrahlung endpoint energy, and neutron energy.
30	Measure neutron azimuthal rate ratios for a variety of other targets to investigate the possibility of false positives.
34	Perform an overall assessment of the effectiveness of the technique for safeguards applications.
36	Publish results in peer reviewed journals.

Table 2: Work Plan Timeline

Roles of Participants and Team Qualifications

Participant A - Project Manager, specialist in photonuclear physics:

Participant A has published extensively in the area of photonuclear physics in energy ranges which cover the the giant resonance region to several GeV. This work has been accelerator based and has utilized polarized and unpolarized photons and electrons. He has previously built beamline instrumentation similar to that proposed here, and has been involved in a number of detector development and construction projects.

Participant B - Data analysis coordinator:

Participant B has recently received her PhD in computational physics. Her PhD work involved nuclear resonance vibrational spectroscopy measurements at the Advanced Photon Source in Argonne National Lab. Her experiences include extensive data analysis, including simulations and program optimization. The results of her work were published in peer-reviewed journals as well as presented at the number of conferences. Since joining our group, she performed preliminary calculations for our photofission efforts and mentored students analyzing preliminary data. She will contribute to this proposal by continuing in the above role.

Participant C - Data acquisition manager:

Participant C has a breadth of experience in high precision asymmetry measurements, data acquisition systems, and elementary particle detectors. For over 10 years, participant C has performed and published experiments measuring asymmetries similar to those proposed here. Participant C has a similar level of experience setting up data acquisition systems used by nuclear physics experiments. The above experiences will provide a strong foundation to execute the work within this proposal.

Participant D - Beamline instrumentation:

Participant D has published extensively in the area of photonuclear physics in energy ranges which cover the the giant resonance region to several GeV. He has played a prominent role in establishing, constructing, and calibrating both the photon tagger and the coherent bremsstrahlung facility in Hall B of JLab. He has extensive experience with all aspects of the beamline instrumentation for producing linearly polarized photons.

Three of the above participants have extensive experience in accelerator based experimental physics and nuclear instrumentation. One of the above participants is a new investigator. She has recently joined the group and was involved in previous photofission measurements. In addition to the above personnel, there are two Ph.D. students and one M.S. student currently available and ready to immediately begin their graduate studies on this project. In addition, we plan to recruit another M.S. student for this project.

Work scope challenges and expected innovations:

This project poses a number of technical challenges. It involves the improvement of our existing electron beamline in which the beam can be steered up and down two degrees in order to change the photon polarization state. This will involve a set of coil magnets placed around the beam pipe upstream of the bremsstrahlung radiator. Since we are proposing to measure a yield, a critical aspect of these measurements will involve the relative normalization of the photon flux between the two polarizations states. We propose the construction of a pair spectrometer, which will measure the coincidence between momentum analyzed electrons and positrons which are produced in a thin converter. This will ensure a high precision relative photon flux measurement at the photon energy of interest. Before making measurements on actinide targets, we will unambiguously ascertain that we are producing polarized photons in a reliable fashion by measuring the known rate ratio arising from the photodisintegration of the deuteron [6].

The possibilities of using the azimuthal neutron rate ratios for materials control and accountability hinges upon the results of the fundamental measurements proposed here. If the rate ratios are indeed favorable, one advantage of a set up where the position of the electron beam is alternated with respect to a fixed photon collimator is that target absorption and neutron attenuation and scattering effects are the same for the two polarization states, as the photon beam - target - neutron detector geometry is the same. In the experimental configuration proposed, photons will be produced with two polarizations states, each at 45 degrees with respect to the horizontal. One means of checking for rate ratios unrelated to polarization will be provided by a second neutron detector which will be placed in the horizontal plane where the rate ratio is expected to be unity.

The technique proposed here seeks to exploit the unique kinematics of photofission in the development of a signature for actinides. Should this prove to be a viable technique, we propose to perform a systematic study of a variety of targets of interest to determine the possibility of neutron rate ratios arising from other mechanisms which could potentially cause false positive signals. Here, an investigation of the dependence of the polar angle dependence of the rate ratio (see Fig.) may prove useful as well.

Quality assurance

The procedures used to carry out this research and the results obtained will be documented in refereed journals. In addition, full documentation will be recorded in graduate student theses and dissertations. Laboratory notebooks will be maintained throughout the project and will be available for inspection by the funding agency at any time.

References

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10 pages