ABSTRACT for CWS 2002, Chernogolovka, Russia
Ulf Israelsson

Use of the International Space Station for Fundamental Physics Research

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NASA's research plans aboard the International Space Station (ISS) are discussed. Experiments in low temperature physics and atomic physics are planned to commence in late 2005. Experiments in gravitational physics are planned to begin in 2007. A low temperature microgravity physics facility is under development for the low temperature and gravitation experiments. The facility provides a 2 K environment for two instruments and an operational lifetime of 4.5 months. Each instrument will be capable of accomplishing a primary investigation and one or more guest investigations. Experiments on the first flight will study non-equilibrium phenomena near the superfluid 4He transition and measure scaling parameters near the 3He critical point. Experiments on the second flight will investigate boundary effects near the superfluid 4He transition and perform a red-shift test of Einstein's theory of general relativity. Follow-on flights of the facility will occur at 16 to 22-month intervals. The first couple of atomic physics experiments will take advantage of the free-fall environment to operate laser cooled atomic fountain clocks with 10 to 100 times better performance than any Earth based clock. These clocks will be used for experimental studies in General and Special Relativity. Flight definition experiment studies are underway by investigators studying Bose Einstein Condensates and use of atom interferometers as potential future flight candidates.

Use of the International Space Station for Fundamental Physics Research

Presented at CWS-02

Chernogolovka, Russia

Ulf Israelsson

August 13, 2002

Agenda

- *Past*
  - *Experiment Results using the Space Shuttle*
- *Present*
  - *Establishing a research program to make efficient use of the International Space Station*
- *Future*
  - *Research plans for the International Space Station*
- *Conclusions*

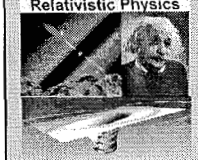
The NASA/JPL Fundamental Physics Research Program

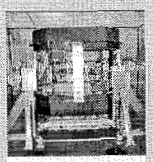
Two Research Quests:

To Discover and Explore Fundamental Physical Laws Governing Matter, Space, and Time

To Discover and Understand Organizing Principles of Nature from which Structure and Complexity Emerge

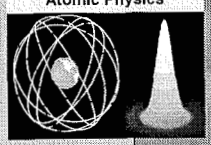
Gravitational and Relativistic Physics

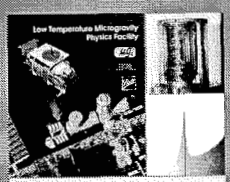




Alpha Magneto Spectrometer

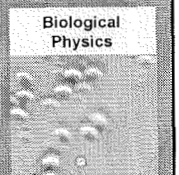
Laser Cooling and Atomic Physics





Low Temperature and Condensed Matter Physics

Biological Physics



Five Research Campaigns:

The Benefits:

Fulfill the Innate Human Desire to Understand our Place in the Universe

Build the Foundation for Tomorrow's Breakthrough Technologies

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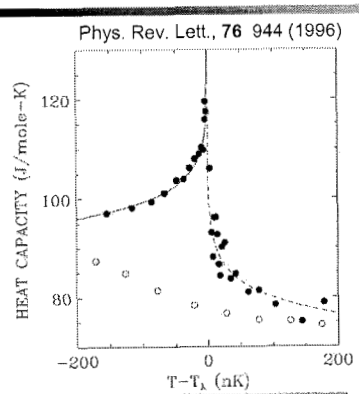
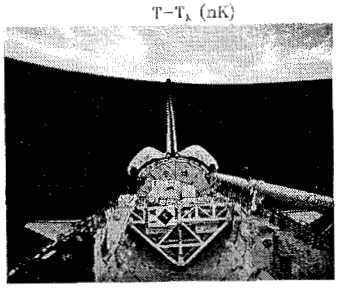
Lambda Point Experiment (LPE) Results





- *John Lipa, USMP-1, STS-52 10/92*
- *Lambda-point still sharp at ~ 1nK*
- *Heat capacity exponent*
  - $\alpha = -0.01285 \pm 0.00038$
  - Agrees with RG theory
  - LPE error bar 15 times smaller
- *RG Scaling relation $\alpha = 2 - 3\nu$*
  - Agrees with ν ground data
- *Thermal conductivity above T_λ*
  - Good agreement with functional form of DRG calculation
- *Technology demonstration*
  - High resolution LT experiments can survive launch and operate in space
  - Heritage for current and future experiments

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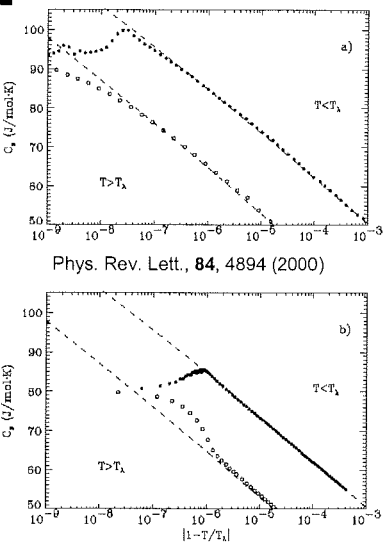
Confined Helium Experiment (CHeX) Results



Phys. Rev. Lett., **84**, 4894 (2000)

- ***John Lipa, USMP-4, STS 87 11/97***
- ***Heat capacity measured of helium confined to 57 micron thick slabs***
- ***Data agrees with RG theory predictions and Monte-Carlo estimates***
- ***Data removes earlier indications of finite size scaling violation***
  - Scaling behavior now confirmed over three orders of magnitude in size
- ***Surface specific heat exponents measured far from transition agrees with 0.658 predictions***
  - $\alpha_s = 0.64 \pm .05$ below transition
  - $\alpha_s = 0.65 \pm .2$ above transition

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Low Temperature and Condensed Matter Physics Ground Investigations (24)

96 NRA	S. Chui	University of Delaware	Droplets of 3He-4He Mixtures
96 NRA	D. Jacobs	The College of Wooster	Turbidity and Universality around a Liquid-Gas Critical Point
96 NRA	D. Lee	Cornell University	Studies of Atomic Free Radicals Stored in a Cryogenic Environment
96 NRA	J. Lipa	Stanford University	High-Resolution Study of the Oxygen Critical Region
96 NRA	R. Packard	University of California, Berkeley	Superfluid Gyroscopes for Space
96 NRA	J. Parpia	Cornell University	Capillary Condensation of Phase-Separated Liquid 3He-4He Mixtures in Aerogel
96 NRA	P. Roach	NASA Ames Research Center	A Microgravity Helium Dilution Cooler
96 NRA	P. Taborek	University of California, Irvine	3He-4He Mixtures and Droplets in Cesiated Containers
00 NRA	T. Chui	Jet Propulsion Laboratory	Heat Curent, Q, Effects on the Superfluid Transition (QUEST)
00 NRA	Larson	Jet Propulsion Laboratory	Experiments Along Coexistence near Tricriticality (EXACT)
00 NRA	Y. Liu	Jet Propulsion Laboratory	Heat Current near Tlambda in a Low-Gravity Simulator
00 NRA	F. Zhong	Jet Propulsion Laboratory	Measurements of the Thermal Conductivity near the Liquid-Vapor Critical Point of Helium-3 and Helium-4
00 NRA	G. Ahlers	UC, Santa Barbara	The Superfluid Transition of 4He under Unusual Conditions
00 NRA	A. Babkin	University of New Mexico	Surface Physics with Helium Crystals in Microgravity
00 NRA	D. Ceperley	University of Illinois, Urbana-Champaign	Prediction of the Properties of Liquid Helium from Computer Simulation
00 NRA	M. Chan	Pennsylvania State University	Critical Casimir Forces
00 NRA	R. Ferrell	University of Maryland	Theory of Phase Transitions and Simulations in Superfluid Helium of Cosmological Phenomena
00 NRA	H. Kojima	Rutgers University	Stress-Driven Instability on Helium-4 Crystals
00 NRA	D. Landau	University of Georgia Research Foundation, Inc.	Computer Simulations of Confined Quantum Systems in Microgravity
00 NRA	J. Lipa	Stanford University	The Effects of Large-Scale One-Dimensional Confinement on the Specific Heat of Helium near the Lamnda Line
00 NRA	E. Manousakis	Florida State University	Predicting Static and Dynamic Critical Properties of Bulk and Confined Helium
00 NRA	H. Maris	Brown University	Coalescence of Superfluid Helium Drops in Microgravity
00 NRA	D. Osheroff	Stanford University	Fundamental Physics Studies of Superfluid Helium-3
00 NRA	A. Wilkinson	NASA Glenn Research Center	Measuring the Distribution Function Moments of Sub-Correlation Length Critical Fluid Fluctuations

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Laser Cooling and Atomic Physics Ground Investigations (17)

96 NRA	J. Hall	University of Colorado	Fundamental Physics Using Frequency-Stabilized Lasers as Optical "Atomic Clocks"
96 NRA	T. Ho	Ohio State University	Gravitational Effects in Bose-Einstein Condensate of Atomic Gases
96 NRA	R. Hulet	Rice University	A Quantum Degenerate Gas of 6Li Atoms
96 NRA	J. Javanainen	University of Connecticut	Bose-Einstein Condensate and the Atom Laser: Coherence and Optical Properties
96 NRA	M. Kasevich	Yale University	Atom Interferometry in a Microgravity Environment
96 NRA	W. Ketterle	Massachusetts Institute of Technology	Towards Precision Experiments with Bose-Einstein Condensates
96 NRA	W. Phillips	NIST-Gaithersburg	Evaporative Cooling and Bose Condensates in Microgravity: Picokelvin Atoms in Space
00 NRA	H. Gould	University of California, Berkeley	Theoretical Studies of Bose-Einstein Condensates
00 NRA	D. Heinzen	Univesity of Texas, Austin	Search for Time-Reversal Symmetry Violation with Laser-Cooled Atoms
00 NRA	T. Ho	Ohio State University	Quantum Gases in Novel Environments: Optical Lattices and Rapidly Rotating Potentials
00 NRA	L. Hollberg	NIST, Boulder	Advanced Optical Frequency Standard for Space
00 NRA	R. Hulet	Rice University	Superfluid Phase Transition in an Ultracold Fermi Gas
00 NRA	W. Ketterle	Massachusetts Institute of Technology	Towards Precision Experiments with Bose-Einstein Condensates II
00 NRA	P. Meystre	University of Arizona	Atom Optics in Controlled and Microgravity Environments
00 NRA	W. Nagourney	University of Washington	Ultra-High Resolution Optical Frequency Standard Using Individual Indium Atoms
00 NRA	J. Thomas	Duke University	Quantum Coherence in Ultracold Fermionic Vapor
00 NRA	T. Walker	University of Wisconsin-Madison	All-Optical High Density Cold Atom Sources

Gravitational and Relativistic Physics Ground Investigations (8)

96 NRA	J. Lipa	Stanford University	A Test of Supersymmetry Theory by Searching for Anomalous Short Range Forces
96 NRA	H. Paik	University of Maryland	Search for a Spin-Mass Interaction with a Superconducting Differential Angular Accelerometer
96 NRA	A. Sanders	University of Tennessee	Research and Analysis in Support of Project See (Satellite Energy Exchange): Test of the Equivalence Principle and Measurement of Gravitational Interaction Parameters in an Ultra-Precise Microgravity Environment
96 NRA	R. Walsworth	Smithsonian Institution	Ground-based Investigations with the Cryogenic Hydrogen Maser and the Double-Bulb Rubidium Maser
00 NRA	E. Adelberger	University of Washington	Feasibility Study for a Space-Based Test of the Strong Equivalence Principle Using Lunar Laser Ranging
00 NRA	V. Kostelecky	Indiana University	Theoretical Studies of Lorentz and CPT Symmetry
00 NRA	K. Nordtvedt	Northwest Analysis	Optimizing Science from a STEP Mission: Equivalence-Principle-Violating Multipole Moments of the Non-Spherical Earth and Mission Observation Schedules
00 NRA	R. Walsworth	Smithsonian Institution, Astrophysical Observatory	Probing Planck-Scale Physics with a 21Ne-3He Zeeman Maser

Biological Physics
Ground Investigations (7)

00 NRA	M. Benjaminson	NSR-Touro College Applied Bioscience Research Consortium	Gravity, Time Interactions and the Cycle of Life
00 NRA	C. Batt	Cornell University	Biodegradable Polymers
00 NRA	T. Butt	LifeSensors, Inc.	Microfabrication of a Cell-Based Estrogen Sensor Switch on a Plastic Microchip
00 NRA	L. Pollock	Cornell University	Microscale Mixer for Protein Folding
00 NRA	A. Ponce	Caltech	Biomimetic Self-Assembly of Mesostructures in Microgravity: The Nature of the Capillary Bond
00 NRA	C. Rosenblatt	Case Western Reserve University	Simulated Microgravity Measurement Techniques for the Study of Dynamic Effects in Phospholipid Surfactants
00 NRA	J. Valles	Brown University	Magnetid Field Gradient Levitation System for Physics and Biophysics

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Flight Investigators

NRA	Launch	Carrier	Investigator	Affiliation	Investigation Name
Low Temperature and Condensed Matter Physics Experiments					
PACE	2002	STS-107	R. Berg	NIST, Gaithersburg	CVX-2 - Critical Viscosity of Xenon - 2
1991	2005	ISS/LTMPF (M1)	R. Duncan	University of New Mexico	DYNAMX - Critical Dynamics in Microgravity
1994	2005	ISS/LTMPF (M1)	M. Barmatz	Jet Propulsion Laboratory	MISTE - Microgravity Scaling Theory Experiment
2000	2005	ISS/LTMPF (M1)	I. Hahn	Jet Propulsion Laboratory	COEX(MISTE - Guest)
2000	2005	ISS/LTMPF (M1)	D. Goodstein	Caltech	CQ (DYNAMX - Guest)
1996	2007	ISS/LTMPF (M2)	G. Ahlers /F. Liu	UC, Santa Barbara /JPL	BEST - Boundary Effects on Superfluid Transition
2001	2007	ISS/LTMPF (M2)	TBD	TBD	2 LTMPF Guest PIs
2001	2009	ISS/LTMPF (M3)	TBD	TBD	3 LTMPF PIs (2 to fly)
2002	2009	ISS/LTMPF (M3)	TBD	TBD	2 LTMPF Guest PIs
Laser Cooling Experiments					
1996	2005	ISS/JEMEF	D. Sullivan	NIST, Boulder	PARCS - Primary Atomic Reference Clock in Space
1996	2008	ISS/JEMEF	K. Gibble	Yale University	RACE - Rubidium Atomic Clock Experiment
2000	TBD	ISS/JEMEF	M. Kasevich	Yale University	QuITE - Quantum Interferometer Test of Equivalence Principle
2000	TBD	ISS/JEMEF	W. Phillips	NIST, Gaithersburg	CLASS - Condensate Laboratory on the Space Station
2002	TBD	ISS/JEMEF	TBD	TBD	2 LCAP selections for one future flight
Gravitational Physics Experiments					
1996	2007	ISS/LTMPF-2	J. Lipa	Stanford University	SUMO - Superconducting Microwave Oscillator
1996	TBD	Free Flyer	F. Everitt	Stanford University	STEP - Satellite test of the Equivalence Principle
2000	TBD	Ballon Flight	I. Shapiro	Harvard - Smithsonian	TPEEE - Test of the Principle of Equivalence in an Einstein Elevator

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PLANNED INVESTIGATOR SELECTIONS

FLIGHT RESEARCH INVESTIGATIONS							
	FY02	FY03	FY04	FY05	FY06	FY07	FY08
PACE # PI	2	2	2	1	1		
91 NRA # PI	1	1	1	1	1	1	
94 NRA # PI	1	1	1	1	1	1	
96 NRA # PI	6	5	5	5	5	5	5
00 NRA # PI	5	5	5	5	4	4	2
01 NRA # PI		6	6	4	4	4	4
02 NRA # PI			3	3	2	2	2
03 NRA # PI				5	5	3	3
04 NRA # PI					3	3	2
05 NRA #PI						5	5
06 NRA # PI							3

GROUND RESEARCH INVESTIGATIONS							
	FY02	FY03	FY04	FY05	FY06	FY07	FY08
96 NRA PI	15						
00 NRA PI	37	35	28				
00 ITD PI	1	1					
01 NRA PI		15	15	15	15		
02 NRA PI			10	10	10	10	
03 NRA PI				28	28	28	28
04 NRA PI					20	20	20
05 NRA PI						20	20
06 NRA PI							20

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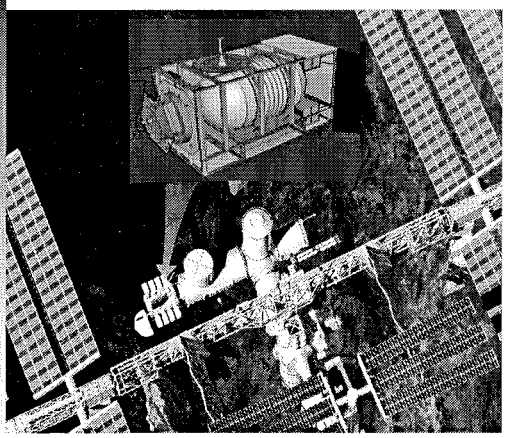
Low Temperature Microgravity Physics Facility (LTMPF)



- ISS cryogenic facility
  - Cold (≈ 2 K) volume for experiments
  - 5 months lifetime
  - Microgravity environment
  - Environments monitored
  - Multiple-experiments per flight
- Launched on the Space Shuttle
- Attached to the Japanese External Module Exposed Facility
- First launch planned November 2005
  - 2 instruments conducting 4 experiments
- Brought to Earth following helium depletion to refurbish with new instruments for next flight
  - 22 months between launches

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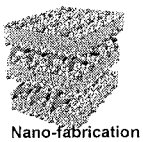
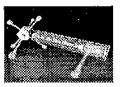
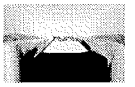
NASA's Laser Cooling and Atomic Physics Program

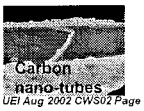
- ***LCAP is an emerging sub-discipline of NASA's fundamental physics program***
- ***Exciting cutting-edge research area composed of top researchers in field (2 Nobel Laureates)***
- ***Studies of atoms and simple molecules explores link between fundamental physical laws and complexity of nature***
  - What is the origin of Life itself?
- ***Compelling space environment need***
  - Confinement against gravity limits ground based research
  - New discoveries are certain
  - Different gravitational potential enables clock tests of Einstein's theories
- ***LCAP techniques are used for cutting edge research on bio-molecular and nano-scale systems***
- ***A permanent ISS space clock will provide 100-fold improvement in time keeping and make available for applications on Earth***
  - Most cutting edge research are limited by frequency resolution
  - Much improved GPS with potential for profound societal impact



Nano-fabrication



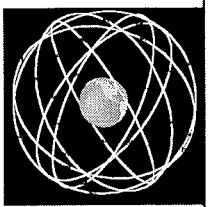




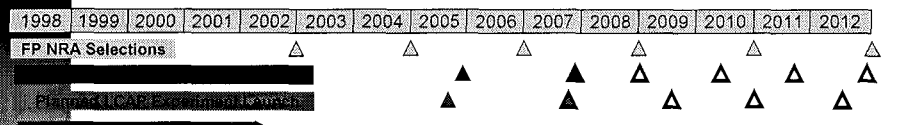
Carbon nano-tubes

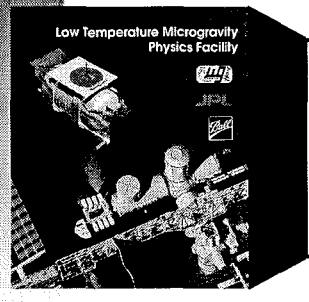
The importance of Clocks

- Time is the most precisely determinable of all physical quantities. The unit of time is defined as: "The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium atom 133."
- Clocks and timekeeping play a unique and pivotal role on everyday life of society, the government, commerce, and scientific research.
  - Scientific Research
    - Tests of fundamental laws of physics
    - Deep space navigation and radio science experiments
    - VLBI; Astronomical observatories
    - Particle Detectors
  - Government
    - DoD related activities including tracking and position information via GPS
    - Participation in the international realization of time (NIST, USNO)
    - Autonomous aircraft operation
  - Commerce
    - Power Grids
    - Transportation
    - Communication (Ground and Satellite)
    - Banking
  - Societal
    - Satellite communication system are reaching remote locations
    - GPS employed in search and rescue efforts.
    - GPS aided farming to pinpoint pesticide, fertilization, and water use



Fundamental Physics on the International Space Station





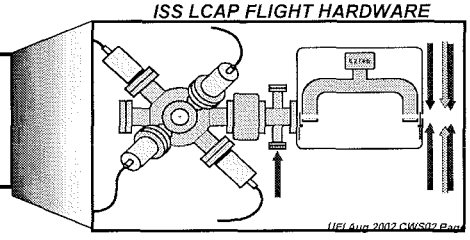
Low Temperature Experiments under Development
- **M1** Critical Dynamics in Microgravity Experiment (DYNAMX) **R. Duncan, UNM**
- **M1** Microgravity Scaling Theory Experiment (MISTE) **M. Barmatz, JPL**
- **M1 Guest Investigations Goodstein, CIT; Hahn, JPL**
- **M2** Boundary Effects on the Superfluid Transition (BEST) **G. Ahlers, UCSB**

Gravitational Experiments under Development
- **M2** Superconducting Microwave Oscillator (SUMO) **J. Lipa, Stanford**

Other Experiments to be Selected from future NRAs
- **M3 - Mn** flown at ~ 16 -22 month intervals

ISS LCAP FLIGHT HARDWARE

Laser Cooling Experiments under Development
- Primary Atomic Reference Clock Experiment (PARCS) **D. Sullivan, NIST Boulder**
- Rubidium Atomic Clock Experiment (RACE) **K. Gibble, Yale University**
- **Phillips, Kasevich** recent selections



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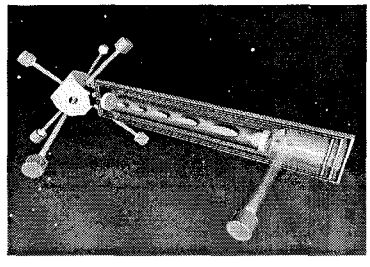
Primary Atomic Reference Clock in Space (PARCS)



Science Objectives
- To measure the gravitational red-shift and second order doppler shift by comparing *clock frequency to a ground unit*
- To test local position invariance by comparing clock frequency to a second clock of different composition
- To measure the anisotropy of the speed of light by comparing clock frequency to a second clock of different composition
- To improve the realization of the second to 10^{-16} accuracy.
- To make available improved time coordination for clocks on Earth

Technology
- Magneto Optical Trap (MOT)
- Diode Lasers suitable for Rb
- High-stability Microwave link
- High-stability Optical link
- Optical components
- Non-magnetic, high-speed shutters

Mission Description
- EXPRESS Rack mounted aboard the International Space Station
- Multi-frequency high stability microwave link.
- Optical link for time transfer

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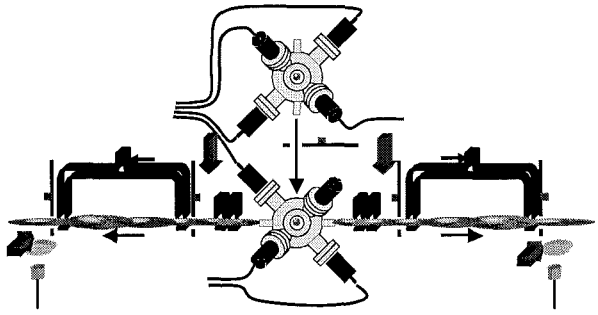
Rubidium Atomic Clock Experiment (RACE)



1. Advance atomic clock science and techniques to enable measurements with accuracy of 1 part in 10^{17}.
2. Significantly improve the classic clock tests of general relativity.
3. Distribute the highest accuracy time and frequency from the ISS.

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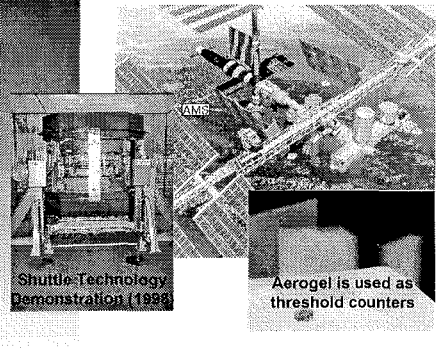
Alpha Magneto Spectrometer (AMS)



Technology
- Aerogel technology
- Silicon microstrip particle trackers
- Superconducting magnet technology

Science Objectives
- To increase our understanding of the composition and origin of the universe.
- To study charged particles, including antimatter, outside the Earth's atmosphere using their measured trajectories in a magnetic field.

Mission Description
- The 3.5 ton instrument will be launched on the Space Shuttle and operated for 3 years as an attached payload on the International Space Station.

Measurement Strategy
- Time of flight counters are used to detect the approach of an incoming particle.
- The particle path is determined by its charge as it traverses the magnetic field.
- The Silicon microstrips measure the trajectory.
- Veto counters are used to discriminate against secondary background particles.
- The electronics is used to recognize interesting events and transmit the data to scientists on Earth.

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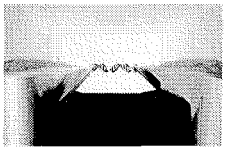
Biological Physics

- *Seven ground investigations selected from the 2000 NRA*
- *NASA is asking the scientific community to justify need for experimentation in space*
- *If space justification can be documented, NASA is interested to select flight experiments from future NRAs*



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Conclusions

- *Past*
  - *The NASA/JPL Fundamental Physics Program has a heritage of successful experiments performed on the Space Shuttle*
- *Present*
  - *Using Space Shuttle heritage to develop research hardware for the ISS*
    - *LTMPF and LCAP*
  - *Have built up a strong ground based research program from which to select future flight investigations*
  - *Have already selected many ISS investigations and are using their requirements to help define research hardware needs*
- *Future*
  - *Fundamental Physics has a bright future, once the ISS is fully assembled*

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