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PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 04-23

PD 05-1517 **02/07/06**

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TITLE OF PROPOSED PROJECT **Nanoscale Electron Optics Devices**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ **380,587**	**0** months	**07/01/06**	

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☐ HISTORIC PLACES (GPG II.C.2.j)
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Physics

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CERTIFICATION PAGE

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By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 04-23. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

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Nanostructure Electron Optics Devices
PI: Alex Cronin, University of Arizona

Project Summary:

The goal of this project is to create an electron interferometer using nano-fabricated gratings. This will harness nanotechnology to improve devices in two existing fields: electron holography, and electron-energy-loss spectroscopy. Nanostructures that transmit and diffract low-energy electrons will serve as the electron-optics components needed to make two new sensors: an electron holography microscope with very-low-energy electrons, and an electron-energy-loss spectroscope with ultra-high sensitivity.

Fundamental questions about the electronic properties of materials will also be addressed. For example, the two-body state of a free-electron and its image charge will be studied. The rate of quantum decoherence for electron waves caused by nanoscale surfaces will also be measured. This work combines quantum optics, NEMS, and nano-electronics.

Intellectual Merit:

There is a strong ‘image charge’ interaction between free electrons and nanostructures. Furthermore, for a free electron moving near a surface, an ‘image current’ can cause Joule heating and hence quantum entanglement between the position-state of an electron and the internal electronic and vibrational state of a nanostructure.

By addressing the question “How can nanostructures be used as coherent and efficient beam splitters for electron waves?” this research provides novel ways to study the physics of coulomb drag, the spectrum of plasmon excitations in nanostructures, the connection between dephasing and decoherence due to charge fluctuations, velocity-dependent corrections to the image-charge potential, and electronic resonances in thin metal films.

Broader Impact:

Two new sensors will be developed using nanotechnology for electron optical devices: An energy loss spectrometer and an electron interference microscope. Pioneering the use of nanoscale electron optics components for these devices is important for understanding fundamental limitations to quantum computation and nanoscale electronics.

Graduate and undergraduate education is another broad impact of this work. Two graduate students (one female) and two undergraduates (one female) will develop these nanostructure electron optics systems. This research also stimulates interaction between the College of Optical Sciences, the School of Engineering, and the Physics Department. Additionally, our lab gives over 45 tours a year to high school, college, and PhD level visitors whom we teach about nanotechnology and matter wave optics.

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References Cited	3	
Biographical Sketches (Not to exceed 2 pages each)	2	
Budget (Plus up to 3 pages of budget justification)	6	
Current and Pending Support	1	
Facilities, Equipment and Other Resources	2	
Special Information/Supplementary Documentation	0	
Appendix (List below.) **(Include only if allowed by a specific program announcement/ solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**		

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Nanostructure Electron Optics Devices

Recent Results

We recently used nanofabricated gratings to observe electron diffraction. These results are encouraging evidence that nanostructures can be used as coherent electron optics devices.

The 100-nm period gold-coated silicon nitride nanostructures were used to observe diffraction of 500 eV ($\lambda_{dB} = 10^{-11}$ m) electrons that were transmitted through the gratings (McMorran 2006). Now we can use electron diffraction to study nanostructures themselves, and also to study the electron-nanostructure interactions. We already showed that nanofabricated gratings are very efficient beam splitters for low-energy electrons if the nanostructures have free-standing bars. Furthermore, **to explain the asymmetric diffraction patterns (Figures 1 and 2) we developed a theory of diffraction that incorporates an electron-surface 'image charge' interaction.**

Images of the nano-gratings and a sketch of the geometry used to diffract electrons are shown in Figures 3, 4, and 5. Figure 6 shows a simulation of electron wave propagation in the very near field during passage through a nano-grating. This simulation highlights the idea that phase shifts are caused by a potential energy landscape for electrons around the nanostructures. To complete our theoretical model for electron diffraction, the far-field wave function (used to calculate the electron flux in Figures 1 and 2) is calculated by a Fourier transform of the transmitted electron waves shown in Figure 6.

Now we are motivated to build a new electron holography machine based on these nanostructures to learn see how nanostructures can revolutionize existing electron optics technologies. First, several fundamental questions must be addressed.

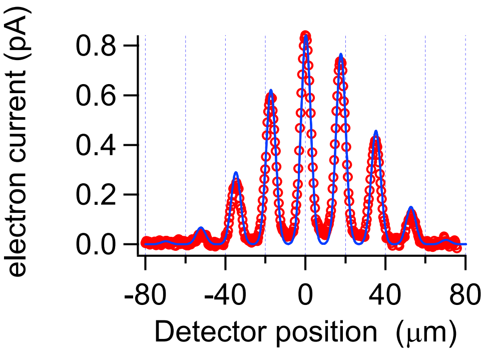


Figure 1.
Diffraction of 500 eV ($\lambda_{dB} = 10^{-11}$ m) electrons from 100-nm period nanostructure gratings at an incident angle of +11 degrees. The theory (blue curve) includes the image-charge effect (McMorran 2006).

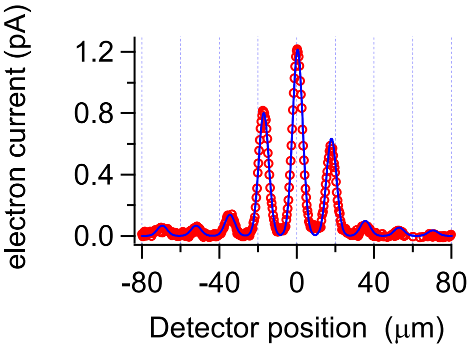


Figure 2.
Similar to Fig. 1, but an incident angle of -4 degrees.

Recent Results (continued)

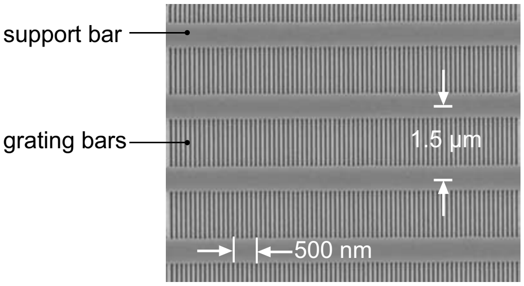


Figure 3.
SEM image of a nano-structure grating. For fabrication of the nanostructures see (Savas 1995), and (Savas 1996).

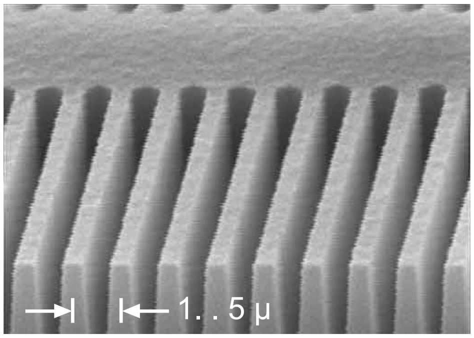


Figure 4.

SEM image of free-standing bars in cross-section. The perforations go entirely through the structure.

Figure 5.

The modified electron microscope configuration. This setup generated the diffraction patterns shown in Figures 1 and 2. (McMorran 2005)

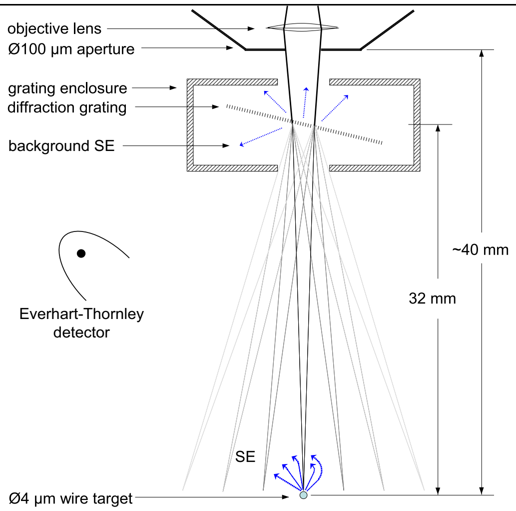
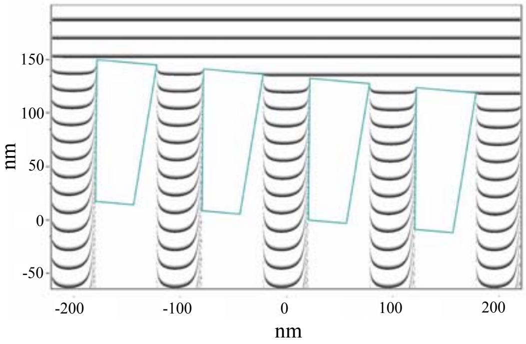


Figure 6.

Simulation of electron de Broglie waves propagating from top to bottom through a nanostructure grating. Phase fronts are shown in black, nanostructure grating bars are shown in blue. Interactions between free electron waves and the trapezoidal bars cause phase shifts that lead to asymmetric diffraction patterns. The electron de Broglie wavelength is exaggerated 1000 times in this figure.



Motivation: Interaction between nanostructures and free electrons

In (McMorran 2006) we considered only an attractive 'image charge' potential for electrons that is non-dissipative and independent of electron velocity. The potential is:

$$U = -\left(\frac{e^2}{4\pi\varepsilon_0}\right)\left(\frac{\varepsilon-1}{\varepsilon+1}\right)\left(\frac{1}{2r_1}+\frac{1}{2r_2}\right) \qquad \text{Eq. 1}$$

in S.I. units where $r_{1(2)}$ represents the distance to the surfaces of the nearest two grating bars and ε is the static dielectric constant of the bars. Since the grating slots are 50 nm wide, the transmitted electrons must pass within 25 nm of one surface or another. Hence the interaction energy is large. At 10 nm, for example, if $|\varepsilon|>>1$, then U is 80 meV. This is 25,000 times stronger than the van der Waals interaction that we measured between a neutral sodium atom and the grating bars (Cronin 2004, Perreault 2005a, 2005b, 2006). The force on the electrons at 10 nm is 0.6 pN towards the surface (this is 10^{17} times an electron's weight, and 6000 times the vdW force on atoms at the same distance from). Due to quantum and thermal fluctuations in U, it will be surprising if the diffraction is 100% coherent. It also is expected that U can depend on velocity.

(Note: if electrons hit the bars, they are inelastically scattered after a few angstroms. Hence the diffraction patterns are due to the electrons passing through the grating channels where they have the potential U. We therefore have a very pure system – a free electron in vacuum several nm from a metal-coated surface.)

The theoretical method of images is not completely justified for analyzing these experiments because the situation is not time-independent. Each electron spends only 10^{-14} seconds inside the grating structure (the velocity of 500 eV electrons is 1.3 x 10^7 m/s, and these gratings are 150 nm thick). This is close to the inverse plasma frequency, $\omega_p^{-1}= 10^{16}$ s, in most metals. Hence the material polarization may lag the electron's passage. Furthermore, the electron sea in the nanostructures can fluctuate. Dozens of theoretical articles offer more detailed studies of a moving charge interacting with a nearby solid; now we have a new experimental tool to study predictions such as:

- The potential U depends on electron velocity and deviates from the $1/r$ power law.
- Energy can be transferred to the nano-structure.
- A reaction force in the direction opposite velocity may exist.
- Finite conductivity nano-gratings will cause decoherence of electron waves.

These predictions – and our proposed tests – are outlined next.
Then, our experimental plans to observe these effects are discussed in more detail.
Finally, some distinctions from related techniques (biprism, LEED, RHEED, EELS) are discussed. We conclude by emphasizing how electron optics with nanostructures will enable new fundamental investigations and will lead to new technologies in nano-electronics and electron optics.

Discussion of 3 Theoretical Questions

1. Modified 'image charge' potential

Schieber (1998) predicted the attractive force normal to the surface can increase for a point charge moving over a dielectric. In his prediction the force peaks in the vicinity of the Chrenkov condition, i.e. when $v = c/\sqrt{\varepsilon}$, as indicated in Figure 8.

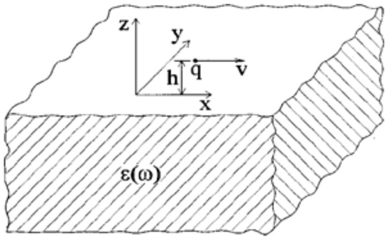
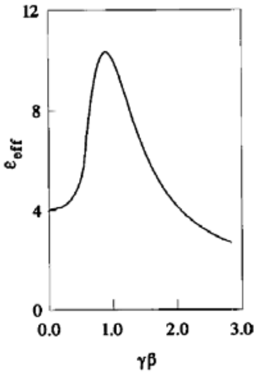


Figure 7.
Schematic of the system under consideration, taken from (Schieber 1998). In this proposal the material is a nano-grating bar

Figure 8. (right)

Chart taken from (Shcieber 1998) predicting how $F_z(v)$ can be described by an effective dielectric constant "measured" by the moving particle as a function of its velocity.



It is noteworthy that Schieber (1998) considers the material dielectric constant to be independent of frequency. It is solely the physics of Chrenkov radiation in the material that is responsible for the enhancement of the conservative image-charge potential. For metals, Schieber (1998) offers a different prediction shown in Figure 9.

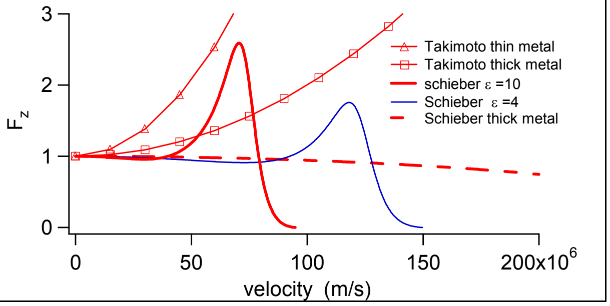
Takimoto (1966), Echenique (1975) , Muscat (1977), and Rivacoba (2000) each discuss modifications to the image-charge potential due to the frequency-dependent dielectric constant of materials. They expand the polarization field in the material in Fourier components, starting with the free-electron Drude model summarized by Jackson (1975) and (Ordal 1983). Here the well-known description of $\varepsilon(\omega)$ begins:

$$\varepsilon(\omega) \;=\; 1 + i\frac{Ne^2}{m\varepsilon_0\omega(\gamma - i\omega)} \;\approx\; 1 - \frac{\omega_p^2}{\omega^2} \qquad \text{with} \qquad \omega_p^2 \equiv \frac{Ne^2}{\varepsilon_0 m}.$$

The normal component of the force F_z is then calculated under several different assumptions, leading to the different predictions shown in Figure 9.

Figure 9.

Various predictions for the normal force F_z as a function of charge velocity. F_z is normalized to $-\nabla U$, with U given by Equation 1.



In our proposed experiments with silicon nitride nanostructures, the $\varepsilon(0)$ in the bulk material is 4 (Bruhl 2002). Therefore Schiebner's prediction would lead to an increase by a factor of 1.5 for U for 25 keV electrons as compared to 500 eV electrons. **Measurements of $F_z(v)$ that can distinguish between the theories plotted in Figure 9 will be made using an electron interferometer.**

2. Electronic Friction from Nanostructures

It was also shown by Takimoto (1966) that a point charge e moving with velocity v in a direction parallel to a metal film a distance z_0 away will excite plasmons in the material, and as a result there will be a reaction force on the charge given approximately by

$$F_x = -\hat{v}\left(\frac{e}{2z_0}\right)^2 \left(\frac{\pi}{8}\right)^{\frac{1}{2}} \left(\frac{\sqrt{2}\omega_p z_0}{v}\right)^{\frac{3}{2}} \exp\left(\frac{-\sqrt{2}\omega_p z_0}{v}\right).$$

Several more theoretical predictions on Coulomb drag are (Gramila 1991, 1993, 1994, Giordano 1994, Flensberg 1995, Laikhtman 1990, Solomon, 1989, Sivan 1992) as well as the previously mentioned references (Schiebner 1998, Echenique 1975 , Muscat 1977, Rivacoba 2000).

For conditions we can create experimentally using nanotechlology, the predicted drag force, F_x, ranges from 10^{-6} to10^{-1} times the normal force, F_z. Since the plasmon density of states is peaked about a specific energy $\hbar\omega_p$, the rate of excitation (Γ_{ex}) can be found from equating $-F_x \cdot v = \hbar\omega_p \Gamma_{ex}$. The probability P of exciting a plasmon can then be found from

$$P = \Gamma_{ex} t = \frac{F_x \cdot \ell}{\hbar\omega_p}$$

where t is the time of flight through the nanostructure with thickness $\ell = 150$ nm.

If the plasmon spectrum is sharply peaked at $\hbar\omega_p = 10$ eV, then even the largest drag force predicted by Takimoto causes a plasmon excitation rate of $\Gamma_{ex} = 10^{12}$ sec^{-1}, and this is too slow to excite plasmons in nanostructures. However, if energy can be transferred to the nanostructure in quanta of less than $\hbar\omega_p = 0.1$ eV, then **Coulomb drag will change the electron's deBroglie wavelength**. An electron interferometer of the type proposed here will be an extremely sensitive device to search for low energy plasmon excitation or other mechanisms of energy loss.

In our proposed electron interferometer, if all the electrons in one branch of the interferometer loose an energy of $\delta E > E\lambda_{dB}/L$ where L is the length to the output of the interferometer then the fringes will be shifted by half a cycle. Here E is the electron energy, and λ_{dB} is the electron de Broglie wavelength. For a 1 meter interferometer and 500 eV electrons, this means an **easily detected phase shift of π given a miniscule energy loss of $\delta E = 5 \times 10^{-9}$ eV.**

Even more dramatically, the interference fringes would have no contrast left if the position of an electron is shifted by a displacement on the order of the longitudinal coherence length $\sigma_x = \lambda_{dB}(E/\Delta E)^{1/2}$ of the electrons. Here ΔE is the energy spread of the electron beam. In our proposed experiment (ΔE= 1eV), contrast would be lost entirely if δE is 10^{-4} eV.

This proposal will enable energy loss spectroscopy with a resolution of 10^{-9} eV. This will be tremendously more sensitive than state of the art electron energy loss spectroscopy (EELS) that currently can resolve energy losses of 0.2 eV (Kimoto 2005, Alexandrou 2005).

3. Quantum Decoherence

Figure 10 shows the picture proposed by Anglin (1997) in which the image charges due to two components of an electron's wave function are both dragged through a metal resistivity ρ. Joule heating in the metal is predicted to cause decoherence of the electron wave function. In our proposal we will consider decoherence caused by the nanostructure grating in the middle of a 3-grating interferometer. Here each electron in the interferometer will be in a coherent superposition of states located some distance $\Delta x = 100$ nm to 10 μm apart.

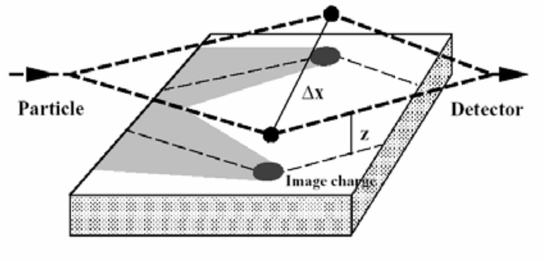


Figure 10.

Anglin's idea for decoherence due to image currents. Figure taken from (Anglin 1997). In our proposal several bars of the nano-grating will fit in-between the two paths of the electron probability current. But the same conundrum exists: Will the nanostructure record which path the electron took?

Anglin's proposal has just recently been investigated by the Hasselbach group (Sonnentag 2005) using a bi-prism interferometer and a 1-cm long slab of material located 15 to 45 micrometers from the electron paths. So, in Table I we compare Haselbach's geometry to our proposed geometry and see that electrons in our gratings should be influenced by much stronger interactions on the nanometer (not micrometer) scale. Therefore we can explore the transition from zero to nearly complete decoherence by changing the size of the superposition in our interferometer. Anglin predicts the decoherence time (i.e. the lifetime for electrons to exist in a coherent superposition of states) is

$$\tau_d = \frac{4h^2 z^3}{\pi e^2 k_b T \rho \left(\Delta x\right)^2}$$

Where T is temperature and ρ is the resistivity of the material. Also, the contrast in the interferometer is predicted to be $C = \exp(-\tau_d / t)$ where t is the interaction time with the solid.

Factor	***Hasselbach experiment***	***This Proposal***
z	15 μm	10 nm
Δx	10 μm	100 nm (TLI) to 1 um (MZ)
τ_d	1 nsec (measured)	0.1 to 10 fsec (predicted)
v	0.1 c	Same
Interaction length	1 cm	150 nm
Contrast	variable (measured)	Ranging from 0 to 50% (predicted)

Table 1. Comparison of decoherence times and interaction lengths for Hasselbach's experiment and this proposal. TLI referrs to the Talbot Lau interferometer regime, and MZ refers to the Mach-Zehnder regime.

This proposed experiment is similar to earlier work by the PI on matter-wave decoherence (Uys 2005, Cronin 2003, Kokorowski 2001), but in this case it is the electronic activity of nanostructures themselves that will be investigated. An alternative viewpoint based on dephasing due to e^--e^- interactions is presented by Seelig (2001). **In either view, It is attractive to use free electrons to study decoherence because for elementary particles the interactions with their environment are in principle so simple compared to more complex compound particles like atoms and molecules.**

Experimental Approach

An interferometer for electron waves based on a system of nano-gratings is shown in Figure 11. Modifications to *U*, Coulomb drag, and decoherence will all be studied with this system.

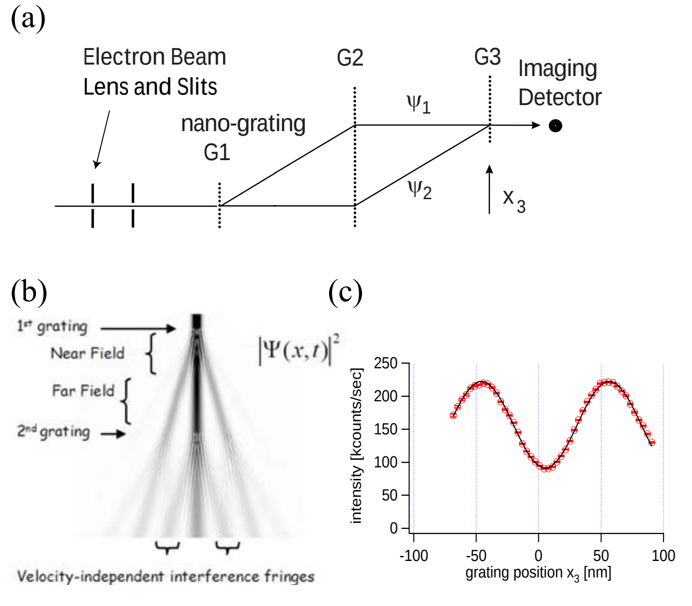


Figure 11.

(a) Sketch of an interferometer based on nano-gratings G1, G2, and G3.

(b) Simulation of matter-wave interference based on the split-step Fourier numerical method for solving the Schroedinger equation. The third nano-grating will be translated along x_3 in the plane where fringes in $|\psi|^2$ are predicted.

(c) Observed *atom* wave interference pattern using three nano-gratings. The main question in this proposal is "Can we generate such clear fringes due to quantum interference of electrons with a system of nanostructures for electron optics?"

The image potential *U* will cause a relative phase shift for the diffracted beams ψ_1 and ψ_2. This will make the interferograms either side of Figure 11b out of phase. The PI has already proven this is a sensitive way to measure *U* for atom-nanostructure interactions (Perreault 2006). Now we propose to measure *U* for electrons as a function of velocity using this technique. Modifications to Talbot Lau interferometer contrast due to U are also expected (Brezger 2002)

Coulomb drag, if it acts equally on both ψ_1 and ψ_2 will change the period of the fringes in $|\psi|^2$, because the de Broglie wavelength shifted. In our experiments 1,000 grating periods will be illuminated (with a 100 μm wide beam at G3), so a small change to the fringe period will cause a moiré pattern due to transmission through the third "analyzing" nano-grating. This moiré pattern will be imaged with a 5 um resolution imaging detector, and will be monitored as a function of electron velocity and applied electric fields.

Decoherence can be interpreted as a statistical fluctuation in the difference of Coulomb drag on ψ_1 and ψ_2. This will reduce the fringe contrast. As in the theory of the Feynman's gedanken Heisenberg microscope, if the plasmon wavelength is larger than the separation Δx, then a record of which path the electron took ("ψ_1 *or* ψ_2") will be left in the second grating, and interference fringe contrast will be lost. Note, Δx will be varied by changing the electron velocity, and also by building the interferometer with gratings G1, G2, G3 separated by distances as short as the Talbot length (Bermann 1997) ($L_T = d^2/\lambda = 2$ mm in this experiment, so that Δx is 100 nm), or by much larger distances (up to 1 meter) in which case Δx can be increased to 50 μm – a truly macroscopic wavefunction for an electron.

An auxilliary grating that interacts only with ψ_1 *or* ψ_2 will be used to study phase shifts due to *U* and decoherence due to dissipation. Note: the PI has recently performed a similar experiment with atom waves (Perreault 2005b).

If the nano-grating electron interferometer functions perfectly, i.e. with no decoherence, then we can use this nanostructure device for several new experiments: low energy electrons are needed for a first-ever demonstration of the scalar AB effect (Aharonov 1959); measurements of the phase shift due to an auxiliary grating will be an ultra precise way to measure *U* due to nanostructure surfaces (see Perreault 2005b); and measurements of the index of refraction for electrons due to a dilute gas of atoms will measure the real part of the electron-atom scattering amplitude (Forrey 1999). A brief list intended to give a feel for the numerous applications of an electron interferometer based on nanostructures is given in Table II.

Applications for nanostructures in electron optics:

- Coherent beam splitters for electron holography (Gabor 1949, Tonomura 1987, 89, 94, 99)
- Talbot effect to generate more, smaller nanostructures (Bermann 1997)
- Smith Purcell effect to generate sub-millimeter wavelength radiation (Smith 1953, Wachtel 1979)
- Demonstrate the scalar Ahanonov-Bohm effect for electrons (Aharonov 1959)
- Electron wave index of refraction due to dilute gases of atoms and thin films (Forrey 1999)
- Search for velocity-dependent image charge potential
  (Takimoto 1966, Schiebner 1997, Echenique 1975 , Muscat 1977, Rivacoba 2000)
- Measure the Decoherence time for electrons near surfaces (Anglin 1997)
- Ultra-sensitive electron energy loss spectroscopy
- Measure plasmon excitation probability and plasmon spectrum (see Coulomb drag references)
- Study phase shifts and energy loss due to an auxiliary 'interaction grating' (Perreault 2005b)

Table II. A list of experiments possible with a nano-structure based electron interferometer.

If, in the other extreme, the nano-grating electron interferometer will not render fringes at all, then we will perform experiments studying how transmission through one and two nano-gratings causes coherence to be lost from the near-field (where ψ_1 and ψ_2 must be coherent to make the recently observed diffraction patterns) to the far-field where, as Anglin and Zurek predict, decoherence occurs more rapidly.

The basic expectation is that the nano-grating interferometers for electrons will let us explore the onset of decoherence. Then we will study the image charge potential, plasmon excitation, coulomb drag, and decoherence due to nanostructures acting on free electron waves.

Distinction from other electron optics techniques

Electron diffraction was demonstrated by (Davisson 1927) and an interferometer based on three crystal diffraction gratings was built by (Marton 1952, 1954). However this interferometer design was not used for many experiments, in part because of low transmission efficiency and contrast. Our nano-gratings have relatively high transmission efficiency, even for low-energy (500 eV), electrons because of the complete perforations between free-standing bars. This overcomes the signal and contrast limitations of crystal-based interferometers. Nanofabricated gratings based on thin gold strips on thin organic films were developed by (Jönsson 1974) but their regularity was poor. Partial perforations in materials can serve as phase gratings for high energy (100 keV) elelectrons (Ito 1993, 1998) but these also have not yet been used for interferometry.

The biprism, invented by (Mollenstedt 1955) has been the main tool for electron holography and interferometry (Tonomura 1987, 1989, 1994, 1999). However, a large transverse electron coherence length is required at the plane of the biprism and therefore this device normally requires a 'coherent' field emission electron gun. The use of nanostructure gratings as beam splitters will reduce the demands on electron wave transverse coherence length (since it is an amplitude division as opposed to a wave front division technique). This will permit use of much more economical tungsten filament sources (as was used to generate Figures 1 and 2) and will also permit higher fluxes to be used. These advantages were discussed by (Mertens 1999) who concluded that, "the main factor presently hampering the formation of high contrast hologram fringes is the quality of the beam splitter". This proposal is devoted to characterizing nano-structure gratings that will serve as a better splitter for new types of interferometers.

To distinguish this work from established techniques of Low Energy Electron Diffraction (LEED) and Electron Back Scatter Diffraction (EBSD), let it be emphasized that LEED and EBSD work in refection mode. The refection geometry in LEED and EBSD setups is not amenable to the interferometer arrangements used by Mertens (1999) or proposed by (Matteucci 1981, Missiroli 1981, Pozzi 1977, 1983) Also, while similar gratings have been used for Low Energy Electron Beam Proximity Projection Lithography (LEEPL) (Yoshizawa 2002), LEEPL takes place in the extreme near-field with the goal of minimizing diffraction effects. Here we seek to emphasize diffraction effects to learn more about electron-surface interactions.

Electronics Photonics and Device Technology Research Criterion

Using nano-gratings as coherent electron optics devices will enable new measurements in solid state and electron-wave physics. Electronic activity of nanostructures will be investigated by directly monitoring the de Broglie wave phase of electron waves, thus an extremely sensitive form of electron energy loss spectroscopy will be developed. This has direct application to the study of ballistic electrons in mesoscopic and nano-electronic devices, and will lead to deeper understanding of the limitations to quantum computation, quantum information processing, and nano-electronics. This research will produce new quantum optics technologies by exploiting nanostructures to make a new kind of electron interferometer.

Intellectual Merit:

Nanoscale image-charge effects in electron optics will be understood in terms of quantum decoherence, plasmon excitation, Coulomb drag, and electronic resonances in thin films.

Broader Impact:

In addition to pioneering new electron optics devices and establishing new nano-electronic measurement techniques, education of graduate and undergraduate students is another broad impact of this work. Two graduate students (one female) and two undergraduates (one female) will work on this research. Our lab also gives over 45 tours a year to classes and visitors whom we teach about nanotechnology and electron (and atom) optics. This research will enhance existing collaborations between the PI and physicists at MIT, the University of Lincoln, Nebraska, and Arizona State University. The PI also collaborates on related projects with researchers at the College of Optical Sciences, the Department of Engineering, and the department of Chemistry at the University of Arizona.

Conclusion

Under this proposal, coherent electron optics techniques will be used to study electronic properties of nanostructures. A new type of electron interferometer will be created using three nano-scale grating structures, and this will enable new technologies such as low-energy electron holography. By directly monitoring the de Broglie wave phase of electron waves, an extremely sensitive form of electron energy loss spectroscopy will be developed. This will teach us about image-charge effects in electron optics, quantum decoherence, plasmon excitation, coulomb drag, and velocity-dependent corrections to the image-charge potential.

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Professional Preparation

Univ. of Arizona Asst. Professor of Optical Sciences	2004-Present
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Postdoctoral Fellowship with D.E. Pritchard, M.I.T.	1999 – 2002
Consultant, Amadon Labs (telecommunications)	2001
TeraBeam Corp., Product Inventor, Product Manager	1998

Honors

Outstanding Undergraduate Teaching Award, U.A.	2005
Dahlstrom Award for Excellence in Experimental Physics, U.W.	1998
NSF Graduate Research Fellowship	1995-1998
ARCS Graduate Research Fellowship	1994-1997
Shell Foundation Fellowship U.W.	1994
Undergraduate Research Opportunity Grant, Stanford	1992

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Synergistic Activities

University of Arizona, AMO Network coordinator	2004 - present
New Enterprises, Sloan School of Business,	2000
Entrepenurial Business Policy, U.W. School of Business,	1997
Union of Concerned Scientists	1999 – present

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SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION **University of Arizona**	**FOR NSF USE ONLY** PROPOSAL NO.	DURATION (months) Proposed	 Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Alex D Cronin**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Alex D Cronin - none**	1.00	0.00	0.00	$ 7,183	$
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)	1.00	0.00	0.00	7,183	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (**1**) GRADUATE STUDENTS				22,605	
4. (**2**) UNDERGRADUATE STUDENTS				10,000	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (**0**) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				39,788	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				9,396	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				49,184	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
Channeltron Detector System $ 14,000					
Data Acquisition Computer 7,000					
Electron Gun System 12,000					
Others (See Budget Comments Page...) 55,000					
TOTAL EQUIPMENT				88,000	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (**2**) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				15,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				1,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				16,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				154,184	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 51.0000, Base: 61460)**					
TOTAL INDIRECT COSTS (F&A)				31,345	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				185,529	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.C.6.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 185,529	$

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME **Alex D Cronin**	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET COMMENTS - Year 1

** D- Equipment
Fast Oscilloscope (Amount: $ 7000)
Ion Pump (Amount: $ 5000)
MCP imaging detector (Amount: $ 12000)
Nanostructure grating set (Amount: $ 10000)
Turbomolecular pump (Amount: $ 15000)
Ultra-Stable Power Supply System (Amount: $ 6000)

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION **University of Arizona**	**FOR NSF USE ONLY** PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Alex D Cronin**	AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Alex D Cronin - none**	1.00	0.00	0.00	$ 7,183	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	1.00	0.00	0.00	7,183	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				22,605	
4. (2) UNDERGRADUATE STUDENTS				10,000	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				39,788	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				9,396	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				49,184	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (2) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				15,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				1,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				16,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				66,184	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 51.0000, Base: 61460)**					
TOTAL INDIRECT COSTS (F&A)				31,345	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				97,529	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.C.6.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 97,529	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $		
PI/PD NAME **Alex D Cronin**	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

YEAR 3

	FOR NSF USE ONLY		
ORGANIZATION **University of Arizona**	PROPOSAL NO.	DURATION (months)	
		Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Alex D Cronin**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Alex D Cronin - none**	1.00	0.00	0.00	$ 7,183	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	1.00	0.00	0.00	7,183	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				22,605	
4. (2) UNDERGRADUATE STUDENTS				10,000	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				39,788	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				9,396	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				49,184	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (2) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				15,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				1,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				16,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				66,184	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 51.0000, Base: 61460)**					
TOTAL INDIRECT COSTS (F&A)				31,345	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				97,529	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.C.6.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 97,529	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $		
PI/PD NAME **Alex D Cronin**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION **University of Arizona**	FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	 Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Alex D Cronin**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Alex D Cronin - none	3.00	0.00	0.00	$ 21,549	$
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	3.00	0.00	0.00	21,549	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL ASSOCIATES	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (3) GRADUATE STUDENTS				67,815	
4. (6) UNDERGRADUATE STUDENTS				30,000	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				119,364	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				28,188	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				147,552	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) $ 88,000					
TOTAL EQUIPMENT				88,000	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				3,000	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (6) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				45,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				3,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				48,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				286,552	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				94,035	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				380,587	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPG II.C.6.j.)				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 380,587	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $

PI/PD NAME **Alex D Cronin**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

C ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

Budget Justification Page

Funding for one graduate student and two undergraduate research assistants is requested. The undergraduates will be paid stipends of $5000 each for work during the accademic year and summer. One month of PI summer salary is included in the budget.

Travel expenses will be used for attendance for two students at the DAMOP, the March meeting of the APS, and a conference on Quantum Electronics.

The largest equipment costs are all listed on the budget for the first year. These include:

Nanostructure grating set	**$ 10,000**
Electron Gun System	**$ 12,000**
Fast Oscilloscope	**$ 7,000**
Turbomolecular pump	**$ 15,000**
Ion Pump	**$ 5,000**
MCP imaging detector	**$ 12,000**
Ultra-Stable Power Supply	**$ 6,000**
Channeltron Detector System	**$ 14,000**
Data Acquisition Computer	**$ 7,000**

A description of each of these large equipment items follows. The nanostructure grating set will be fabricated at the MIT nanostructures facility by T.A. Savas. The cost of the set is a nominal charge to defray the clean room and materials expenses incurred during fabrication of the nanostructure gratings. The electron gun system includes a precision lens system and power supply from Kimball physics. The fast oscilloscope from Tektronix includes a fast charge-sensitive preamplifier for detecting single-electron events on a custom CEM detector system. The turbomolecular pump from Varian Vacuum systems is needed to evacuate the electron interferometer machine.The ion pump from Varian Vacuum systems is needed for vibration-free operation. The ultra-stable power supply system from HP is needed to operate the custom-built electron beam system lenses. The channeltron detector system from Ampteck is needed to monitor fast changes in electron beam flux to the various interferometer output ports. The MCP imaging detector from Colutron is needed for high precision observation of diffraction patterns and interference fringes in space. The data acquisition computer, equipped with Labview hardware and software from National Instruments is required to log the data from the electron interferometer machine.

Additional equipment costs, listed under materials and supplies, are for vacuum system components, electronics, and translation systems for the electron beam experiments.

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: **Alex Cronin**

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Atom Wave Phase shifts due to atom-surface Interactions**

Source of Support: **Research Corporation**

Total Award Amount: $ **35,000** Total Award Period Covered: **06/01/03 - 06/01/06**

Location of Project: **University of Arizona**

Person-Months Per Year Committed to the Project. Cal: **1.00** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **New Applications for Atom Interferometry using New Applications for Atom Interferometry using New Applications for Atom Interferometry using Material Gratings**

Source of Support: **NSF PHY-0354947**

Total Award Amount: $ **420,000** Total Award Period Covered: **06/01/04 - 05/31/07**

Location of Project: **University of Arizona**

Person-Months Per Year Committed to the Project. Cal: **4.00** Acad: **0.00** Sumr: **0.00**

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **Collaborative Research: Acquisition of an Atom Interferometer/Diffractometer for Materials Research and Education**

Source of Support: **NSF DMR**

Total Award Amount: $ **49,000** Total Award Period Covered: **05/15/05 - 11/05/06**

Location of Project: **University of Arizona and Arizona State University**

Person-Months Per Year Committed to the Project. Cal: **2.00** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: **This Proposal: Nanostructure Electron Optics Devices**

Source of Support: **NSF EPDT**

Total Award Amount: $ **0** Total Award Period Covered: **07/01/06 - 06/30/09**

Location of Project: **University of Arizona**

Person-Months Per Year Committed to the Project. Cal: **2.00** Acad: **0.00** Sumr: **0.00**

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

USE ADDITIONAL SHEETS AS NECESSARY

FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. USE additional pages as necessary.

Laboratory: **The PI operates an atom beam interferometer in one laboratory and an electron beam machine in a separate laboratory in the U. of Arizona physics department. A large supply of vacuum equipment components and support electronics is already available in these laboratories.**

Clinical:

Animal:

Computer: **Seven computers are already in the lab for data acquisition, analysis, manuscript editing, and electronic archiving.**

Office: **The office of the PI is five doors away from the matter-wave interferometry labs. Office space for 5 students is located next door to the laboratories.**

Other: **There is an electron microscope facility, an atomic force microscopy laboratory, a professional machine shop and a microelectroncs facility nearby. The PI has used each of these facilities to characterize the nanostructure diffraction gratings. The student shop facility is also heavily used for this research.**

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate identifying the location and pertinent capabilities of each.

A 5-meter long atom beam interferometer machine is in opperation in our lab. The machine was partially constructed at MIT where the PI was a postdoc with Dave Pritchard. The machine is versatile and has been significantly rebuilt in Tucson for new experiments.

We also have a modified ISI electron microscope that is currently being used to create the electron beam for this research.

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual arrangements with other organizations.

The Optical Sciences Center on this campus has four PIs who are helpful resources for problem solving and collaboration in this research. The Gould-Simpson instrument shop will machine and weld parts for us. The Nanostructures laboratory at MIT is prepared to supply and modify additional gratings as needed.

FACILITIES, EQUIPMENT & OTHER RESOURCES

Continuation Page:

LABORATORY FACILITIES (continued):

OTHER FACILITIES (continued):

MAJOR EQUIPMENT (continued):