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First Class

MIT Admission

PRIORITY MAIL

VASANT NATARAJAN
2113, 15th Street
Troy, NY - 12180

Vasant

Call Peggy

@ 617-253-4870

to find out if you have

any aid. Keep calling every week.

Don't call Dr. Bekefi. Amrits

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF PHYSICS
CAMBRIDGE. MASSACHUSETTS 02139

12/19/89

Vasant Natarajan
2113 15th St.
Troy, NY 12180

Dear Mr. Natarajan,

I am pleased to inform you that the Graduate Committee of the Department of Physics is recommending your admission for February, 1990 to the Graduate School at the Institute.

We are eager to have you join us in study and research in physics, and very much hope that you will decide to come to MIT. We shall be grateful if you will let us know your decision as soon as you can. A reply card is enclosed for your convenience.

Sincerely,

Prof. George Bekefi
Graduate Admissions Officer

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Office of Admissions
77 Massachusetts Avenue
Cambridge, MA 02139

Room 3-108
Phone: 617-253-4791
Telex: 92-1473

January 22, 1990

Mr. Vasant Natarajan
2113, 15th St
Troy, NY 12180

Dear Mr. Natarajan:

Congratulations! You have been admitted to the Graduate School as a degree candidate in the Department of Physics for the term beginning February 5, 1990.

In order to receive the Certificate of Eligibility for an American Visa, you need to complete the Financial Certification form in the Practical Planning Guide and return it, along with supporting documents, to the International Student Office, Room 5-106.

Registration material will be held for you at the Registrar's Office, E19-335, where you may pick it up after you arrive on campus.

Please return the enclosed Reply Form as soon as you know whether or not you will be coming to M.I.T. We are limited in the number of graduate students we can accept and if you will not be coming we can offer your place to another student. If you plan to postpone your admission, new approval will be required.

We hope you will decide to continue your studies at MIT.

Sincerely,

Michael C. Behnke
Director of Admissions

MCB:mh

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DEPARTMENT OF PHYSICS

Cambridge, Massachusetts 02139

Students Accepted For Degree	FIELDS		
	Physics	Astronomy	Related Fields
Doctorate	X		
Master's	X		

1. General

President: Paul E. Gray
Dean of Graduate School: Frank E. Perkins
Department Chairman: Robert Birgeneau
Department Telephone Number: (617) 253–4870 (C)
Type of Institution: University
Control: Private
Setting: Urban
Total Faculty: 1,095
Total Graduate Faculty: 1,095
Total Students: 9,510
Total Graduate Students: 4,500
Annual Graduate Tuition:
In-state residents: Full-time—$13,400
Part-time—$215*/credit
Out-of-state residents: Full-time—$13,400
Part-time—$215*/credit
Tuition rates for: 1988–89
Deferred tuition plan: No
Other Fees: Medical Insurance—$336
Term: Semester
*(9–12 units/course)

2. Number of Faculty in Department

The combined total of full-time faculty in the three professorial ranks is 88. The combined total of full-time, part-time and other faculty at all ranks is 88.

3. Admission, Financial Aid, and Housing

Address admission inquiries to: Graduate Registration Officer, Dept. of Physics, Room 6–107

Graduate application fee required: $40

Admission deadline (Fall admission): 1/15

Admission information: For fall admission, 1988–89, 170 students were accepted from 570 applicants.

Admission requirements: For admission to the graduate programs a bachelor's degree in physics is required with no minimum undergraduate GPA specified. The GRE Advanced is required. Students from non-English speaking countries are required to demonstrate proficiency in English via the TOEFL exam. Minimum acceptable score for admission is 575.

Undergraduate preparation assumed: Reif, *Fundamentals of Statistical and Thermal Physics*; Marion, *Classical Dynamics*, and *Classical Electromagnetic Radiation*; Eisberg, *Fundamentals of Modern Physics.*

Address financial aid inquiries to: Graduate Registration Officer, Dept. of Physics, Room 6–107

GAPSFAS application required: No

Financial aid deadline: 1/15

Loans available: Yes

Address housing inquiries to: Campus Housing Information E19–307

On-campus, single student housing available: Yes
Cost / term: $1,100–1,265

On-campus, married student housing available: Yes
Cost / month: $470–700

Table A—Faculty, Enrollments, and Degrees Granted

Research Specialty	1987–88 Faculty	Enrollment[1] Fall 1987		No. of Degrees Granted[2] 1987–88			Median No. of Years for
		Master's	Doctorate	Master's	Terminal Master's	Doctorate	1987–88 Ph.D.'s
Astronomy	17	1	23	0 (2)	0 (2)	3 (14)	5.3
Astrophysics	6	0	11	1 (1)	0 (2)	1 (17)	5.3
Atmos./Space Phys., Cosmic Rays	2	0	2	0 (0)	0 (0)	0 (2)	–
Atomic & Molecular Phys.	4	1	22	0 (0)	0 (2)	4 (18)	5.5
Biophysics	3	0	6	0 (0)	0 (0)	0 (0)	–
Elem. Particles & Fields	22	0	42	0 (1)	0 (1)	13 (45)	5
Fusion & Plasmas	5	2	32	0 (1)	0 (2)	3 (22)	6
Materials Sci./Metallurgy	1	2	1	1 (1)	0 (0)	0 (1)	–
Medical & Health Physics	4	2	2	1 (1)	0 (1)	0 (2)	–
Nuclear Physics	18	4	38	1 (4)	0 (5)	6 (34)	5.4
Optics	2	1	7	0 (0)	0 (5)	0 (0)	–
Solid State	15	4	75	0 (3)	4 (15)	13 (63)	5.2
Non-specialized	0	3	17	0 (0)	0 (0)	–	–
Total		20	278	4 (14)	4 (35)	43 (218)	
Full-time Grad. Stud.		20	278				
Part-time Grad. Stud.		0	0				
First-year Grad. Stud.		3	42				
Median Years in Grad. Study (1987–88 Degrees)				2	2	5.3	

Undergraduate Degrees, 1987–88 (1983–88): 64(383)

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[1] Students not yet committed to a research specialty are entered under non-specialized.
[2] Five-year totals in parentheses.

4. Graduate Degree Requirements

Master's: Approximately six graduate level courses in physics are required. A B^- average must be maintained. A diagnostic examination is taken soon after entrance. Thesis required. Residence: one semester. There are no foreign language or comprehensive exam requirements.

Doctorate: Two academic years of full-time graduate work (including thesis) are required for the Ph.D. degree. There are no formal course requirements. A B^- average must be maintained. A diagnostic examination is taken upon arrival to test the student's undergraduate preparation. A general Doctoral examination consisting of a written and oral part must be passed in the second or third year of graduate work. Original research, demonstrated through a thesis is required. The thesis and oral defense of the thesis complete the requirements for the doctorate.

Thesis: Thesis may be written *in absentia* (with special permission only).

Reprinted from the *1988–89 Graduate Programs in Physics, Astronomy and Related Fields* published by the American Institute of Physics.

Table B—Appointments to Graduate Students, 1986–87

Title of Appointee	Appointments		Academic Load Allowed in Credit Hours	Hours of Service Per Week	Stipend for Academic Year ($)
	Total	First-year			
			Semester		
Teaching Assistant	34	10	Varies (about ¾ full load)	20	9,540[1]
Research Assistant	220	35	Varies (about ¾ full load)	20	8,640[1]
University Fellow	6	2	–	–	10,800[1]
Total	260	47			

[1] In addition a tuition scholarship is provided.

5. Personnel Engaged in Separately Budgeted Research, 7/87–6/88

Professorial faculty	80
Postdoctoral appointments	16
Graduate students	220
Undergraduate students	52
Nonteaching research personnel	19
Total	387

6. Separately Budgeted Research Expenditures by Source of Support

	Departmental Research	Physics-related Research Outside Department
Federal government	$3,290,000	$
Private, non-profit organizations	270,000	
Total	$3,560,000	$

7. Separately Funded and Managed Laboratories

Laboratory for Nuclear Science	$25,000,000
Research Laboratory for Electronics	13,000,000
Center for Space Research	8,000,000
Plasma Fusion Center	24,000,000
National Magnet Laboratory	9,000,000
Total	$79,000,000

Table C—Separately Budgeted Research Expenditures

Research Specialty	No. of Grants	Expenditures ($)
Biophysics	4	550,000
Medical & Health Physics	2	310,000
Solid State	20	2,700,000
Total	26	3,560,000

FACULTY

Professors

Baranger, Michael, Ph.D., Cornell, 1951. Theoretical physics; nuclear structure.

Becker, Ulrich J., Ph.D., Hamburg, 1964. Experimental physics; high energy.

Bekefi, George, Ph.D., McGill, 1952. Experimental physics; plasma physics.

Belcher, John W., Ph.D., Cal. Tech., 1970. Theoretical physics; solar plasma.

Benedek, George, Ph.D., Harvard, 1953. Experimental physics; light scattering and biophysics.

Berker, Nihat, Ph.D., Illinois, 1977. Theoretical physics; solid state.

Bernstein, Aron M., Ph.D., Pennsylvania, 1958. Experimental physics; nuclear structure.

Bertozzi, William, Ph.D., MIT, 1958. Experimental physics; nuclear structure.

Birgeneau, Robert, Ph.D., Yale, 1966. Chairman of the Department. Experimental physics; x-ray scattering and neutron scattering.

Bradt, Hale V.D., Ph.D., MIT, 1961. Experimental physics; space astronomy–cosmic rays.

Burke, Bernard, Ph.D., MIT, 1953. Experimental physics; radio astronomy.

Busza, Wit, Ph.D., London, 1964. Experimental physics; high energy.

Canizares, Claude, Ph.D., Harvard, 1972. Experimental physics; x-ray astronomy.

Chen, Min, Ph.D., California, Berkeley, 1969. Experimental physics; high energy.

Clark, George, Ph.D., MIT, 1952. Experimental physics; space astronomy–cosmic rays.

Coppi, Bruno, Ph.D., Milan, 1961. Theoretical physics; plasma physics and astrophysics.

Cosman, Eric R., Ph.D., MIT, 1966. Experimental physics; nuclear structure.

Davidson, Ronald, Ph.D., Princeton, 1972. Experimental physics; plasma physics.

Demos, Peter D., Ph.D., MIT, 1951. Experimental physics; nuclear structure.

Dresselhaus, Mildred S., Ph.D., Chicago, 1958. Experimental physics; solid state.

Dupree, Thomas H., Ph.D., MIT, 1960. Theoretical physics; plasma physics.

Elliot, James, Ph.D., Harvard, 1972. Experimental physics; astronomy.

Feld, Bernard T., Ph.D., Columbia, 1945. Theoretical physics; elementary particles.

Feld, Michael S., Ph.D., MIT, 1967. Experimental physics; modern optics.

French, Anthony P., Ph.D., Cambridge, 1948. Physics education.

Friedman, Jerome I., Ph.D., Chicago, 1956. Experimental physics; high energy.

Goldstone, Jeffrey, Ph.D., Cambridge, 1958. Theoretical physics; elementary particles–the many-body problem.

Greytak, Thomas J., Ph.D., MIT, 1967. Experimental physics; light scattering.

Grodzins, Lee, Ph.D., Purdue, 1954. Experimental physics; nuclear structure.

Guth, Alan J., Ph.D., MIT, 1972. Theoretical physics; elementary particle physics.

Huang, Kerson, Ph.D., MIT, 1953. Theoretical physics; elementary particles.

Ingard, K. Uno, Ph.D., MIT, 1950. Theoretical physics; plasma physics and acoustics.

Jackiw, Roman W., Ph.D., Cornell, 1966. Theoretical physics;

elementary particles.

Jaffe, Robert, Ph.D., Stanford, 1972. Theoretical physics; elementary particles.

Javan, Ali, Ph.D., Columbia, 1954. Experimental physics; modern optics.

Joannopoulos, John, Ph.D., California, Berkeley, 1974. Theoretical physics; solid state.

Johnson, Kenneth A., Ph.D., Harvard, 1955. Theoretical physics; elementary particles.

Joss, Paul C., Ph.D., Cornell, 1971. Theoretical physics; astrophysics.

Kastner, Marc, Ph.D., Chicago, 1972. Experimental physics; semi-conductors.

Kendall, Henry W., Ph.D., MIT, 1955. Experimental physics; high energy.

Kerman, Arthur K., Ph.D., MIT, 1953. Theoretical physics; nuclear structure.

King, John G., Ph.D., MIT, 1953. Experimental physics; molecular beams and biophysics.

Kistiakowsky, Vera, Ph.D., California, Berkeley, 1952. Experimental physics; high energy.

Kleppner, Daniel, Ph.D., Harvard, 1959. Experimental physics; atomic resonance and scattering.

Koster, George F., Ph.D., MIT, 1951. Theoretical physics; solid state.

Kowalski, Stanley B., Ph.D., MIT, 1963. Experimental nuclear and particle physics.

Lee, Patrick, Ph.D., MIT, 1970. Condensed matter theory.

Lewin, Walter H.G., Ph.D., Delft, 1965. Experimental physics; space astronomy–cosmic rays.

Litster, J. David, Ph.D., MIT, 1965. Experimental physics; light scattering.

Lomon, Earle L., Ph.D., MIT, 1954. Theoretical physics; nuclear structure.

Low, Francis E., Ph.D., Columbia, 1949. Theoretical physics; elementary particles.

MacVicar, Margaret, Sc.D., MIT, 1967. Experimental physics; superconductivity and tunneling.

Matthews, June, Ph.D., MIT, 1967. Experimental physics; nuclear structure.

Moniz, Ernest, Ph.D., Stanford, 1971. Theoretical physics; nuclear structure.

Negele, John, Ph.D., Cornell, 1969. Theoretical physics; nuclear structure.

Osborne, Louis S., Ph.D., MIT, 1950. Experimental physics; high energy.

Pless, Irwin, Ph.D., Chicago, 1955. Experimental physics; high energy.

Porkolab, Miklos, Ph.D., Stanford, 1967. Experimental physics; plasma physics.

Pritchard, David E., Ph.D., Harvard, 1968. Experimental physics; atomic resonance and scattering.

Rappaport, Saul A., Ph.D., MIT, 1968. Experimental physics; space astronomy–cosmic rays.

Rosenson, Lawrence, Ph.D., Chicago, 1956. Experimental physics; high energy.

Tanaka, Toyoichi, Ph.D., Tokyo, 1972. Experimental physics; biophysics.

Ting, Samuel C.C., Ph.D., Michigan, 1962. Experimental physics; high energy.

Villars, Feliz M., Sc.D., Swiss Fed. Inst., 1946. Theoretical physics; nuclear structure.

Weiss, Rainer, Ph.D., MIT, 1962. Experimental physics; gravitation research and infrared astronomy.

Wolff, Peter A., Ph.D., California, Berkeley, 1951. Theoretical physics; solid state.

Yamamoto, Richard K., Ph.D., MIT, 1963. Experimental physics; high energy.

Young, James E., Ph.D., MIT, 1953. Theoretical physics; elementary particles.

Associate Professors

Farhi, Edward H., Ph.D., Harvard, 1978. Theoretical physics; elementary particle.

McNutt, Ralph, Ph.D., MIT, 1980. Theoretical physics; space plasma.

Polonyi, Janos, Ph.D., Roland University, 1979. Theoretical.

Redwine, Robert, Ph.D., Northwestern, 1973. Experimental physics; nuclear structure.

Assistant Professors

Bertschinger, Edmund W., Ph.D., Princeton, 1984. Theoretical, astrophysics.

Cooper, Susan, Ph.D., California, Berkeley, 1980. Experimental physics; elementary particle.

Freese, Katherine, Ph.D., Chicago, 1984. Theoretical, astrophysics.

Graybeal, John M., Ph.D., Stanford, 1985. Experimental; solid state.

Herten, L. Gregor, Ph.D., RWTH, 1983. Experimental physics; elementary particle.

Kardar, Mehran, Ph.D., MIT, 1983. Condensed matter theory.

Kotliar, Gabriel, Ph.D., Princeton, 1983. Condensed matter theory.

Ledoux, Robert, Ph.D., MIT, 1981. Experimental physics; nuclear structure.

Manohar, Aneesh V., Ph.D., Harvard, 1983. Theoretical physics; elementary particle.

Meyer, Stephan S., Ph.D., Princeton, 1979. Experimental physics; infrared astronomy.

Mochrie, Simon, Ph.D., MIT, 1984. Experimental solid state.

Revol, Jean-Pierre, Ph.D., MIT, 1981. Experimental physics; elementary particle.

Stahler, Steven, Ph.D., California, Berkeley. Astrophysics.

Tonry, John, Ph.D., Harvard, 1980. Astrophysics.

Wurtele, Jonathan S., Ph.D., California, Berkeley, 1985. Experimental physics; plasma physics.

Zwiebach, Barton, Ph.D., Cal. Tech., 1983. Theoretical, elementary particle theory.

RESEARCH SPECIALTIES AND STAFF

Theoretical

Astrophysics. Coppi, Joss, Bertschinger, Freese, Stahler.

Atmospheric/Space Physics. Belcher, McNutt.

Elem. Particles and Fields. B. Feld, Goldstone, Guth, Huang, Jackiw, Jaffe, Johnson, Low, Moniz, Fahri, Manohar, Polonyi, Young, Zwiebach.

Fusion and Plasmas. Coppi, Dupree, Ingard.

Nuclear Physics. Baranger, Kerman, Lomon, Negele, Villars.

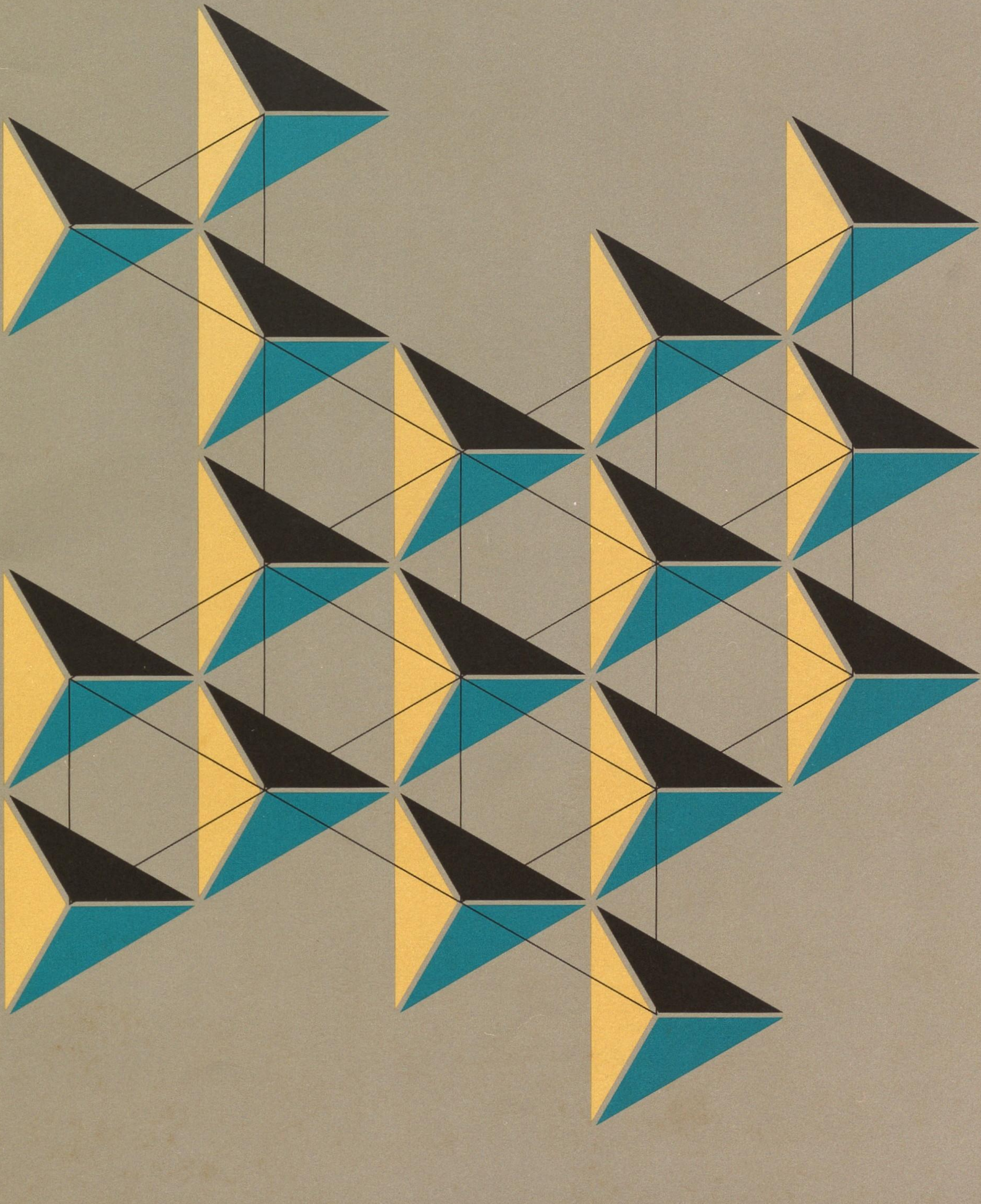
Solid State. Joannopoulos, Koster, Wolff, Berker, Kardar, Kotliar.

Experimental

Astronomy. Bradt, Burke, Canizares, Clark, Elliot, Lewin, Rappaport, Meyer, Tonry.
Astrophysics. Weiss.
Atmospheric/Space Physics. McNutt.
Atomic and Molecular Physics. Greytak, King, Kleppner, Pritchard.
Biophysics. Benedek, King, Litster.
Elem. Particles and Fields. Becker, Busza, Chen, Friedman, Frisch, Kendall, Kistiakowsky, Osborne, Pless, Rosenson, Ting, Yamamoto, Cooper, Herten, Revol.
Fusion and Plasma. Bekefi, Davidson, Porkolab, Wurtele.
Low Temperature Physics. Greytak.
Materials Science/Metallurgy. MacVicar.
Medical and Health Physics. Benedek, Tanaka.
Nuclear Physics. Bernstein, Bertozzi, Cosman, Demos, Grodzins, Redwine, Matthews, Kowalski, Ledoux.
Optics. M. Feld, Javan.
Solid State. Benedek, Birgeneau, Dresselhaus, Greytak, Kastner, Litster, Graybeal, Mochrie.

Physics Research At MIT

Department of
Physics
Massachusetts
Institute
of Technology



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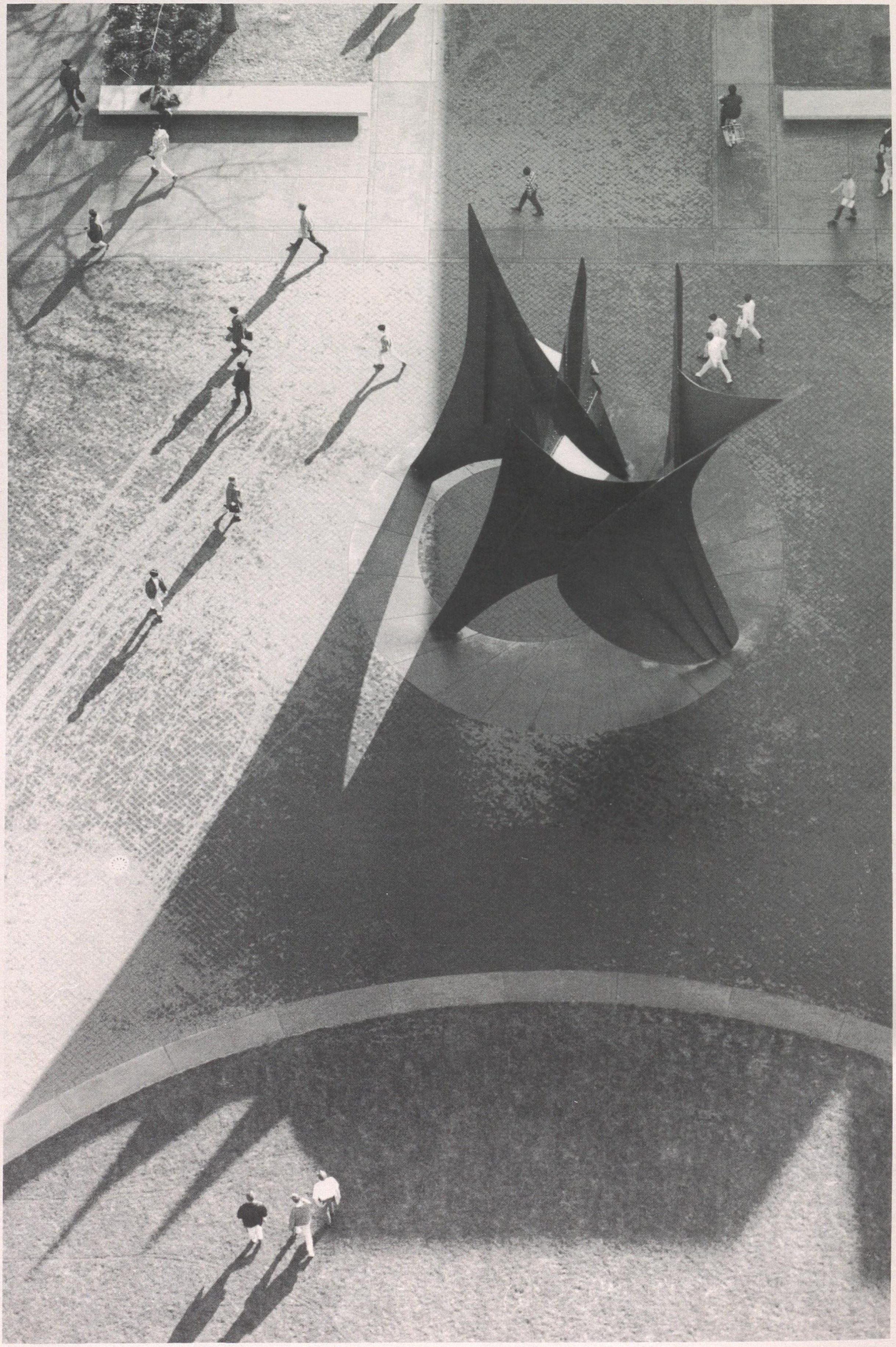
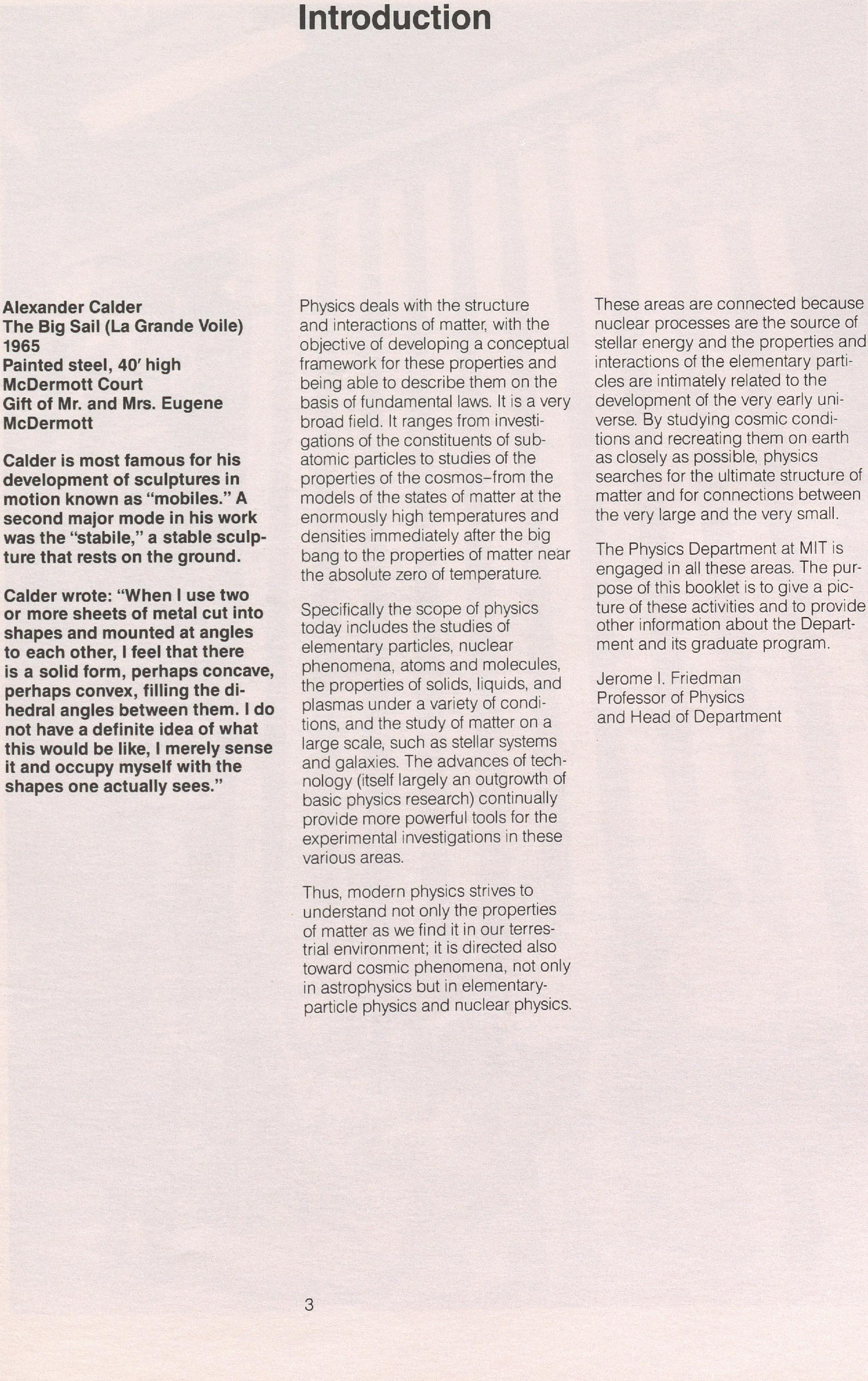


Introduction



Alexander Calder
The Big Sail (La Grande Voile)
1965
Painted steel, 40′ high
McDermott Court
Gift of Mr. and Mrs. Eugene McDermott

Calder is most famous for his development of sculptures in motion known as "mobiles." A second major mode in his work was the "stabile," a stable sculpture that rests on the ground.

Calder wrote: "When I use two or more sheets of metal cut into shapes and mounted at angles to each other, I feel that there is a solid form, perhaps concave, perhaps convex, filling the dihedral angles between them. I do not have a definite idea of what this would be like, I merely sense it and occupy myself with the shapes one actually sees."

Physics deals with the structure and interactions of matter, with the objective of developing a conceptual framework for these properties and being able to describe them on the basis of fundamental laws. It is a very broad field. It ranges from investigations of the constituents of subatomic particles to studies of the properties of the cosmos–from the models of the states of matter at the enormously high temperatures and densities immediately after the big bang to the properties of matter near the absolute zero of temperature.

Specifically the scope of physics today includes the studies of elementary particles, nuclear phenomena, atoms and molecules, the properties of solids, liquids, and plasmas under a variety of conditions, and the study of matter on a large scale, such as stellar systems and galaxies. The advances of technology (itself largely an outgrowth of basic physics research) continually provide more powerful tools for the experimental investigations in these various areas.

Thus, modern physics strives to understand not only the properties of matter as we find it in our terrestrial environment; it is directed also toward cosmic phenomena, not only in astrophysics but in elementary-particle physics and nuclear physics. These areas are connected because nuclear processes are the source of stellar energy and the properties and interactions of the elementary particles are intimately related to the development of the very early universe. By studying cosmic conditions and recreating them on earth as closely as possible, physics searches for the ultimate structure of matter and for connections between the very large and the very small.

The Physics Department at MIT is engaged in all these areas. The purpose of this booklet is to give a picture of these activities and to provide other information about the Department and its graduate program.

Jerome I. Friedman
Professor of Physics
and Head of Department


PROPERTY O
CSULB
ATHLETIC DEP

Elementary Particle Physics

A drift chamber plane used in the FNAL LAB C Neutrino Detector.

Experiment

It appears that strongly interacting particles (hadrons) are made up of quarks–particles that started out as a mathematical construct but have acquired more and more reality. The first experiment that provided dynamical evidence for this simple composition for hadrons was done in the late 1960's by an MIT-Stanford group[2] at the Stanford Linear Accelerator Center.

It is natural to assume that some field gives rise to the interactions among quarks, but until recently one had only inferences of this. Experiments at the electron-positron ring in Hamburg, Germany, in which an MIT group[3] participated, may have given us a first direct look at gluons (the field particles), in an observation of "jets" of hadrons in high energy collisions, presumed to arise from the struck quarks and the radiated gluons.

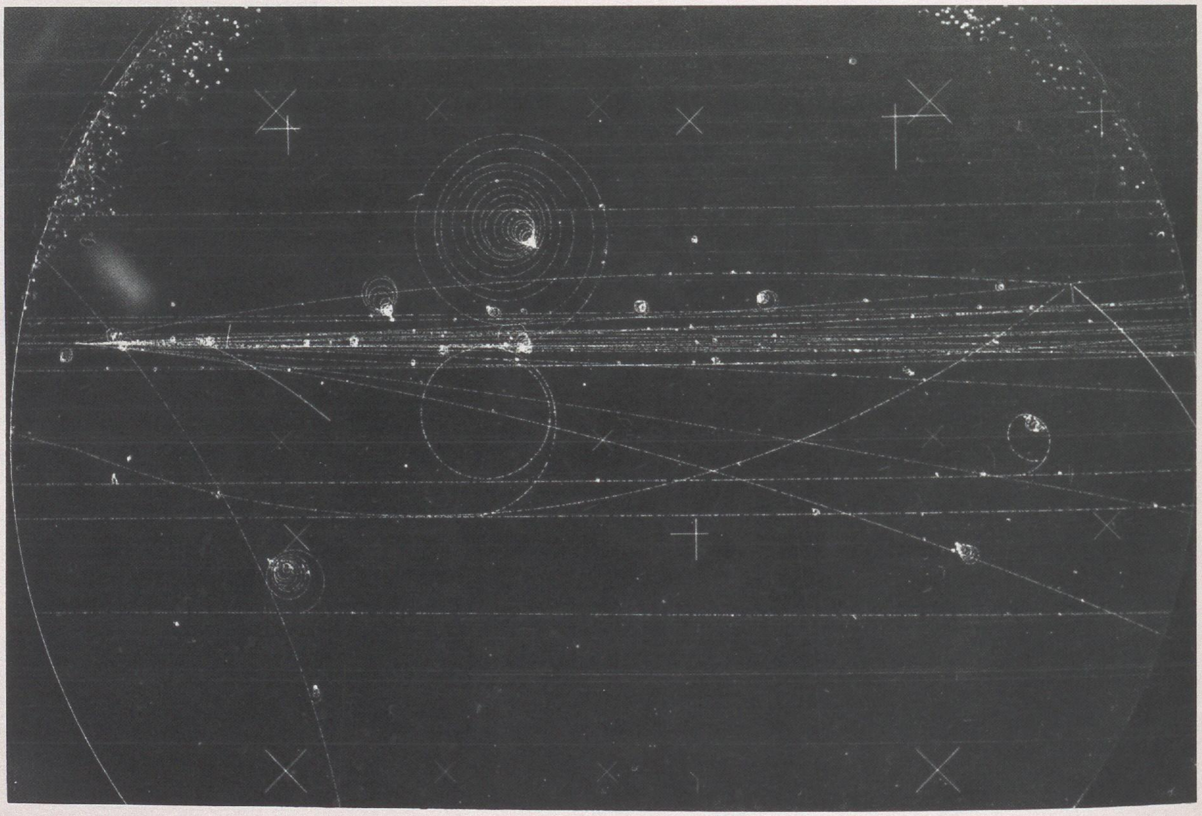
A recent success in particle physics has been the prediction and discovery of so-called weak vector bosons. Experiments UA1 and UA2 at the European Laboratory CERN in Geneva, Switzerland, have detected these particles (the $W^{\pm}$ and Z^0 bosons), and are continuing to study their properties. An MIT group[5] is collaborating on one of these experiments, UA1, which with improved apparatus aims at studying further the properties of proton-antiproton collisions at very high energies, to search for new particles such as a sixth quark, new leptons, etc.

The accelerator at the Fermi National Accelerator Laboratory (Fermilab) has recently been upgraded by a factor of two to one teraelectronvolt (10^{12}eV). In the past such jumps in energy have usually led to new and unpredicted revelations. This higher energy machine (called the Tevatron) brings us into a range where measurable effects from the expected new particles may be observed. There are several MIT experiments that will take advantage of this opportunity. In addition, several years from now, two new high energy electron-positron colliders will become available, one at the Stanford Linear Accelerator Center, called the Stanford Linear Collider (SLC), and one at CERN, called the Large Electron Positron machine (LEP). Both of these accelerators are designed to produce Z^0 bosons, as well as to search for new particles such as the postulated Higgs mesons and to study the validity–or the breakdown–of the standard model of the electro-weak interaction. MIT groups[2,3,4] are actively participating in the construction of detectors to be used in the experiments.

At Fermilab, an MIT group[6] is participating in new experiments involving neutrinos. The first is a study of particles containing the charm quark. The "charmed" particles are produced by neutrinos striking nuclei and are detected in a high resolution bubble chamber that uses holography to photograph the bubble tracks. The same apparatus is designed for use in a future experiment to search for a third neutrino, the tau neutrino.

Another MIT group[2] is using neutrinos and muons in two separate programs at the Tevatron to study the structure of nucleons and the nature of the weak interactions. The group is now utilizing one of the largest neutrino detectors at any laboratory.

Elementary particle interactions can be studied by taking photographs of the interactions as they occur in a bubble chamber. This photograph, taken in the 30-inch hydrogen bubble chamber at Fermilab, shows a spray of seventeen charged particles that are produced when a 147 GeV/c pion enters the chamber from the left and collides with a proton in the bubble chamber's liquid. While most of the secondaries, mainly pions, have a small curvature in the chamber's magnetic field, the low momentum electrons are bent more and often curl up to create the many spiraling tracks in the photograph.



This device incorporates a new technique, the flash chamber, which permits optimum measurement of the features of neutrino-nucleon interactions. It is particularly valuable in studying the dynamics of neutral current interactions (e.g. neutrino in, neutrino out). The data from the most recent run are now being analyzed and will provide a first look at the physics of deep inelastic neutrino scattering processes in this unexplored energy region. The group has also undertaken a role in another Tevatron project, namely the study of deep inelastic scattering of muons by nucleons and nuclei. A large new spectrometer is under construction to provide data on the interactions of muons with the quark substructures in nucleons. This experiment should provide important insight into the processes by which hadrons are created when quarks are struck.

The Electromagnetic Interactions (EMI) Group[3] at MIT began a series of fundamental experiments on electron pair production at the Deutsches Elektronen Synchrotron (DESY) in Hamburg, West Germany, in 1968 by verifying the validity of Quantum Electrodynamics. Subsequently, the group studied the photon-like particles ρ, ω, ϕ and ρ' with increasingly refined techniques. They later used their experience with pair spectrometers to set up a highly sensitive experiment to study electron pair production in proton-proton interactions at the Brookhaven National Laboratory (BNL). This experiment culminated in 1974 with the discovery of the J/ψ particle which provided the first evidence for the existence of the charm quark. For this discovery, Professor Samuel C.C. Ting of MIT was awarded the Nobel Prize, jointly with Professor Burton Richter of Stanford University.

At the DESY electron-positron storage ring PETRA, the group is now using the large acceptance calorimetric and charged track detector, known as MARK J, to perform tests of quantum electrodynamics down to very small distances ($\sim 10^{-16}$cm). The gluon, crucial force carrier of quantum chromodynamics, was detected by the examination of the topology of hadron jets produced in electron-positron annihilation. Searches for new quarks, leptons, and supersymmetric particles are underway.

The group is now leading a large cooperative effort to build a very large detector (L3) for the LEP machine at CERN, which will produce high energy electron-positron annihilations. The detector specializes in detecting all leptons with high (1%) precision, and will employ the largest magnet so far instrumented with forefront-accuracy drift chambers to measure particle trajectories. Twelve thousand crystals of the new material bismuth germanate will detect electrons and photons with unprecedented accuracy. The group will study the physics of the Z, W, and Higgs bosons, as well as search for new phenomena.

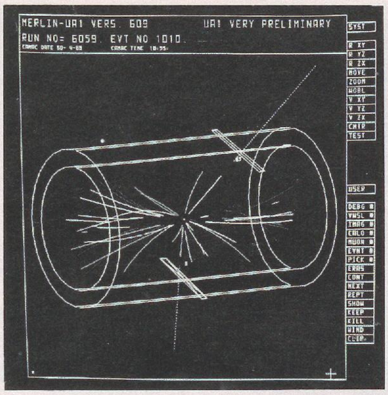
Not all high energy experiments are performed with accelerators. An MIT group[6] is involved in building a detector to be installed in the Gran Sasso tunnel in Italy. The purposes of the experiment are to look for muons coming from Cygnus X-3 and other intense sources in the galaxy and to study neutrino emission from the sun and from exploding supernovae. This detector is scheduled to start operating in January, 1987.

Theory

Particle theory tries to discover the fundamental structures of matter. We believe that the quantum theory of gauge fields is the theoretical tool for exploring these structures. The prototypical model is the totally successful theory of the electromagnetic field and its interactions with atomic particles–quantum electrodynamics. Today we know how to describe sub-nuclear particles and their interactions by similar theories. The strong interactions between quarks and gluons which account for the structure of the atomic nucleus are governed by the field theory of quantum chromodynamics. The electromagnetic field itself and the weakly interacting fields which account for radioactive decays are unified in a single gauge field theory of the electro-weak interaction. But this theoretical framework is incomplete since it depends on ad hoc assignments of particle masses and interaction strengths. We can use the theory to make predictions but we are left groping for the still deeper structures which must underly our present understanding.

Research on this problem has many facets which are represented in the work of the MIT particle theory group.[1] Deep mathematical studies of the structure and solutions of gauge field theories keep modifying our ideas of their nature. In fact, particle theory now uses a wider range of classical and modern mathematical techniques than ever before, and the reaction back on mathematical

A module of the big Muon Detector developed by Prof. Ulrich Becker (2nd from left) for Prof. Samuel Ting's L3 experiment at CERN.



A computer reconstruction of an event at the UA1 detector at CERN.

research has been significant. There is also a strong two-way flow of ideas and techniques between particle theory and condensed matter theory since there are close analogies between the complex systems they analyze.

Many particle theorists believe that the strong and electro-weak interactions can be unified with the gravitational interaction by studying physics at the Planck scale of 10^{-33} cm where the quantum fluctuations of the gravitational field become important. This physics is of course not directly accessible to experiment–the biggest projected accelerator will still be 15 orders of magnitude below the energy corresponding to the Planck scale. But the constraints on a consistent quantum field theory of gravity are perhaps so strong that we may be able to construct this theory without direct experimental input. This is the aim of the theory of superstrings, developed since 1984 and currently the focus of exciting research.

Physics at the Planck scale does govern speculations about the nature of the "Big Bang" at the beginning of our universe. Ideas about the fundamental structure of matter lead to cosmological scenarios which take us back to the first 10^{-40} seconds in the life of the universe. Less drastic extrapolations of known microscopic physics can be tested against the less speculative astrophysics of the first few millenia. And the vast flow of astronomical data continues to provide surprises which can test our fundamental theories.

Those particle physicists who find the gap to the Planck scale uncomfortably wide put their hopes in new experimental input from the highest energy accelerators. We are currently beginning to get data from collisions of particles each with energy 1 TeV (10^{12} electron volts), and we hope to see 20 TeV particles colliding sometime in the 1990's. The analysis and interpretation of this information may settle some of the outstanding questions. With any luck, the data will also be full of surprises and will provide much work for particle theorists.

Working out the predictions of a theory of strong interactions is a highly non-trivial problem. Quantum chromodynamics can probably only be usefully applied by a combination of powerful mathematical analysis, insightful approximation techniques, and massive computing. It is very likely that the same will be true of any unified theory that is discovered.

Faculty in Elementary Particle Physics

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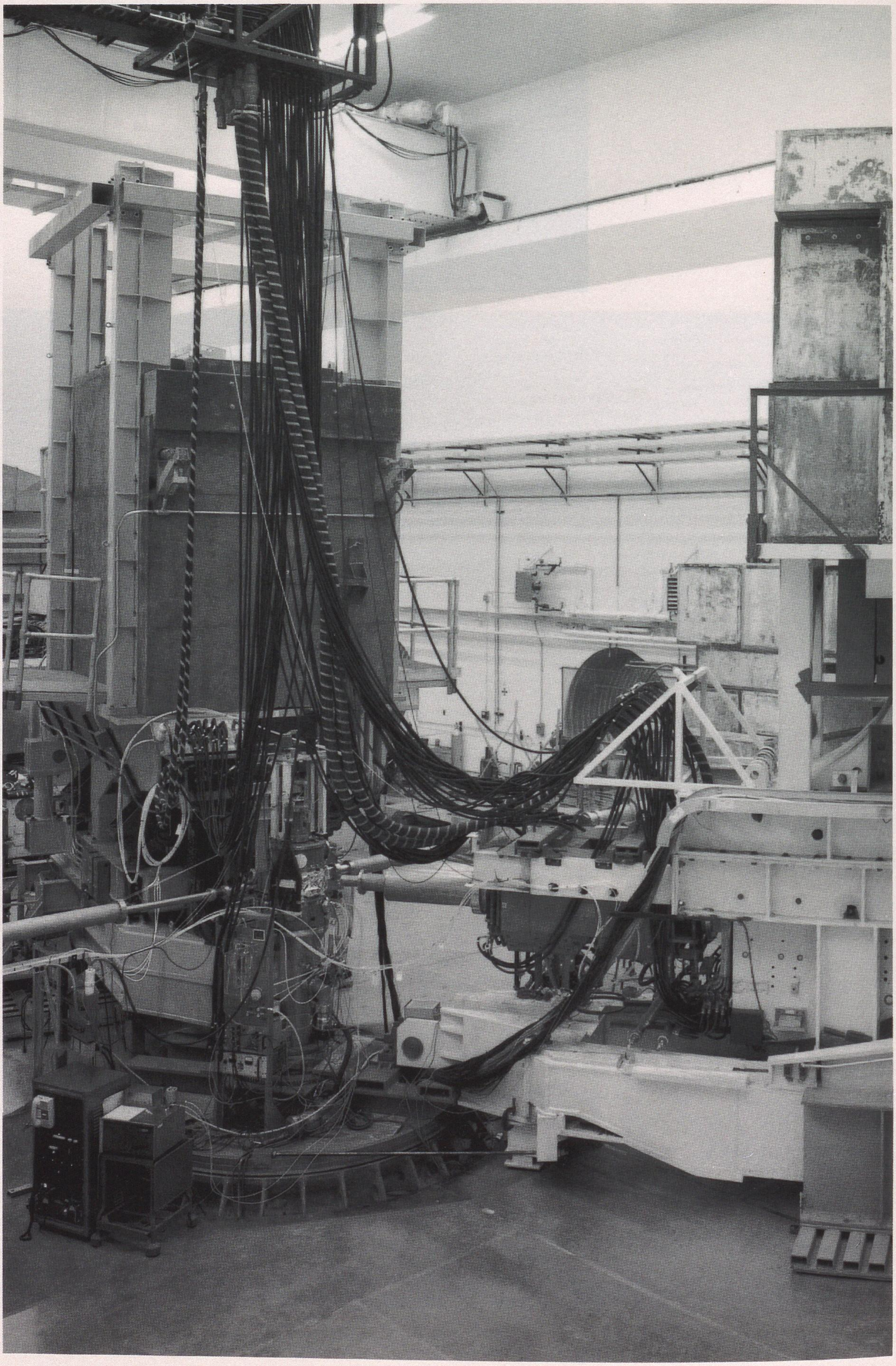


Nuclear Physics

Magnetic Spectrometers at the Bates Laboratory used for the detection of electrons, protons, and π mesons.

Experiment: Intermediate Energy Physics

There are many unanswered questions in nuclear physics. While the highly successful nuclear "shell model" provides a good framework for the understanding of many different types of experiments, a vital ingredient, the nucleon-nucleon interaction, is not yet fully understood. The development of intermediate energy (100 to 1000 MeV), high intensity electron and proton accelerators has provided new opportunities for studies of this fundamental interaction, as well as for studies of nuclear structure and reaction mechanisms in previously inaccessible regions of momentum and energy transfer. We are just beginning to be able to investigate important aspects of nuclear structure, such as the high momentum components of nuclear wave functions, short-range correlations of nucleons in nuclei, and the influence of the nuclear medium on the interactions of nucleons and mesons. The underlying quark-gluon structure of the nucleons and mesons must also, in some way, influence nuclear properties and it is a challenge to intermediate energy nuclear physicists to devise experiments to elucidate these effects.

The major intermediate energy electron accelerator in the United States, the 850 MeV Bates Linear Accelerator, located in Middleton, Massachusetts, is operated by MIT and is the focus of the research done by the Intermediate Energy Nuclear Physics Group[2]. Complementary experiments on pion-induced reactions[3] and on proton-induced reactions[4] are also being pursued at the Los Alamos Meson Physics Facility and at the Indiana University Cyclotron Facility, respectively. Another group[5] is studying the production of hypernuclei at the Brookhaven National Laboratory and also developing a detector for solar neutrinos.

At Bates, a broad range of problems in nuclear structure and fundamental interactions is studied, primarily via the scattering of electrons by nuclear systems. Because the electromagnetic interaction is well understood, and because this interaction is weak compared with the force that binds nuclei, the results of these experiments can be interpreted in a first order perturbation theory in terms of nuclear structure. Electron scattering thus provides an accurate probe of charge, current, and magnetization densities in nuclei. The development of sophisticated, high-resolution magnetic spectrometer techniques has allowed these studies of nuclear structure and spectroscopy to be carried out with extremely high precision.

A new test of the theory of the electroweak interaction is in progress, in which parity violation in the elastic scattering of polarized electrons by the carbon nucleus will be observed. A measurement of the recoil deuteron polarization in electron-deuteron scattering will provide a sensitive test of models of the nucleon-nucleon interaction. The properties of the three-nucleon system, in particular the effects of mesons and the possible presence of three-body forces, are being studied in electron scattering experiments on ^{3}H and ^{3}He. The properties of nucleons in nuclei are investigated in measurements of deep inelastic electron scattering, in which the electron scatters in a quasi-free interaction with an individual nucleon, which is then ejected from the nucleus. Additional information can be obtained by detecting the knocked-out nucleon in coincidence with the scattered electron in a second spectrometer.

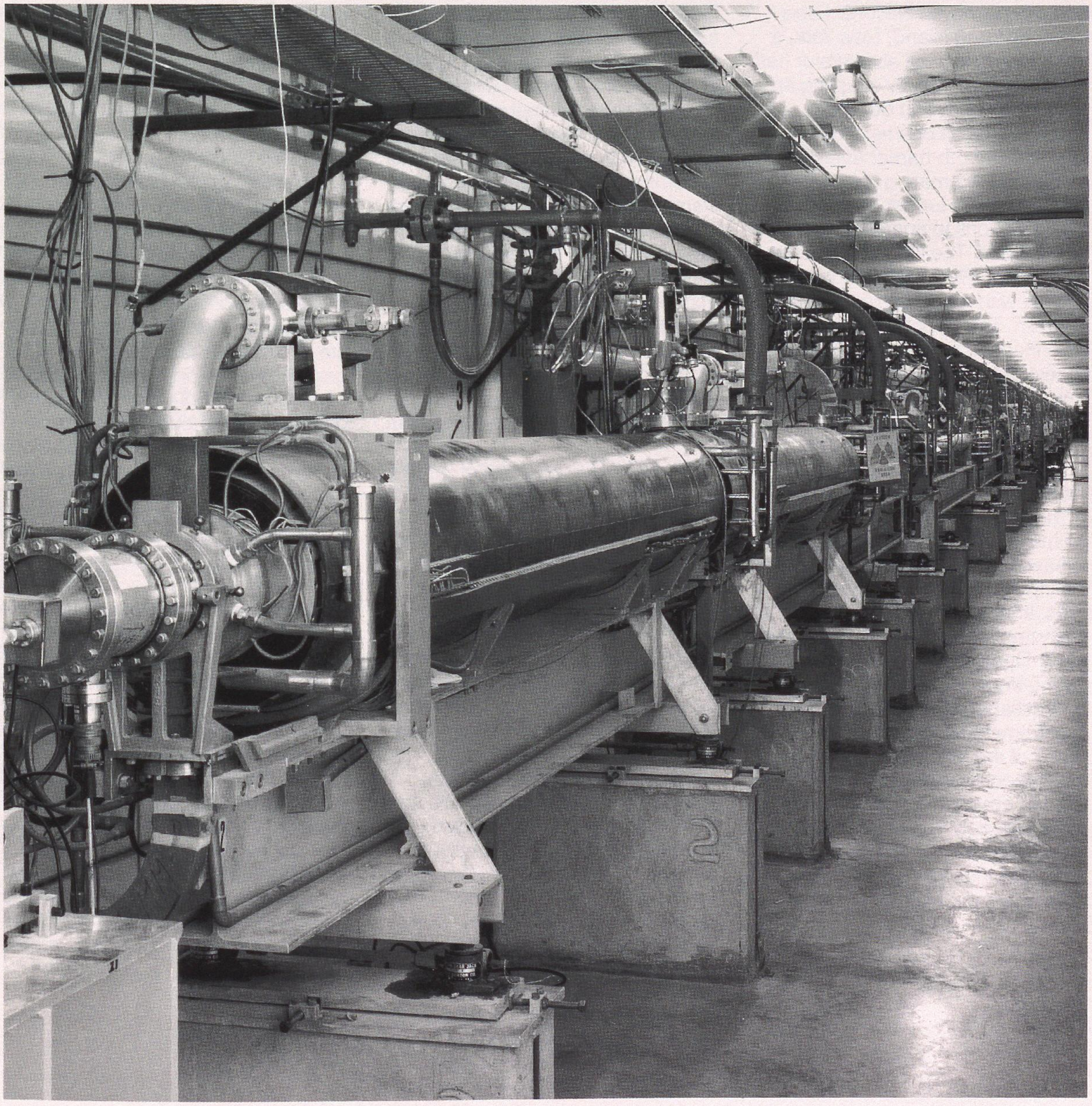
Secondary photon beams produced by electron bremsstrahlung are also employed in a variety of programs at Bates. In measurements which are complementary to the deep inelastic electron scattering studies in which a virtual photon is absorbed, the knockout of neutrons and protons by real photons is observed. These processes are particularly sensitive to high momentum components of nuclear wavefunctions and may reveal new information on nucleon-nucleon correlations. The coherent processes of photon scattering and π^0-photoproduction (in which the initial and final nuclear states are identical) provide an interesting test of the isobar-hole model of the photonuclear interaction in the region of the $\Delta(1232)$ nucleon resonance. The photodisintegration of the deuteron, with a measurement of the polarization of the outgoing neutrons, is being studied over a broad energy range, to elucidate the role of meson exchange and other effects in the nucleon-nucleon problem. The properties of mesons in complex nuclei are investigated directly in experiments on the electro- and photo-production of charged pions. Here three aspects may be addressed: The effective pion production operator in the nuclear medium (does it differ from that in free space?), the nuclear structure matrix element, and the final state interaction of the pion. The experimental kinematics may be selected so as to emphasize the role played by one or another of these ingredients in the process being studied.

The information on nuclear structure and reaction mechanisms resulting from experiments with the electromagnetic probe can often be complemented and supplemented by studies with hadronic probes. Experiments on pion-induced reactions are currently an important part of the MIT research effort in intermediate energy physics. Several of these have been motivated by a unified theoretical framework, the isobar-hole model, available for treating photon- and pion-induced reactions in the $\Delta(1232)$ resonance energy region. Moreover, photons and pions are kinematically similar in being able to transfer large energy with only small momentum to the nucleus; photon and pion absorption processes are thus expected to exhibit sensitivity to multi-nucleon effects. Pion-nucleus scattering, with and without charge exchange, is also under investigation. Particularly interesting is the pion double-charge-exchange reaction, which simply to conserve charge must involve at least two nucleons. Such studies provide yet another means of probing the elusive nucleon-nucleon correlations in nuclei.

Heavy Ion Physics

The study of collisions between heavy nuclei has yielded significant insights into nuclear properties. These studies, carried out until now at energies not greatly in excess of that needed to overcome the Coulomb barrier between the nuclei, have allowed us to investigate properties at the extremes of stability: the limits of proton and neutron number and of angular momentum. The imminent ability of accelerators to produce heavy nuclei with energies a thousandfold in excess of Coulomb barrier energies will give us the tools to study nuclear matter at extreme conditions of matter and energy density. The densities of nuclear matter are expected to reach five to ten times those in stable nuclei. The energy densities are expected to be so high that the quarks and gluons which compose the nucleons in nuclei may form a plasma, which would be a new phase of matter. Moreover, it is hoped that the study of these relativistic heavy ion collisions will provide insight into nuclear matter as it existed during the early formation of the universe. It is to these investigations that the heavy ion nuclear physics group[6] at MIT has turned its attentions.

One GeV electron linear accelerator at MIT-BATES Laboratory; premier facility for research in intermediate energy nuclear physics.



At the Brookhaven National Laboratory on Long Island, New York, a relativistic-heavy-ion accelerator has been implemented by coupling an existing Tandem Van de Graaff, which produces beams of heavy ions at Coulomb-barrier energies, to an existing Alternating Gradient Synchrotron which further accelerates the heavy ions to energies of 15 GeV per nucleon. The first experiments will use 500 GeV sulphur nuclei to interact with nuclei of elements up to uranium. This hybrid accelerator will be enhanced in the coming years to accelerate heavier and heavier particles to higher and higher energies. Even the first studies, however, will yield hundreds of particles in a single event. Among the special instrumentation required to characterize these events are calorimeters for measuring the total energy released, multiplicity arrays for determining the centrality of the interactions, and spectrometers capable of analyzing many particles simultaneously. Designing, constructing, and testing these systems is being done by a collaboration of groups; the spectrometer is the special responsibility of the MIT group. The first experiments will begin in early 1987 and will continue for a number of years with new instrumentation being constructed to keep pace both with the knowledge gained and with accelerator capabilities.

Theory

Nuclear theory addresses the structure and interactions of the nucleons, atomic nuclei, and hadronic matter of which our universe is composed. Our vast observational knowledge of nuclear phenomena, from terrestrial conditions to the extreme conditions occurring in supernovae and neutron stars, and the powerful experimental capabilities now at our disposal, raise a variety of fundamental and challenging questions. Much of the richness of nuclear physics arises from the interplay of many different degrees of freedom, and the broad research effort in nuclear theory at MIT[1] addresses the role of each of these diverse degrees of freedom.

Many aspects of low energy nuclear physics may be understood in terms of nonrelativistic nucleon degrees of freedom with empirically determined two-body interactions. Historically, MIT has played a major role in answering many of the important questions associated with nucleonic degrees of freedom: quantitatively understanding the energies, radial density distributions, and shapes of nuclear ground states; determining the fundamental collective and single-particle excitations; understanding the scattering of nucleons and nuclei from nuclear targets; exploring the origin of statistical behavior in nuclei; and determining the equation of state of neutron star matter up to nuclear density. Questions of current interest in this regime include the quantum theory of nuclear collective motion, the problem of semiclassical quantization, the short range structure of the many-body wave function, and understanding the linear response of the nucleus to an external probe.

Intermediate energy experiments investigating nuclear structure with electromagnetic, pionic, or other hadronic probes involve additional mesonic and excited nucleon degrees of freedom. Although we have come a long way in understanding the role of meson exchange currents in electromagnetic processes and aspects of the propagation of pions and excited nucleons in the nuclear medium, fundamental questions such as the mechanism for absorption of a pion in a nucleus are at present unanswered and of great interest. Many questions concerning the role of mesonic degrees of freedom and relativistic nucleon effects in nuclei are currently studied in the context of meson-nucleon field theory. This approach has interesting phenomenological features and provides a framework for the study of relativistic many-body theory.

An area of fundamental interest in contemporary nuclear physics is understanding the role of underlying quark and gluon degrees of freedom in the nucleon, in nucleon-nucleon interactions, and in nuclear structure. Although it is believed that the structure and interactions of hadrons are governed by quantum chromodynamics, there is, as yet, no quantitative theory which answers even the most basic questions. How do we understand the properties of a nucleon in free space; how is a nucleon altered when it is embedded inside a nucleus; and why is low energy nuclear physics so little affected by the internal structure of nucleons? These questions are being approached both from the perspective of lattice gauge theory, and in the context of simplified bag, flux-tube, quark, and topological soliton models. Relativistic heavy-ion collisions raise fundamental questions concerning the physics of quark and gluon degrees of freedom in an as yet unexplored domain of matter at high energy and density. Research in this area addresses the possibility of a phase transition to a new phase of matter, the quark-gluon plasma, and its experimental signatures.

Contemporary nuclear theory is deeply interrelated with many other areas of physics. In addition to its clear overlap with particle theory in areas such as strong interaction physics, and tests of fundamental symmetries, it addresses problems of astrophysical interest such as the equation of state and novel phases of dense matter. Nuclear many-body theory addresses the same problems of dealing with large numbers of degrees of freedom as arise in condensed matter physics and field theory, and substantial effort has been devoted to the development of mean field, functional integral, and stochastic methods to solve complex many-body problems.

Faculty in Nuclear Physics

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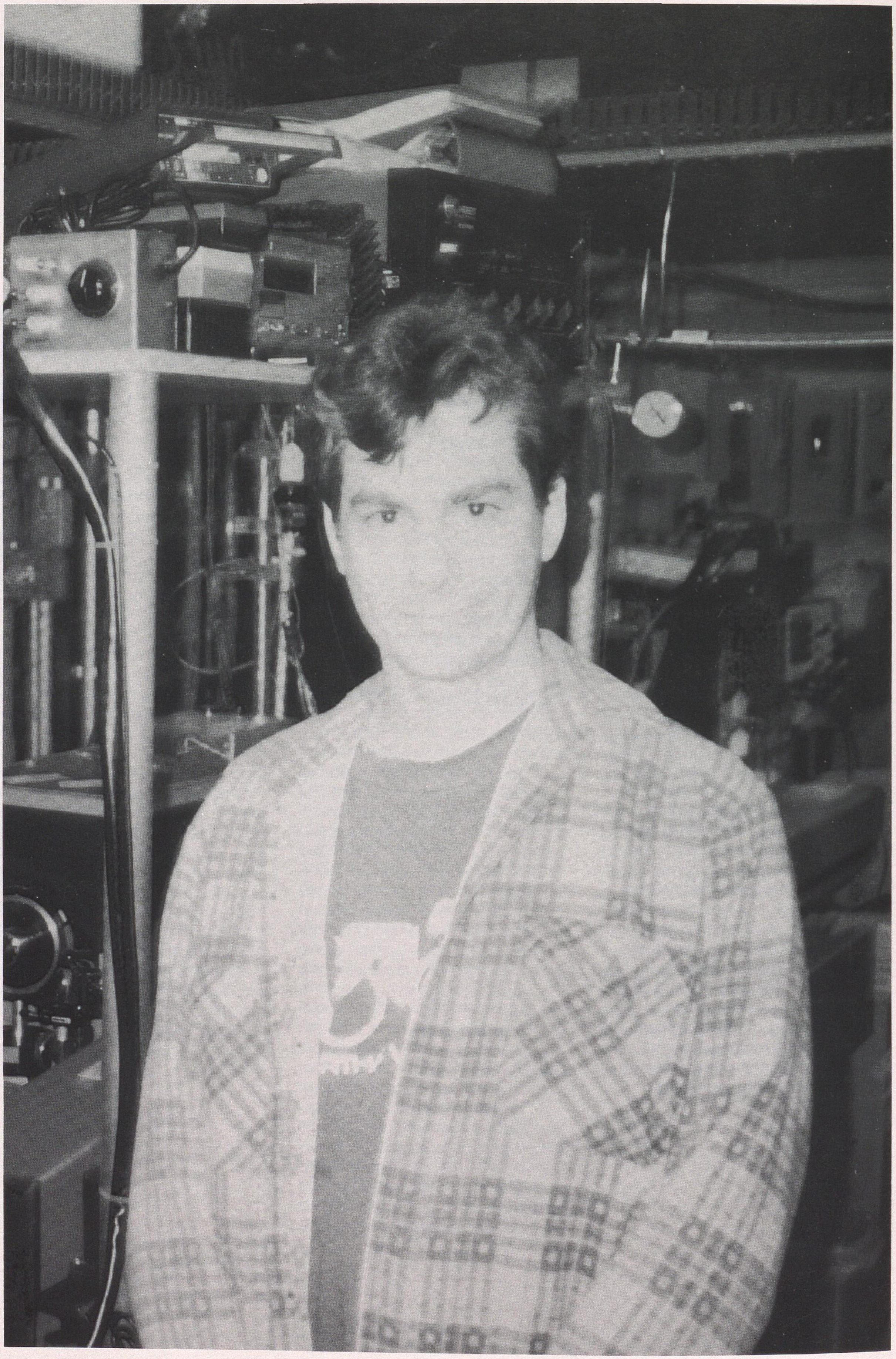
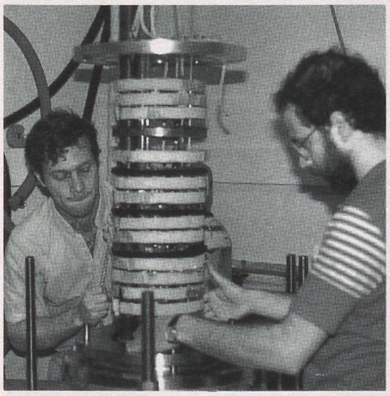
[2] Stanley Kowalski
[6] Robert Ledoux
[1] Earle Lomon
[2,3] June Matthews
[1] Ernest Moniz
[1] John Negele
[1] Janos Polonyi
[2,3] Robert Redwine
[6] Stephen Steadman
[2] William Turchinetz
[1] Felix Villars
[2] Claude Williamson



Atomic, Molecular, and Optical Physics



Top: Lowering superconducting magnet into dewar. This magnet is used to trap neutral atoms which are cooled to submilli-Kelvin temperatures using laser cooling.

Left: A graduate student is shown by his apparatus used to study the radiative decay of atoms in optical resonators. In the experiment, barium atoms in an atomic beam are excited by a continuous wave dye laser very near the center of a concentric mirror resonator. Because of the effect of the resonator on the vacuum density of modes, effects such as enhanced and inhibited spontaneous emission, and modified radiative energy level shifts may be observed.

The central goals of atomic, molecular, and optical physics are to understand how matter is composed and how it evolves at the atomic and molecular level, to understand the interaction of light with matter, and to create new techniques and devices for studying fundamental physics using atoms as probes. At MIT, for example, the basic interaction between radiation and matter is currently being probed by experiments to modify and control the rate of spontaneous emission of atoms and to measure the momentum transferred by intense radiation. As another example, a molecular microscope is being developed for biological studies.

Tunable lasers have revolutionized this field of physics, and are currently being used to study superradiance, the diffraction of atoms by light, quantum electrodynamics in a cavity, and the structure of Rydberg atoms in intense magnetic fields. They also play essential roles in experiments to slow and trap neutral atoms and cool them to 10^{-6}K, and in experiments to orient and study isomeric nuclei. Lasers are also being applied at MIT to study collisions of state-selected molecules, collisions of molecules in precisely defined superpositions of quantum states, and collisions in which the velocity is determined using the Doppler shift. In addition, picosecond lasers and associated spectroscopic techniques are under development.

The techniques of atomic, molecular, and optical physics–high resolution spectroscopy, interferometry, particle traps, supersonic molecular beams and tunable lasers–are usually involved in physical measurements at the frontiers of precision. A current example is the development of techniques to trap individual ions and compare their masses with accuracies of one part in 10^{12}. This has applications to determination of the fundamental constants and also to limits on the neutrino rest mass. Another example is the determination of the Rydberg constant in highly excited atoms where the frequency (rather than the wavelength) of the radiation can be measured to an accuracy approaching one part in 10^{11}.

Faculty in Atomic, Molecular, and Optical Physics

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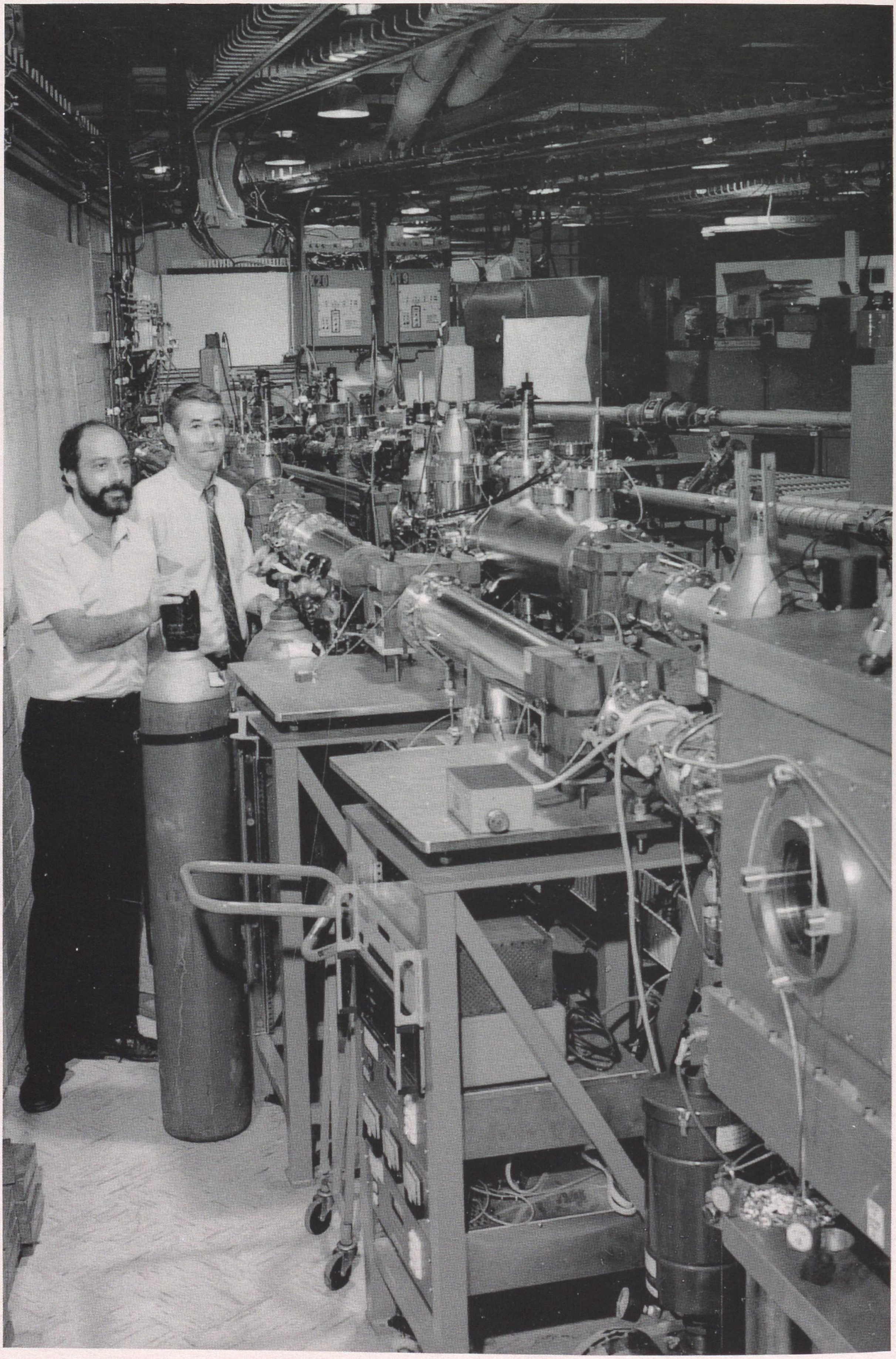
Ali Javan
John King
Daniel Kleppner
David Pritchard



Condensed Matter Physics

MIT-IBM X-ray beam lines at the National Synchrotron Light Source at Brookhaven National Laboratory. This is a cooperative MIT-IBM research program headed by Dr. Paul Horn who is Manager of Statistical Physics at IBM T.J. Watson Research Center and Prof. Robert Birgeneau who is a professor in our department (both shown).

This field covers a wide range of topics which include those of solid-state physics. A decade ago, most solid state physicists were concerned with crystals–of metals, insulators, semiconductors, superconductors, and magnets. Today, their interests have broadened to include non-crystalline solids, organic and biological materials, and liquids. Research in all these areas, both the new and the old, is carried out in the condensed matter group at MIT.

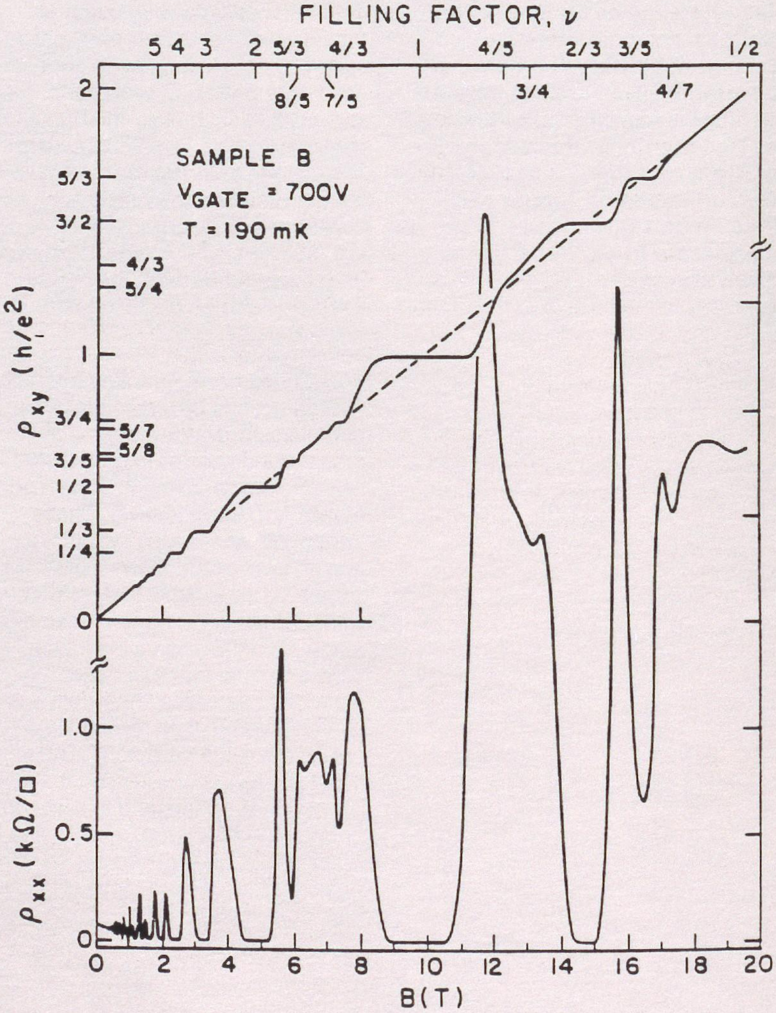
Though the basic quantum mechanical interactions between electrons and atoms are understood, they manifest themselves in remarkable and unexpected ways in condensed matter. Superconductivity, phase transitions, and liquid crystals are examples of phenomena that would be almost impossible to anticipate, without prior knowledge of their existence, from the underlying interactions and quantum mechanics. In each of these cases, the whole is somehow more than, and quite unlike, the sum of the parts. The central challenge of condensed-matter physics is to understand this fact; to understand how large, many-body systems can have properties so grossly different from those of their constituents.

Condensed matter studies demand a continuous interplay of experiment[1-10,17-19,20] and theory.[11-16] Thus, though individual faculty members in the condensed-matter division lead their own research groups, there is also active collaboration between groups. The experimental methods used to study condensed matter are diverse. They include laser light and neutron and x-ray scattering, as well as electronic and optical techniques.

An area in which MIT is one of the leading institutions in the world is in the study of phase transitions. The experimental program is very strong, emphasizing systems which exhibit unusual types of transitions. For example, neutron scattering[2] is used to study the problem of magnetism in random magnetic alloys, and x-ray scattering reveals the fascinating phases of liquid crystals[2,6] and the phases of gases absorbed on surfaces.[2] Ultralow temperatures are used to study the phases of hydrogen maintained as atoms instead of molecules by intense magnetic fields.[4] The techniques of laser light scattering was pioneered at MIT as a probe of phase transitions. They are now used in studies of polymers, gels and microemulsions[1,6,10] and to study biological problems such as antigen-antibody clustering and the structure of the lens of the eye.[1]

The fractional quantum Hall effect (FQHE): (a) Hall resistivity vs magnetic field, (b) diagonal resistivity vs magnetic field. The Landau level filling factor is given at the top. The FQHE consists of the plateaus and minima observed at fractional Landau level filling factor.

In a two dimensional electron system there are plateaus in a plot of ρ_{xy} (Hall resistivity) versus field. The value of ρ_{xy} at the plateaus is accurately given by the formula $\rho_{xy} = h/\upsilon e^2$ where υ is a small integer, or fraction. The former is a single particle effect; the latter a many body effect.



Faculty in Condensed Matter Physics

Many of the fundamental new ideas that have emerged in the study of phase transitions are being applied to the study of the electronic properties of solids. For example, the role of reduced dimensionality is being explored[5] using the capability of the electrical engineers to make electronic devices so small that new quantum mechanical effects are observed. The practical properties of electronic materials and their fabrication and utilization as devices with new applications, are being explored.[20] Intercalation of graphite[3] is used to produce quasi-two-dimensional conductors. These new materials, with various atoms or molecules between the graphite layers, display novel structural, magnetic, and electronic conductivity properties.

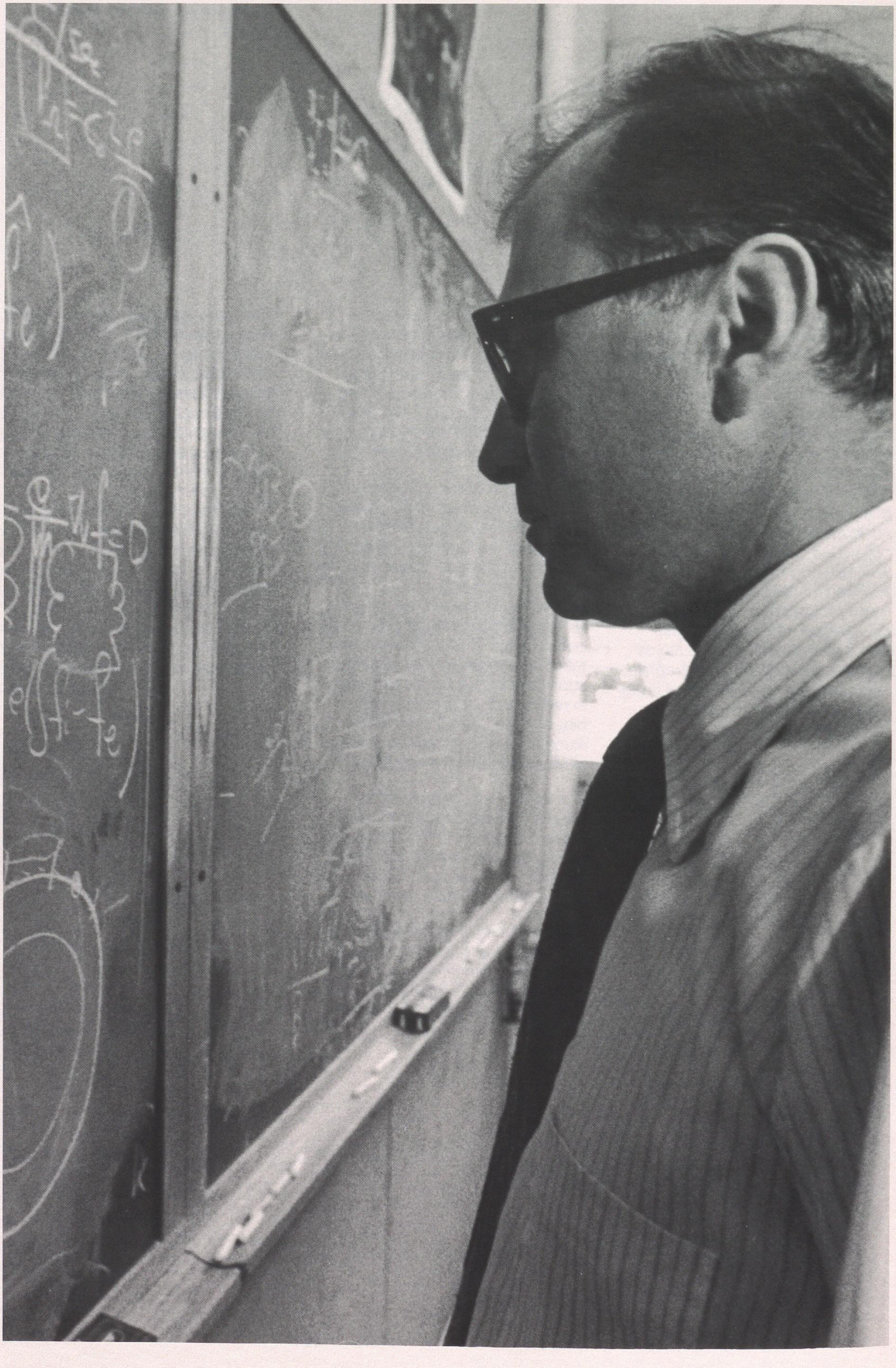
The role of disorder has been of great interest in electronic systems for a long time. There are active programs in the study of disordered semiconductors[5,10] and semimagnetic semiconductors.[10] The role of disorder in phase transitions is now also an active area of research.[2,11]

One strength of the condensed-matter theory group at MIT is the close relationship between the interests of the theorists and those of the experimentalists. Phase-transition problems are being studied[11,12,13,15,16] by a variety of techniques including renormalization-group theory. Many-body theory[15,16] is used to explore the effects of disorder on normal and superconducting metals especially in reduced dimensionality. Techniques have been developed to study electronic states in disordered semiconductors and insulators.[12]

The level of activity is strengthened by the participation of senior research scientists[17-19] working on problems such as nonlinear optics,[17] semimagnetic semiconductors,[18] and superconducting materials.[19]

All in all, there is a spirit of great excitement because of the diverse activity and close interaction between students and faculty using varied approaches to study related problems.

[17]Roshan Aggarwal
[1]George Benedek
[11]Nihat Berker
[2]Robert Birgeneau
[3]Mildred Dresselhaus
[19]Simon Foner
[4]Thomas Greytak
[12]John Joannopoulos
[13]Mehran Kardar
[5]Marc Kastner
[14]George Koster
[15]Gabriel Kotliar
[16]Patrick Lee
[6]David Litster
[20]Margaret MacVicar
[7]Clifford Shull
[8]Malcom Strandberg
[9]Toyoichi Tanaka
[10]Peter Wolff



Plasma Physics

Prof. Bruno Coppi reflecting upon properties of plasmas ignited by nuclear fusion reactions.

The plasma group at MIT studies a wide variety of problems ranging from astrophysical plasmas to laboratory and fusion grade plasmas. This work combines theory and experiment, and involves faculty members from both physics and engineering departments. The program has the dual goals of understanding plasmas throughout the universe and of designing plasma containment devices with the ultimate aim of understanding the physics of plasma confinement and heating.

Studies of Nonneutral Plasmas

A conventional plasma, consisting of electrons and positive ions, is electrically neutral, whereas an unneutralized plasma is composed of a single charged species of particles. An example of such a system is an electron beam propagating in high vacuum and confined against its own repulsive forces by strong magnetic fields. At MIT experimental and theoretical studies are being carried out on unneutralized relativistic electron beams including such topics as studies of electron beam equilibria, novel accelerator physics, and generation of coherent electromagnetic radiation (free electron lasers).

The experimental facilities include three high voltage, high current accelerators that can produce electrons with energies up to 2 MeV and 50 kA currents.

The possibility of developing lasers and masers in which the active medium is a stream of free electrons has evoked much interest in recent years. The potential advantages are numerous and include continuous frequency tuning through variation of the electron energy, and very high-power operation, since no damage can occur to this lasing medium as can happen in solid, liquid, and gas lasers. Some of the potential applications of the new generation of free-electron radiation sources are the following:

Spectroscopy

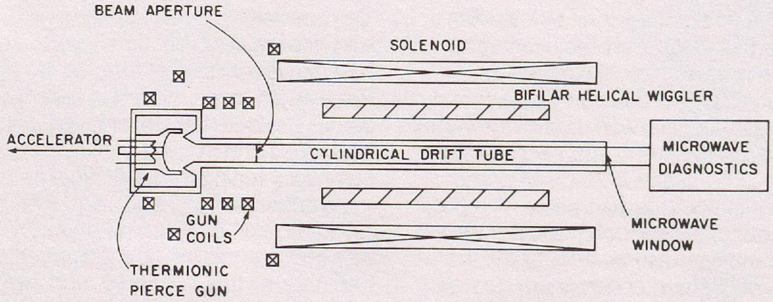
This area involves spectral studies in condensed-matter physics and spectroscopy of atoms, molecules, and ions; isotope separation; surface studies in the presence of absorbed molecular species; dynamics of charged carriers in semiconductors; fast chemical kinetics; and photochemistry.

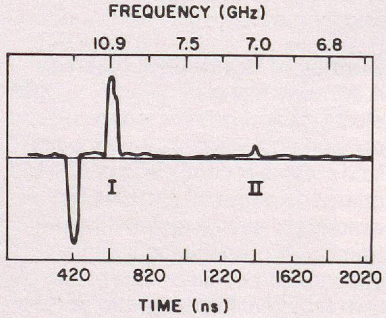
Accelerators

High-power microwave tubes have traditionally been important in the development of radio-frequency accelerators. The development of high-power, centimeter-wave sources could be of much value for the high-energy-accelerator community.

Thermonuclear Fusion

The problems of plasma heating are still impeding the practical development of magnetic fusion power reactors. The development of high-power sources at millimeter wavelengths could solve some of these problems.





(a) Schematic drawing of a free electron laser operating at a wavelength of approximately 3 cm.

(b) Oscilloscope trace showing intense (~1 MW) radiation at a frequency of ~11 GHz.

The three most important free-electron radiation sources actively studied at MIT are (i) cyclotron resonance masers (CRM) of which the gyrotron is a typical example; (ii) the free-electron laser (FEL); and (iii) the relativistic magnetron.

The CRM, which is by far the most advanced as a practical device, consists of a beam of monoenergetic electrons streaming and gyrating in an external guiding magnetic field. The emission mechanism is essentially stimulated synchrotron (or cyclotron) radiation. The radiation frequency is approximately equal to the electron cyclotron frequency, resulting in intense radiation in the centimeter and millimeter wavelength ranges.

In an FEL, a beam of monoenergetic electrons is injected into a spatially periodic magnetic field, which imparts an undulatory motion to the electrons. The wavelength of the radiation is proportional to the periodicity. When a high-voltage accelerator is used to produce electron speeds that approach the speed of light, the constant of proportionality can be very small compared with unity, and extremely short (submillimeter) wavelength radiation can be thereby achieved.

In the relativistic magnetron, an electron stream with relativistic velocity passes over a periodic assembly of resonators in which electromagnetic radiation is induced and stored. High powers (~1-10 GW) are achieved by using field-emission cathodes to create extremely high current streams. The radiation wavelength, being approximately equal to the spacing between resonators, is in the centimeter region.

Studies of Plasma Containment

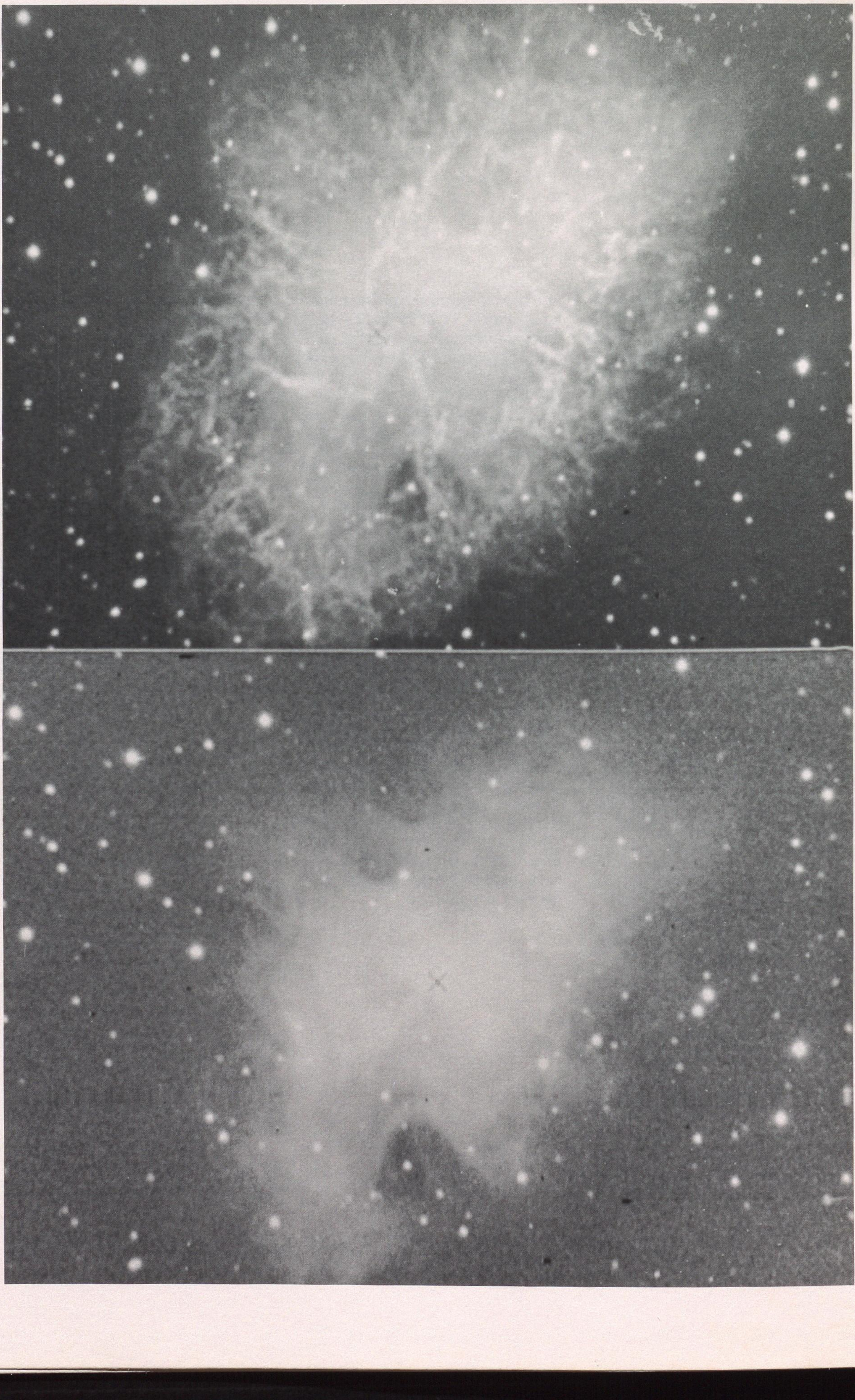
At the MIT Plasma Fusion Center, pioneering investigations are being carried out on the equilibrium, stability, and confinement properties of plasmas at high densities, temperatures, and magnetic fields. Alcator C is a toroidal (tokamak) plasma containment experiment. The device operates at very high magnetic fields (up to 120 kG) and high densities ($\bar{n}_e \sim 10^{21} m^{-3}$), contains plasma energies for up to 50 msec, and has achieved electron and ion temperatures of several thousand electron volts ($> 10^7$ K). In the last few years Alcator C has (a) achieved the world record value of the "confinement parameter," $\bar{n}_e \tau_E \sim 8 \times 10^{19} m^{-3}$-sec using pellet injection; and (b) demonstrated that toroidal plasma currents can be generated efficiently by high power traveling electromagnetic waves with frequences in the GHz range. In particular, several hundred kiloamperes of current were generated upon injection of 1 MW of microwave power at densities $\bar{n}_e \sim 10^{20} m^{-3}$, a world record value. Both Alcator confinement and current drive experiments received the "Excellence in Plasma Physics Research Award " of the American Physical Society. Recently a new experiment (Alcator C-MOD) has been funded. It will replace Alcator C and investigate the basic confinement and stability properties of elongated, diverted plasmas in a high-field, RF-heated tokamak.

The basic physics of high-temperature plasmas, including the development of advanced diagnostics, is also being pursued on the Versator II tokamak and on the TARA and CONSTANCE II mirror machines. In the Versator II and CONSTANCE experiments, detailed investigations of the physics of wave propagation, radiofrequency heating, instabilities, and radiofrequency current generation are carried out, while in the TARA experiment, an innovative design for axisymmetric tandem mirrors, research is being performed on advanced mirror physics, including that of thermal barriers.

Finally, it should be noted that the MIT staff is also involved in collaborating with the fusion research programs of other laboratories, including the Princeton University Plasma Physics Laboratory and Lawrence Livermore National Laboratory. Expansion of such collaboration in the future is expected, including collaboration at the international level. In accordance with growing national interest, there have also been several new proposals submitted to expand the work on nonneutral plasmas.

Faculty in Plasma Physics

George Bekefi
Bruno Coppi
Ronald Davidson
Thomas Dupree
Benjamin Lax
Miklos Porkolab
Richard Temkin



Astrophysics

The Sbc spiral galaxy M51, 5 million parsecs distant, is a prominent member of one of the nearest clusters of galaxies. M51 is not too dissimilar to our own galaxy, except that the tides from its irregular elliptical companion are apparently raising very prominent spiral arms, marked by dust and blue, young stars. This picture is a mosaic of four, 90 second CCD images taken on the Palomar 60″ telescope through a green filter.

These two views of the Crab nebula show its appearance in red light (top) and blue light (bottom). The Crab nebula is the remnant of a titanic supernova explosion that was observed on earth in 1054 A.D. The material hurled outward has been interacting with the interstellar medium and emitting light that we see today. There are two major sources of emission: synchrotron emission of relativistic electrons in the nebula circling magnetic field lines, and line emission from blobs of gas that have been shock-heated to high temperatures and which are now cooling. The blue picture is almost entirely synchrotron radiation; notice the smooth, wispy appearance. The red picture is dominated by a hydrogen emission line that causes the filaments and knots of gas to stand out in sharp relief.

Astronomy, the oldest of the physical sciences, is nonetheless a frontier field of contemporary physics. What is the nature of the non-luminous matter that comprises most of the mass of the Universe? How do systems of many gravitationally interacting bodies evolve? How do the active nuclei of some galaxies hurl thin streams of tenuous plasma across millions of light years of intergalactic space? What does observational cosmology tell us about particle physics at energies beyond the range accessible to accelerator experiments? Do gravitational waves exist? These are among the challenging questions confronting astrophysicists at MIT who observe phenomena with the instruments of modern technology and seek to understand the observations in the framework of classical mechanics, quantum theory, and general relativity.

Research facilities used by faculty and students include several major installations directly associated with MIT, namely the 120-foot radio telescope of the Haystack Observatory in Westford, Massachusetts; the Wallace Observatory with a 0.4-meter and a 0.6-meter telescope, also in Westford; and the 1.3-meter and 2.4-meter telescopes at the McGraw-Hill Observatory on Kitt Peak in Arizona (jointly owned and operated by the University of Michigan, Dartmouth College and MIT). Observers also make frequent use of the national facilities such as the Very Large Array (VLA) for radio observations, the 4-meter telescopes of the National Optical Astronomy Observatories at Kitt Peak and Cerro Tololo in Chile, and the various orbiting observatories. Theorists use the extensive computing facilities available on campus and through the national networks, and they have the benefit of close proximity to the Center for Theoretical Physics where they can discuss developments with colleagues working in the related fields of particle and nuclear physics. The Center for Space Research (CSR) provides engineering and management support for the design and development of instrumentation for ground-based and satellite astronomy, and for space plasma measurements. For radio and infrared astronomy the Research Laboratory of Electronics (RLE) provides expert assistance in the development of detectors and data systems.

Many of the recent major advances in astrophysical knowledge have come from explorations of the sky in the non-visible portions of the electromagnetic spectrum, in particular in the radio, infrared, X-ray, and gamma-ray regions. Such explorations, and the subsequent refinement of observations through measurements with greater and greater resolution, have been dominant themes of observational astronomy at MIT since the end of World War II.

The X-ray astronomy group[1] has carried out many observations with scientific satellites bearing instruments developed in part or entirely in the CSR, e.g. the SAS-3 X-Ray Observatory (1975-1979) for which the entire scientific payload was developed at MIT, the modulation collimator positional survey instrument and the high energy X-ray detector on the High Energy Astrophysics Observatory HEAO-1 (1977-1979), and the focal plane crystal spectrometer on the Einstein X-Ray Observatory (1978-1981). Among the objects most extensively studied with the SAS-3 Observatory are the various kinds of accretion-powered binary X-ray stars, particularly pulsars, bursters, and black hole candidates. The HEAO-1 studies have yielded precise positions of numerous faint X-ray sources which have subsequently been identified through optical observations with many types of objects including neutron-star systems and active galactic nuclei.

The Einstein spectrometer has provided the data for the first analyses of million-degree plasmas in supernova remnants by the use of high-resolution spectroscopic diagnostics. Currently a new generation of instruments is under development at the CSR for the next X-ray astronomy missions, namely the flight data-analysis computer and an all-sky survey instrument for the X-Ray Timing Explorer (XTE), and two instruments for the Advanced X-Ray Astrophysics Facility (AXAF)–a charge-coupled device (CCD) camera and grating spectrometer and a high resolution Bragg reflection spectrometer. The AXAF, planned for launch in the mid 1990's, will be a long-lived national orbiting observatory maintained by astronaut visitations. In the area of ground-based high-energy astronomy, a system of computer-controlled optical telescopes with CCD detectors, the Explosive Transient Camera, has recently been installed on Kitt Peak to carry out the first exploratory survey of the sky for brief optical flashes of the kind that are believed to be associated with the mysterious gamma-ray bursts previously detected by satellite instruments. During the past three years many very successful guest observations have been made with the European X-ray Observatory, EXOSAT.

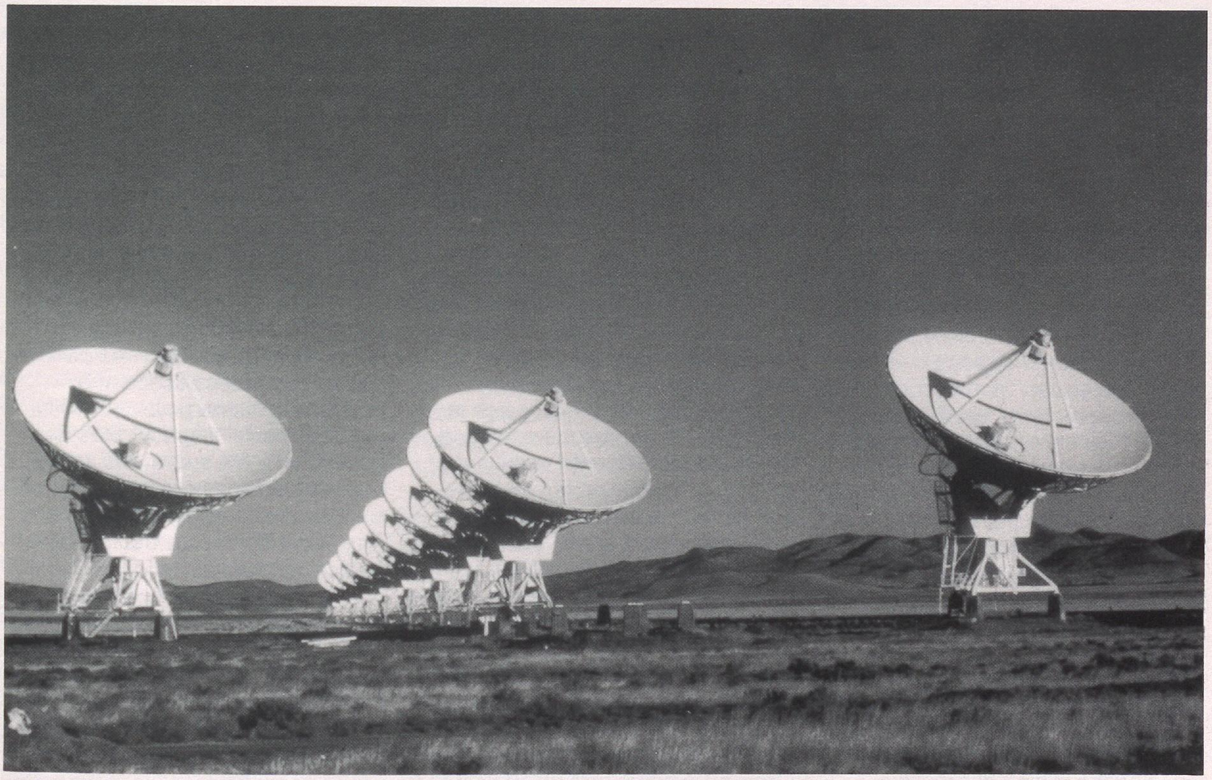
Radio astronomy,[2] concerned with observations at the long-wavelength end of the electromagnetic spectrum, provides complementary information about many of the same objects that are studied in X-ray astronomy. High energy processes often simultaneously produce both X-rays and radio emission, but with relative intensities that depend critically upon the physical conditions. Supernova remnants, radio galaxies, and quasars are well-known classes of radio sources which are also prolific sources of X-rays. Comparative studies in these two widely separated regions of the spectrum contribute much to the growing understanding of these objects.

The very-long-baseline interferometry technique (VLBI) is used in the study the milliarc-second structure of quasars and other active galactic nuclei. This extraordinary angular resolution, far greater than that attainable in any other region of the spectrum, is achieved by computer correlation of signals recorded simultaneously on videotape at radio telescopes separated by thousands of kilometers. Such observations reveal, for example, the structure of plasma jets near their sources in the nuclei of galaxies, and the presence of angular motions in quasars that correspond at their great distances to apparent transverse velocities exceeding by several times the speed of light. MIT is also involved in the development of the new national facility for transcontinental VLBI called the Very Long Baseline Array (VLBA), and in the design work aimed at placing a large radio telescope in a highly elliptical orbit to supplement the VLBA.

Another area of research by MIT radio astronomers is gravitationally lensed quasars. These objects are observed as spectrally identical pairs of quasars separated by a few arc seconds, and they are believed to be the result of the gravitational deflection of light from a single distant quasar by an intervening massive object such as a galaxy or cluster of galaxies.

The Very Large Array (VLA) is the most powerful radio telescope in the world. It has 27 individual antennae, each 25 m in diameter. Spread out over the plains of San Augustine in New Mexico, the data from these antennae can be combined to mimic a radio telescope with a 35 km diameter.

The resulting radio images are of extremely high quality and provide sub-arcsecond resolution. MIT researchers make extensive use of the VLA to study star formation, radio galaxies, gravitational lensing, and many other astronomical phenomena of current interest.



The Haystack Radio Observatory and the millimeter radio telescope of the National Radio Astronomy Observatory are used for microwave spectrometry of the giant molecular clouds in which new stars are forming. Molecules ranging in complexity from OH and CO to formaldehyde, ethanol and even larger compounds are found in surprising abundance, possibly the precursors of life on planets. Observations have also revealed the existence in these clouds of cosmic masers–regions in which certain molecules, "pumped " by radiation from newly formed stars, donate their excess energy to passing radio waves by stimulated emission in such a manner as to amplify the waves, producing for the observer highly variable point-like radio sources with peculiar and unmistakable spectral characteristics.

Optical astronomy is now a principal area of research at MIT following the acquisition of a major telescope, the 2.4-meter at McGraw-Hill Observatory, and the joining of a faculty member[3] primarily interested in optical observations. In addition, several of the faculty working mainly in other areas now spend a substantial portion of their research efforts on problems that require optical observations. Among recent and current topics of research are accretion flows near giant elliptical galaxies, the nature of multiple nuclei in elliptical galaxies, the properties of optical flashes that accompany the production of X-ray bursts, and the correlations between the optical and X-ray characteristics of active galactic nuclei.

Infrared and microwave astronomy is still an exploratory venture in which great strides in sensitivity and analytical capability are being made through the development of sensor technology. At MIT the research in this region of the spectrum, carried out by the experimental cosmology group,[4] is focused on the measurements of the spectrum and directional variations of the 3K background radiation which is believed to be the remnant radiation from the Big Bang. Balloon-borne instruments are being developed and flown to obtain precise measurements at submillimeter wavelengths. The MIT group also has the principal scientific responsibility for the scientific guidance of the Cosmic Background Explorer satellite mission, and for the development of an appropriate data analysis system for the mission.

Another project in experimental cosmology is the development of an interferometric detector of gravitational radiation. Carried out jointly with CalTech and funded by the National Science Foundation, this work is aimed at the deployment of two gravitational radiation detectors to be located on the east and west coasts of the United States, and to be operated in coincidence to achieve a dimensionless strain sensitivity better than one part in 10.^{21}

With such sensitivity, sufficient to detect a shrinkage of one atomic diameter in a rod spanning the distance from the earth to the sun, it may be possible to detect the gravitational radiation emitted in cosmic processes involving rapid relative motions of massive objects such as would occur in the formation or interaction of neutron stars and black holes.

Experimental and theoretical research in the astrophysics division also encompasses space and laboratory plasma physics.[5] *In situ* measurements of space plasmas, governed by the same laws as the confined plasmas now studied intensively in laboratories, afford opportunities to study directly the behavior of plasmas naturally occurring in nature. The space plasma group has developed plasma detectors for many Earth-orbiting and deep space probes. Results from these instruments have delineated the structure of the solar wind throughout the solar cycle, and have elucidated the complex interactions of the solar wind with the planets and with Halley's comet. MIT measurements internal to the five known magnetospheres in the solar system (Mercury, Earth, Jupiter, Saturn, and Uranus) have provided a wealth of information about the plasmas in planetary magnetospheres, their sources, transport, and energization.

Similar information is expected at Neptune from the MIT plasma detector on board Voyager 2, which encounters that planet in 1989. In addition to continuing data analysis, the group is currently involved in developing instrumentation for the WIND spacecraft, a part of NASA's Global Geospace Science program.

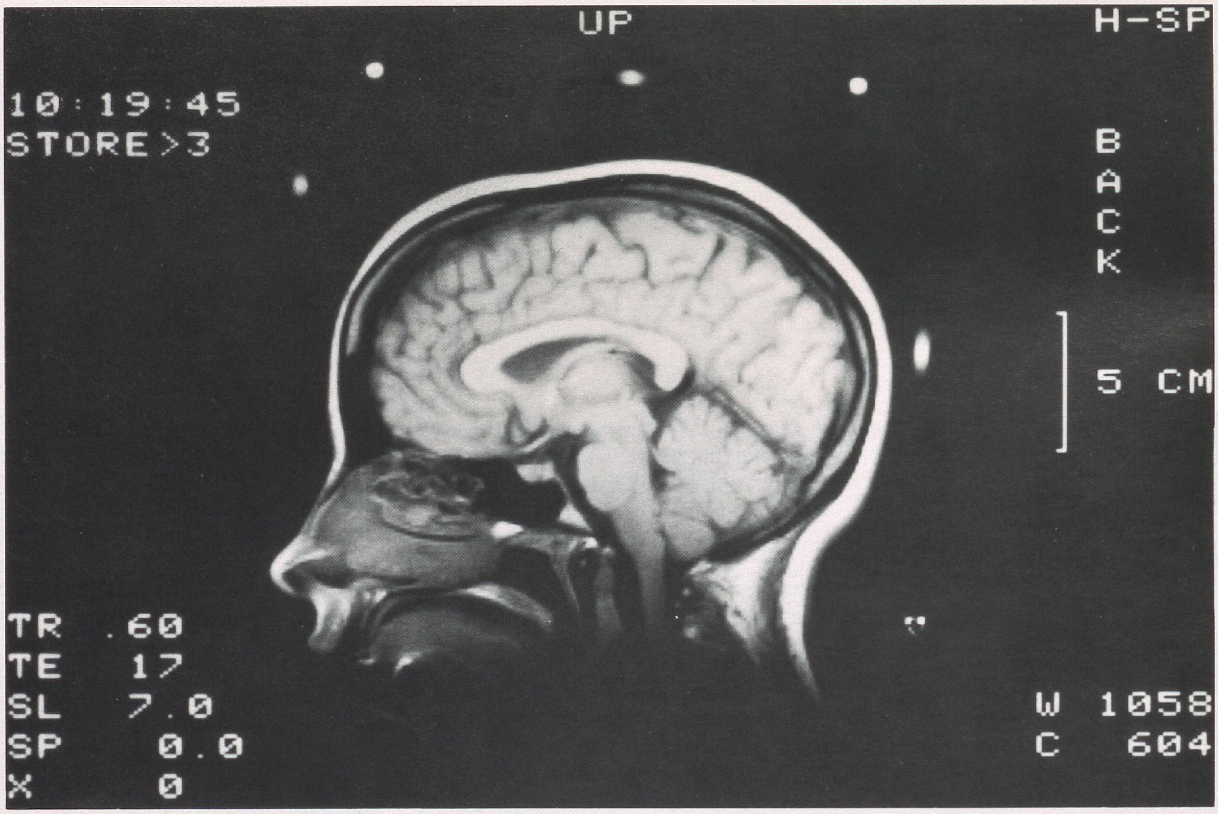
In the area of the theory of space plasmas, a new Center for Theoretical Geoplasma Research has recently been established at MIT, sponsored primarily by the Air Force Office of Scientific Research under the University Research Initiative Program. The goal of this Center is to foster theoretical investigations in terrestrial ionospheric and magnetospheric physics. There is currently a substantial program to study magnetospheric and ionospheric turbulence, as well as wave generation and propagation in the geoplasma environment. These studies apply the basic kinetic theory of charged particles in magnetized environments to problems involving weak and strong turbulence, plasma instabilities, the effects of collective wave-particle interactions, and auroral ionospheric-magnetospheric coupling processes.

Theorists[6] in astrophysics are currently concerned with a wide variety of topics including the early universe, the formation and structure of galaxies, gravitational lenses and their cosmological implications, cosmic masers, star formation, low-mass binary systems, X-ray bursts, millisecond radio pulsars, "brown dwarf" stars, gamma-ray bursts, planetary rings, and the solar wind and its interactions with the various bodies in the solar system. One recent study, involving the close collaboration of particle and astrophysics theorists, has examined the possibility that "strange" matter, consisting of aggregates of up, down, and strange quarks that may have been formed in the Big Bang, survived the high temperatures of the first few moments and is present now somewhere in the universe.

Research in other areas of observational and theoretical astrophysics is carried out in other departments at MIT. In the Department of Mathematics astrophysics research is concentrated in galactic dynamics and hydrodynamics. In the Department of Earth, Atmospheric, and Planetary Sciences[7] the work is concerned with solar system phenomena including planetary atmospheres and surfaces, comets, and planetary rings. Observational work is carried out with ground-based telescopes, the NASA Kuiper Airborne Observatory, and on planetary probe missions such as the Magellan Venus Radar Mapper.

Faculty in Astrophysics

[5]John Belcher
[6]Edmund Bertschinger
[1]Hale Bradt
[2]Bernard Burke
[1]Claude Canizares
[1]George Clark
[5]Bruno Coppi
[2]John Dreher
[7]James Elliot
[6]Paul Joss
[5]Alan Lazarus
[1]Walter Lewin
[5]Ralph McNutt
[4]Stephan Meyer
[6]Philip Morrison
[5]Stanislaw Olbert
[7]Gordon Pettengill
[1]Saul Rappaport
[6]Steven Stahler
[3]John Tonry
[4]Rainer Weiss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SL 7.0
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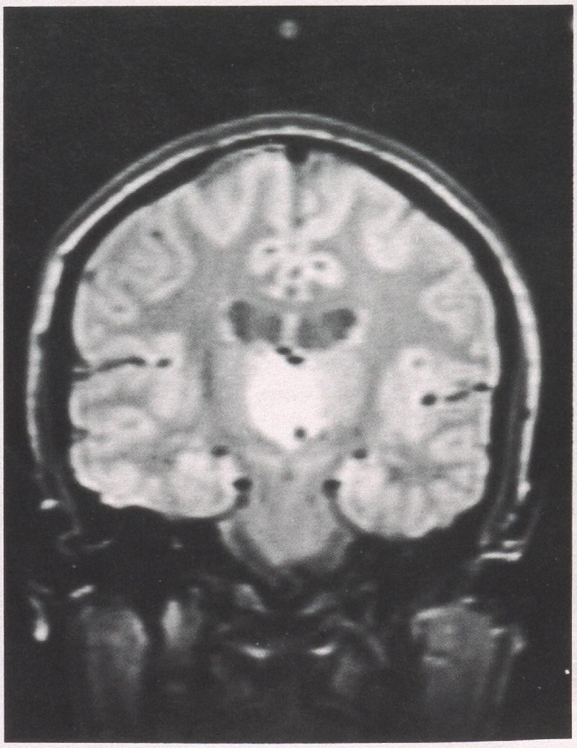


Biological and Medical Physics

These figures are of nuclear magnetic resonance imaging (MRI) of the human brain at 1.0 to 1.5 Tesla magnetic field strength. The intensity on each image is a map of the radio frequency (rf) induction signals from precessing hydrogen proton magnetic moments at each tissue site. The moments are driven into precession about the MRI machine's magnetic field by external rf field pulses. The detected induction signals are decoded spacially by their differing Larmour precession frequencies in a predetermined magnetic field gradient to derive the anatomical images. The brain's structures show up differently because of their differing hydrogen densities and spin-lattice and spin-spin relaxation times, providing exquisite detail of grey and white matter, aqueducts, and nuclei. Progress towards higher resolution, chemical shift and spectroscopic imaging, and accurate image measurements holds great promise for analysis of the body's anatomy and function. Notable are the fiducial image spots about the head in these images. They originate from a localization structure attached to the head, and enable precise position measurements within the brain for clinical studies.

Research in medical physics at MIT has touched on several clinical problems, and involves collaborations with many medical centers both in the United States and abroad. An outline of some of the work that is being done at the present time follows:

Magnetic Resonance Imaging Research[1]

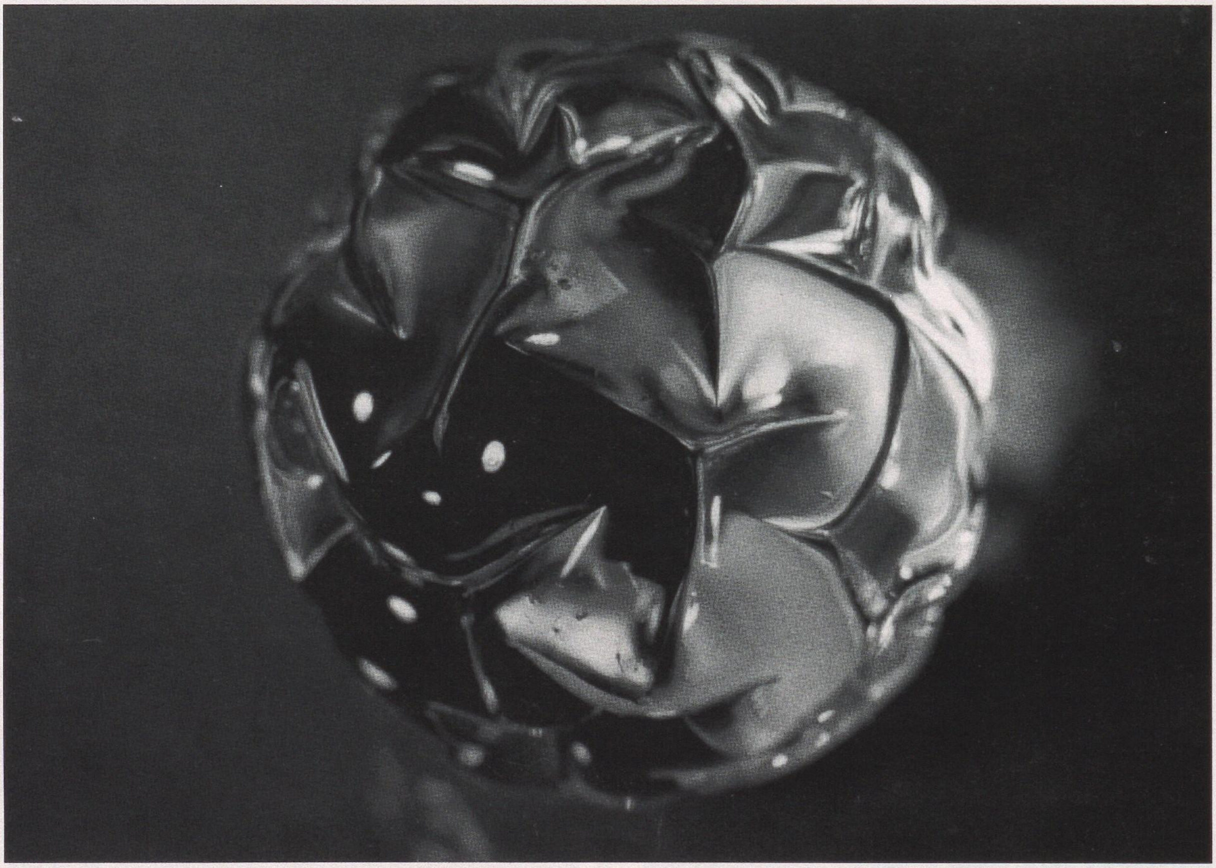
This year MIT will be receiving a 1.5 Tesla field strength magnetic resonance imaging (MRI) machine from the Siemens Corporation in Germany to be installed at the National Magnet Laboratory here on campus. Among the research activities to be conducted with this machine will be development of precise localization means to transform from MRI image data to actual three-dimensional target points and volumes within the head or body. The objective of this is to define more accurately regions of pathology so that they can be reached by surgical means, treated by external beam or interstitial radiation, or to define their morphology as a function of time. Research into advanced surface coil design for high resolution imaging and possibly spectroscopic imaging is also under investigation.

Radiofrequency Interstitial Hyperthermia for the Treatment of Cancerous Tumors[1]

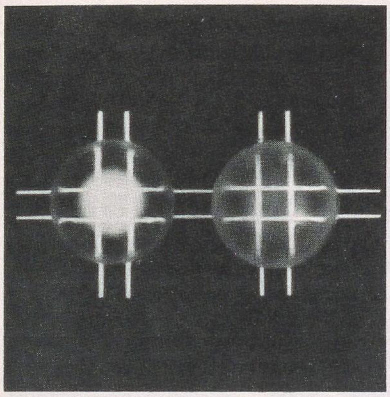
One of the new approaches to cancer therapy now in its early clinical trials is the use of interstitial hyperthermia combined with localized radiation therapy to destroy tumor cells. The basis for this is that tumor cells are apparently more thermosensitive than normal cells at temperatures between 42-45°C. There is reason to believe that cancers of the pancreas and liver which are now unresponsive to therapy may be responsive to hyperthermia plus radiation. A high power, multi-electrode radiofrequency heating system is being developed at MIT to enable uniform heating of tumors deep within the body with precise thermal control.

Intracranial Pressure Studies in Mechanics of the Cranial Cavity[1]

An outstanding clinical problem in neurosurgery is to monitor the intracranial pressure in patients who have brain tumors, head trauma, hydrocephalus, or who have experienced brain surgery. A unique telemetric pressure sensor has been developed at MIT for this purpose, and is now in routine clinical use. A variety of new physiological findings about the behavior of pressure as a function of patient elevation have been discovered which could lead to major advances in treatment of patients with diseases such as hydrocephalus.



When a spherical acrylamide gel swells in water into a large sphere, a regular pattern appears on the surface. The unit size of the pattern doubles with time, becoming comparable to the gel radius, and finally disappears.



A pair of calf lenses photographed at 10°C showing the effects of reagents developed at MIT. The lens on the left has a cold-induced cataract. The lens on the right, which has been treated with a reagent, is clear. While the results are promising, tests on human subjects are still several years away.

Cataract Disease and Microemulsions[2]

An MIT group is engaged in studies of the physical and chemical basis for cataract disease in the eye lens. On a molecular level it is possible to show that phase separation of the proteins in the lens cell cytoplasm or the formation of heavy molecular weight protein aggregates are responsible for cataract formation. Work is now under way to find suitable reagents to block these two processes and thereby inhibit cataract formation. This group is also engaged in a fundamental study of micelles and microemulsions which are the structures responsible for the transport of lipids in the gastrointestinal tract and in the blood. Also being studied is antibody-antigen clustering, the first step in the immune response.

Physics of Gels[3]

Another MIT group is studying phase transitions in polymer gels. This work is believed to have fundamental importance in understanding various biological phenomena including cell mobility, packing of DNA or proteins, osmotic properties of cells and tissues, neuron excitation, etc. Using the photon correlation spectroscopy the group studies the Brownian motion of macromolecules in single, live cells. It is applied in investigating protein synthesis in cells under differentiation, and aggregation of hemoglobin in sickle cell anemia.

Laser Treatment of Atherosclerosis[4]

A multi-disciplinary effort is underway to develop a laser catheter for percutaneous (remote) removal of arterial plaque in the coronary and peripheral arteries. The catheter, designed with an array of optical fibers encased in a transparent protective optical shield, delivers precise doses of laser light to a lesion. Guidance provided from spectroscopic signals collected via the fibers permits differentiation of normal artery wall from plaque and blood. A theory of biological tissue ablation predicts dosages as a function of laser and tissue parameters, and these predictions are in good agreement with experiments performed on human cadaver artery.

Spectroscopic Imaging of Biological Systems[4]

A new concept is being developed in which spectroscopic signals from an array of optical fibers are superimposed to produce spectral images or maps of tissue types and conditions within the body. In the approach, diagnostic pulses of laser light are carried to the area of interest within the body via the fibers, encased in a needle or canula. Each pulse induces a signal which is carried out of the body via the fibers, from which a multi-pixel image can be constructed. Basic research is being conducted on the properties and origin of spectroscopic fingerprints from a variety of tissues. Spectroscopic methods for measuring tissue properties such as temperature are also under study.

Laser Biomedical Research Center (LBRC)[4]

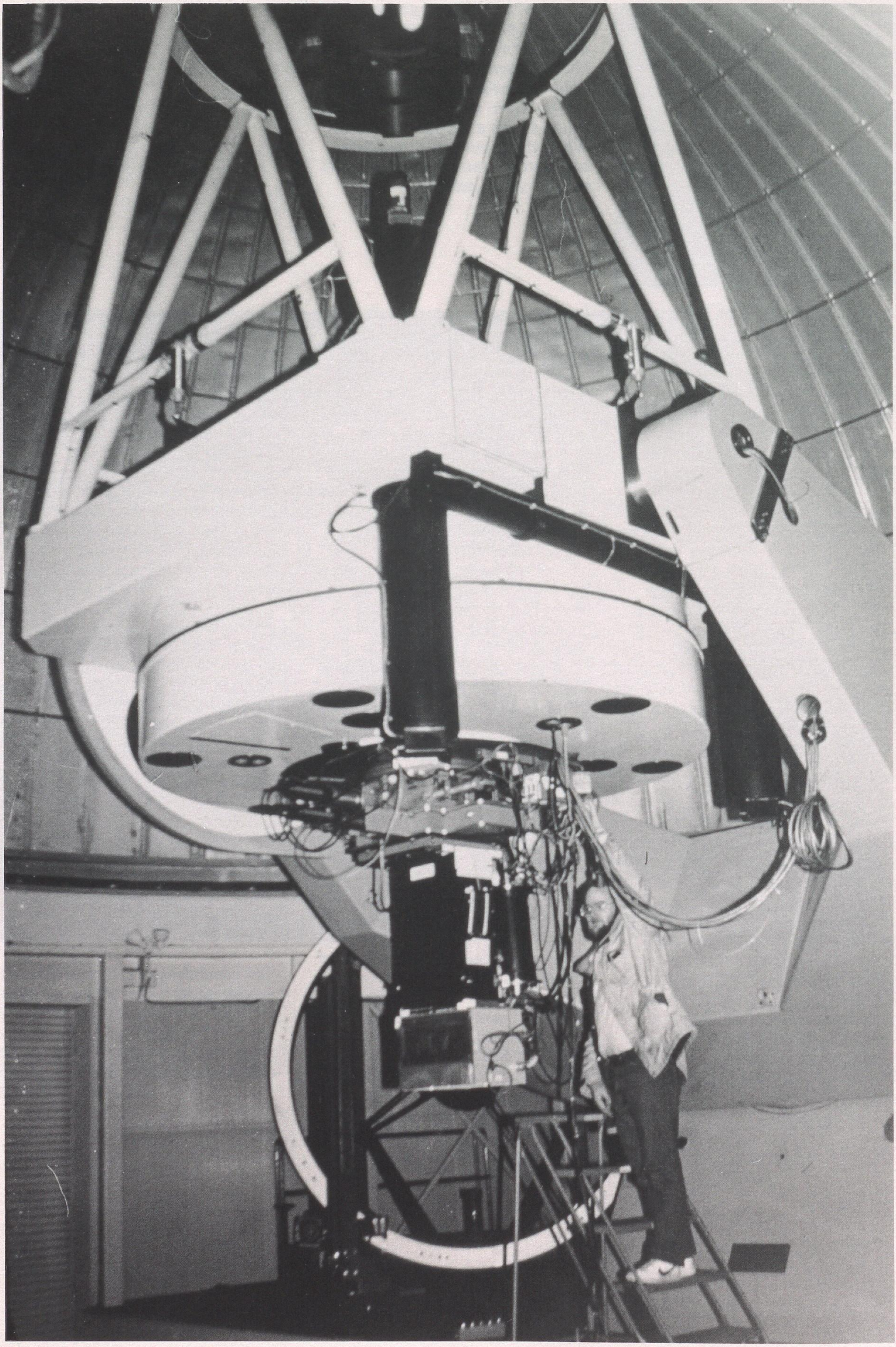
The National Institutes of Health has recently established a biotechnology resource center for research in the field of lasers and medicine in the MIT Spectroscopy Laboratory. The new center is acquiring a set of advanced laser sources, including a capability to produce continuously tunable laser radiation between 216 nm (UV) and 4500 nm (IR), specially adapted for laser biomedical studies. Research is ongoing in a variety of topics of laser biomedicine.

Fertility Control[5]

Another MIT group is investigating human fertility control, but the nonbiological part of this work is more engineering than physics and, thus, is not suitable for physics graduate students.

Faculty in Biological and Medical Physics

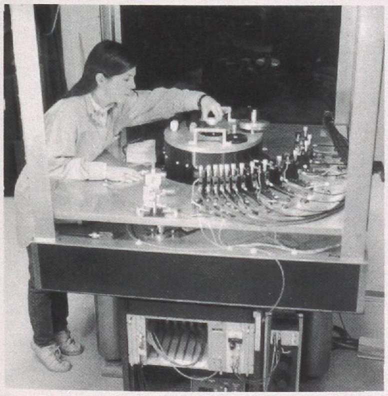
[2]George Benedek
[1]Eric Cosman
[4]Michael Feld
[5]David Frisch
[3]Toyoichi Tanaka



Facilities and Laboratories

Left: Michigan-Dartmouth-MIT 2.4 meter (100 inch) telescope at McGraw-Hill Observatory on Kitt Peak. MIT student with the MIT "MASCOT" CCD instrument.

Below: Quasielastic light scattering spectrometer, used for studies of phase transitions and critical phenomena in macromolecular solutions containing proteins, micelles, and microemulsions.



Bates Linear Accelerator Center

The William H. Bates Linear Electron Accelerator Center, operated under the joint auspices of the United States Department of Energy and the MIT Laboratory for Nuclear Science, is available for use by MIT research staff and by researchers worldwide.

The Bates Laboratory supports a broad program of research in electromagnetic interactions with nuclei. Facilities are available for high precision, high resolution electron scattering, for studying photoreactions including pion production, and for a variety of coincidence measurements. The maximum electron energy available is 850 MeV; a further increase to about 1 GeV is anticipated in 1987. A polarized electron source has been constructed, making possible studies of parity violation in electron scattering and spin effects in nuclear reactions. Plans are being developed to increase the beam duty factor to nearly 100 percent.

Center for Materials Science and Engineering

Major research programs currently supported by the Center emphasize interdisciplinary research in the following areas: 1) flow and fracture in high-temperature alloys; 2) defects in semiconductors; 3) phase transitions; 4) polymers; 5) innovations in high-strength steel technology. These programs are funded primarily through a grant from the National Science Foundation.

Participating in CMSE-funded programs are faculty groups from the Departments of Chemical Engineering, Chemistry, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Physics, and Nuclear Engineering. The Center collaborates with other research laboratories at MIT, including the Francis Bitter National Magnet Laboratory, the Materials Processing Center, and the Microsystems Technology Laboratories.

CMSE maintains excellent modern central service facilities such as crystal growing and characterization laboratories; spectroscopic facilities; scanning, transmission, and scanning-transmission electron microscopy; x-ray diffraction; analytical compositional analysis; ion microprobe; ion implanter; a polymer facility; rapid solidification; and scanning Auger, ESCA, and LEED analysis available in the Surface Analytical facility. Also available are the von Hippel Reading Room and a student machine shop.

Center for Space Research

The Center for Space Research offers students, faculty, and professional research staff opportunities to participate in a broadly based program of space-related research. Its projects draw upon the interests and expertise of scientists and engineers from many MIT departments and laboratories. Research programs are carried on, for example, in X-ray and planetary astronomy, space plasma and gravitational physics, and the life sciences. These experimental studies usually involve experiments carried by balloons, sounding

Aerial view of MIT-BATES Linear Accelerator Center.

rockets, orbiting satellites, or deep space probes. The experimental programs are supplemented by closely related programs of ground-based research in similar fields and by laboratory development of suitable instrumentation for the space-based and ground-based experiments. An active program of theoretical studies in astrophysics is also supported by the Center.

Laboratory facilities include X-ray sources, particle accelerators, vacuum chambers, and conventional electronic test and machine tool equipment. Extensive data handling and computational facilities are available for the analysis and reduction of scientific data. An experienced and well-equipped group of engineers and technicians provides design, construction, and testing of experiments in support of the flight programs.

The Haystack Radio Observatory, located in Westford, Massachusetts, about 40 miles north of Boston, is one of the world leaders in developing new techniques in radio astronomy. The 120-foot reflector is one of the highest-precision antennas in the world. It is used for studies of the structure of our galaxy and quasars, and is one of the key elements in the nation-wide VLBI consortium.

The McGraw-Hill Observatory comprises two modern optical telescopes, 1.3m and 2.4m in diameter, located atop Kitt Peak near Tucson, Arizona. Operated by a three-member consortium consisting of MIT, Dartmouth College and the University of Michigan, the Observatory makes these telescopes available for astronomical research to students and scientists of the member institutions.

Center for Theoretical Physics

The Center for Theoretical Physics houses a large group of theorists including professional staff, postdoctoral fellows, senior visitors, and graduate students engaged in research in theory. Opportunities for communication and collaboration are maximized within the Center; lively interaction among the many specialists in the various areas of interest is characteristic of this MIT group and is one of the major sources of the Center's strength.

The chief emphasis of the Nuclear and Particle Theory research at the Center for Theoretical Physics is on understanding the fundamental particles of nature, as revealed by their interactions and by their decay, and on the characteristic quantum modes of motion of systems composed of strongly interacting particles such as atomic nuclei. Work is also conducted on theoretical astrophysics, as well as on the properties of other forms of matter. In all of this research, close contact is maintained with experimentalists, both within MIT and elsewhere.

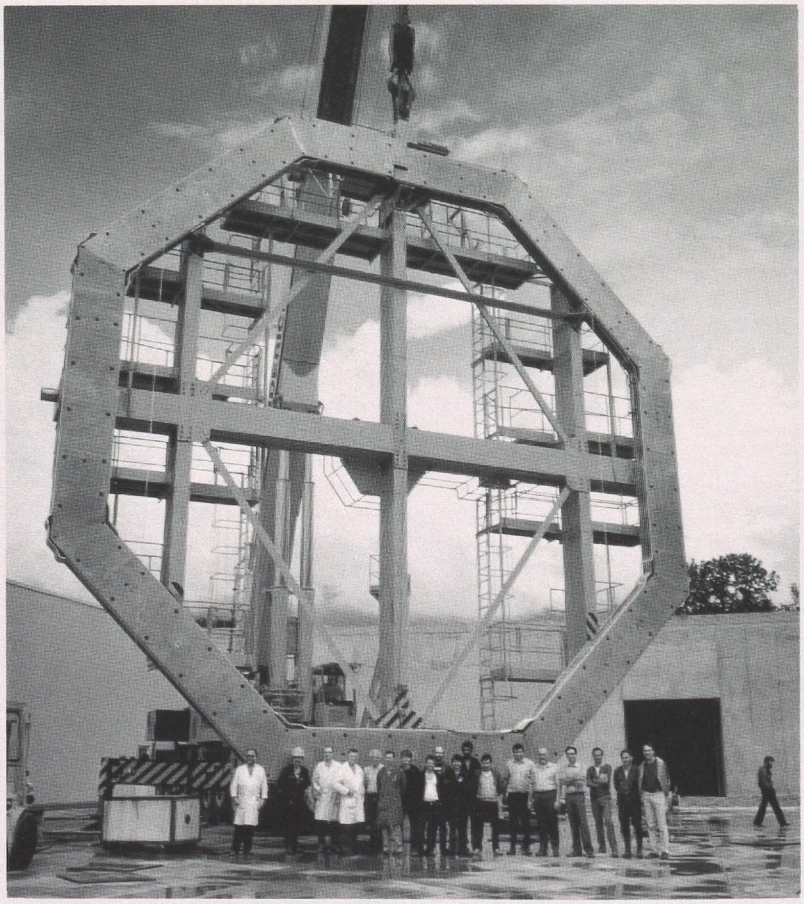
Laboratory for Nuclear Science

The Laboratory for Nuclear Science supports basic research in nuclear and elementary particle physics. It maintains and administers facilities adapted to studies in these fields. The Laboratory operates the Bates Linear Accelerator Center, the Center for Theoretical Physics, and a central computer facility available to students and staff. The Laboratory also is engaged in research in the application of nuclear and particle physics instrumentation to biological problems.

The Heavy Ion Group is part of a consortium at the Brookhaven National Laboratory. It is pursuing a new and exciting branch of physics that combines aspects of nuclear and particle physics as well as theory and experimental methods. Relativistic heavy-ion collisions allow the possibility of producing extreme energy densities, matter densities, and high temperatures (100 MeV). This enables the study of properties of nuclear matter, including collective properties, under conditions never studied before.

As part of the nuclear physics program, members of the Laboratory are engaged in an experimental program at the Bates Linear Accelerator Center and several related experiments are being conducted at the Los Alamos Meson Physics facility. The Bates Center serves as the national user facility for the study of atomic nuclei with electromagnetic probes and has done much to establish high resolution electron scattering and intermediate energy photoreactions as the tools of choice for addressing fundamental questions in our understanding of nuclear forces and structure.

The experimental high energy physics program is primarily off campus with a strong administrative and scientific base on campus. There are two programs at CERN in Geneva, Switzerland. The Electromagnetic Interactions (EMI) Group is building a huge detector (L3) at the Large Electron-Positron (LEP) accelerator now under construction while the smaller UA1 Group continues work aimed at studying the properties of proton-antiproton collisions at high energies. The Counter-Spark Chamber Group and the Lepton-Quark Studies Group are involved with the construction of the SLD detector at the SLAC linear collider. The Lepton-Quark Studies Group is responsible for the central drift chamber and the Counter-Spark Chamber for the warm iron calorimeter. The Accelerator Physics Collaboration is involved in building a large underground detector (LVD) at Gran Sasso in Italy. This group will explore mu-mesons coming from Cygnus X-3 and other intense sources in the galaxy and neutrino emission from the sun and from exploding supernovae. The Counter-Spark Chamber Group and the Accelerator Physics Collaboration are also continuing neutrino experiments at Fermilab.



A 6 turn section of the coil for the L3 experiment at CERN is lifted before installation in the experiment. The experiment is conducted 65 meters underground.

National Magnet Laboratory

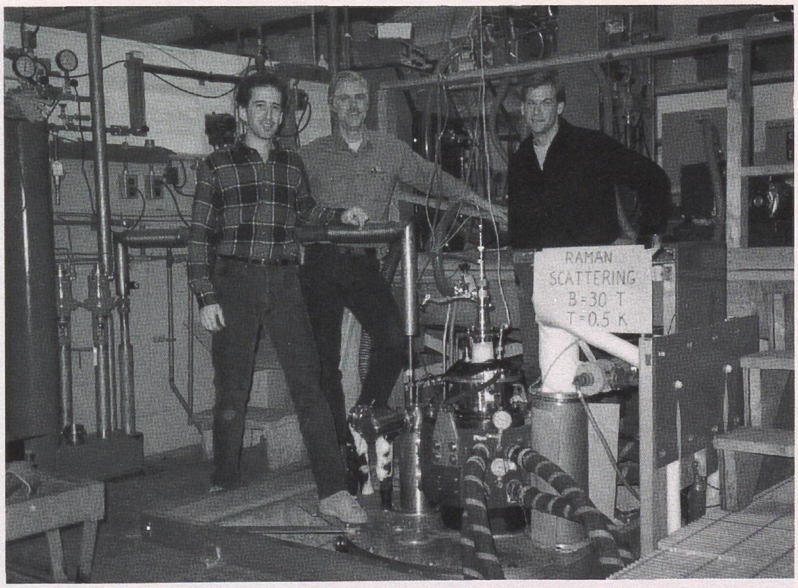
The Francis Bitter National Magnet Laboratory, supported by the National Science Foundation, conducts a program of research and development in science and engineering in areas involving magnetic fields.

Continuous fields up to 30 tesla are available in a variety of configurations. High magnetic field and high resolution nuclear magnetic resonance spectrometers are used for studies of molecules of biological interest. Both the high field magnets and the nuclear magnetic resonance spectrometers are made available on a routine basis to research groups from MIT and from institutions throughout the world. In addition, the Laboratory operates pulsed magnets giving fields up to 45 tesla and a magnetically shielded room of walk-in size.

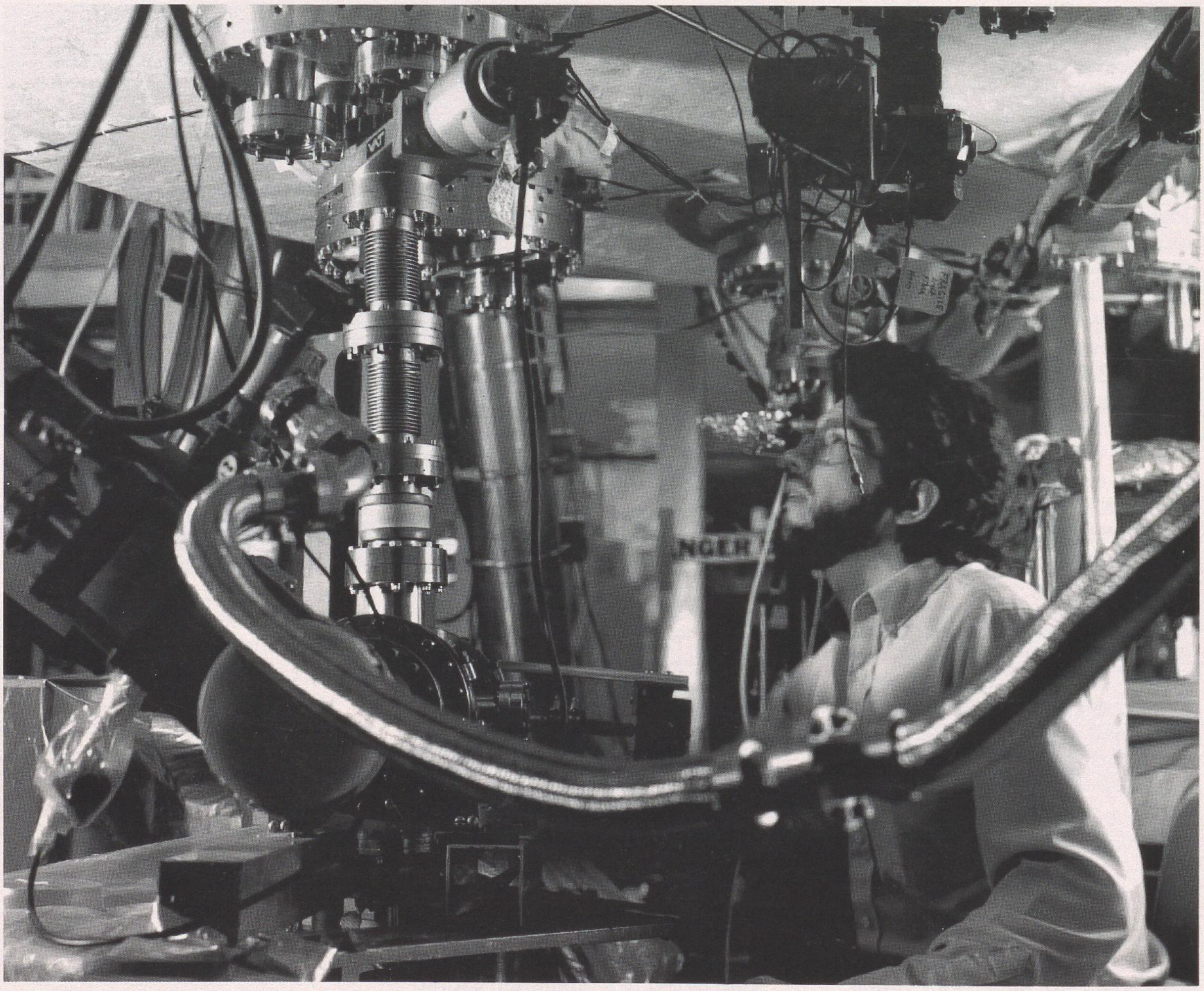
The Laboratory's solid-state physics research program is an experimental and theoretical study of semiconductors, magnetic materials, and superconductors. Molecular biology studies are carried out using high resolution nuclear magnetic resonance spectrometry and the Mössbauer effect.

The Laboratory also conducts research and development programs aimed at the practical application of magnetic fields to technology and medicine. Current projects include studies of the weak magnetic fields of the human body, studies of magnetic separation techniques, and development of nuclear resonance imaging systems.

Collaborative programs are carried out with the Departments of Physics, Electrical Engineering and Computer Science, Mechanical Engineering, Nuclear Engineering, Materials Science and Engineering, Chemistry, and with the Plasma Fusion Center.



This research team measured spin-flip Raman Scattering in (Cd,Mu)Se at T=0.5K and B=30T. The project involves the highest ratio of magnetic field to temperature for a light scattering experiment. The system uses fiber optic cables.



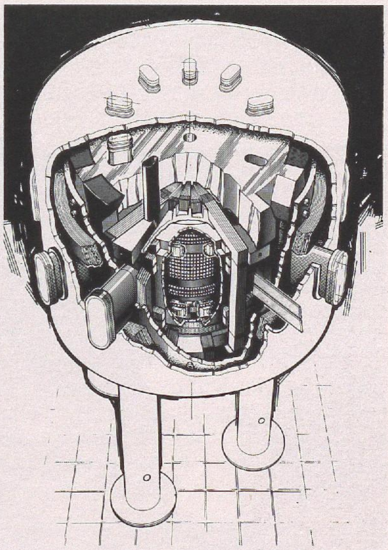
Research scientist working on Alcator C.

The Plasma Fusion Center (PFC), formed in 1976, is recognized as one of the leading university research laboratories in the physics and engineering aspects of magnetic confinement fusion. The overall program has a balance between experimental, theoretical, and engineering studies. Fusion activities in the Departments of Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nuclear Engineering, and Physics, as well as the Francis Bitter National Magnet Laboratory and the Research Laboratory of Electronics, are affiliated with the PFC.

During the 1970's and 1980's, many results of great significance to the international effort to develop fusion energy have been obtained in the Alcator A and C high-field tokamaks, two major experimental facilities in the PFC program. For example, in 1983, Alcator C achieved world-record values in the product of plasma density times energy confinement time, and is also a world leader in developing techniques to drive current by radio-frequency waves. The newly-funded Alcator C-Mod tokomak will serve as a key experimental facility for the continued exploration of advanced tokamak concepts. TARA, a new experiment based on the tandem mirror concept, is expected to make major contributions to fusion development in the alternate concepts area. Versator II and CONSTANCE are used to study particular research aspects of toroidal and mirror-confined plasmas, respectively.

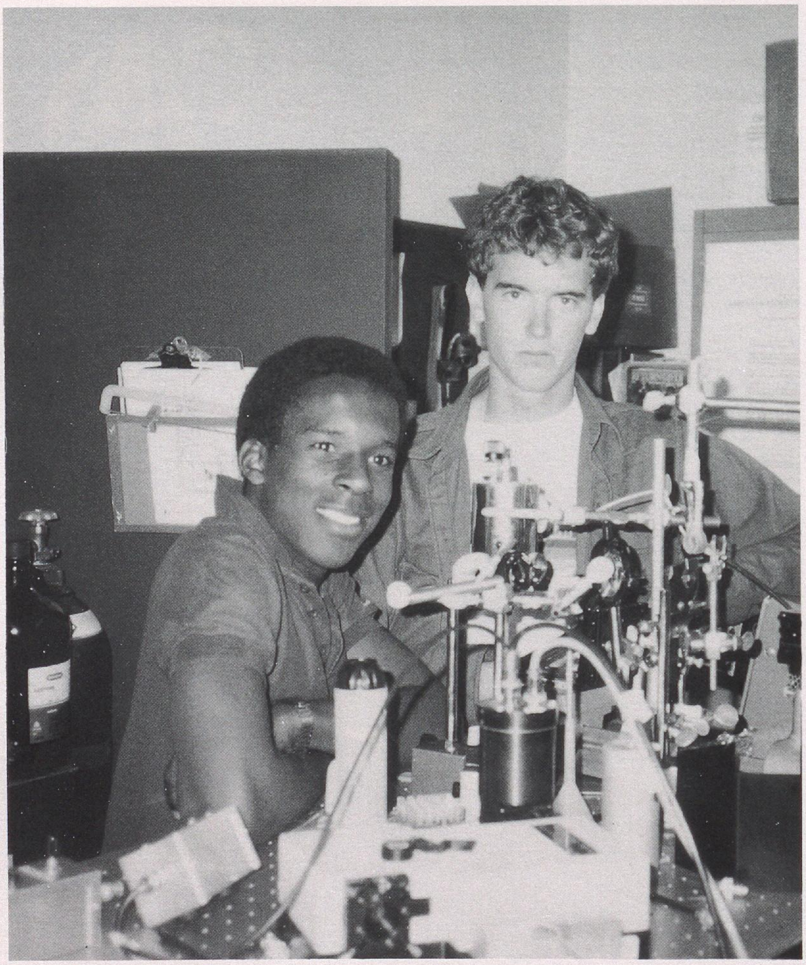
In addition, the PFC supports a broad program of fusion technology and engineering development that addresses problems in several critical subsystem areas (e.g., magnet systems, superconducting materials development, environmental and safety studies, advanced millimeter wave source development, and system studies of fusion reactor design, operation, and technology requirements).

Emphasis is placed on providing an environment that encourages technical excellence and independent creativity both at the individual researcher level and on the scale of major fusion projects such as Alcator C, Alcator C-Mod, and TARA. The PFC, through the expert training of students and professional scientists and engineers, makes a major contribution both to MIT's educational goals and to the scientific and engineering manpower needs of the national fusion effort.



The Alcator C-Mod facility is an upgrade to Alcator C aimed at investigating the characteristics of high-temperature, ICRF-heated plasmas, with the goal of understanding the physics of rf heating, confinement, stability, impurity, control, fueling, and shaping of high-performance tokamaks.

Research Laboratory of Electronics



Physics students with their apparatus used for an experimental study being carried out to devise a working method for high speed temperature measurement using infrared detection. The objective of this study is the development of calibration and measurement techniques for an infrared radiometer utilizing silver halide infrared fibers. This method may be quite useful for determining tissue temperature during laser angiosurgery and laser surgery in general.

Established in 1945 as the Institute's first interdepartmental laboratory, the Research Laboratory of Electronics provides faculty members and their students with the diverse services and facilities of a large laboratory to conduct research in two major areas–electronics and optics–as well as in language, speech, and hearing. In addition, smaller groups are focused on atomic and molecular physics, plasma physics, radio astronomy, digital signal processing, image processing, electromagnetics, and communications. At present there are approximately 20 research groups. Participants come primarily from the Departments of Electrical Engineering and Computer Science, Physics, Chemistry, Materials Science and Engineering, and Linguistics and Philosophy.

Research in electronics and optics covers a broad spectrum of concerns ranging from electronic materials and fabrication through high-speed electronic and optical devices to electronic and optical circuits and, finally, logic, architecture, and large-scale systems. The Laboratory brings together fundamental theoretical and experimental work in the nature of materials and surface interfaces with practical devices, circuits, and systems oriented to high-performance applications.

The program in language, speech, and hearing includes linguistic work in phonology coupled with the structure and design of systems for text-to-speech conversion and speech recognition, as well as fundamental work on articulatory phonetics, auditory psychophysics, and auditory physiology.

Additional research foci include fundamental studies in atomic and molecular physics such as radiation modes and basic constants, both theoretical and experimental research in plasma physics, radio astronomy and astrophysics, digital signal processing theory and hardware architecture, digital processing of two-dimensional signals (including high-resolution television), studies of electromagnetic propagation in nonlinear media, and a variety of studies in communications including structure and protocols for high-speed local networks.

Spectroscopy Laboratory

The George Russell Harrison Spectroscopy Laboratory is dedicated to advancing knowledge of the structure and dynamics of atoms and molecules and the properties of liquids and solids, utilizing the techniques of modern spectroscopy. These techniques include the use of lasers, signal processors, computers, and electro-optic devices. The laser light sources possessed by the Laboratory provide continuously tunable coherent radiation from 216 to 4500 nm.

The Spectroscopy Laboratory encourages participation and collaboration among staff members in various disciplines of science and engineering. At present, several departments (principally Chemistry, Physics, Biology, Electrical Engineering and Computer Science, Applied Biological Sciences, and Health Sciences and Technology) are involved. In addition, scientific visitors from the United States and abroad participate in the work of the Laboratory.

Current research areas include high-resolution laser spectroscopy of excited vibrational and electronic molecular levels, CARS studies, kinetics of intermediates in organometallic complexes, laser optical pumping of atoms, infrared and optical double resonance experiments, laser saturation spectroscopy, coherent transients, photon echoes, laser-nuclear spectroscopy, superradiance, Rydberg atoms, structural studies of biological molecules using Raman techniques and X-ray diffraction data, technical holography, and applications of lasers in medicine.

Within the Laboratory are two laser instrumentation facilities, the MIT Laser Research Center, supported by a grant from the National Science Foundation, and the MIT Laser Biomedical Research Center, a new facility for laser biomedical research supported by the National Institutes of Health. These two Centers make available to scientists, engineers and physicians from various university, industrial, and hospital research groups one of the most extensive collections of lasers in the United States for spectroscopic research. Facilities include tunable excimer lasers, cw and pulsed CO_2 lasers, and state-of-the-art Raman spectrometers with uv capabilities.


M.I.T. A.A.

Graduate Study in Physics

A prototype 5m gravitational wave antenna is being built at MIT. Here students are machining a piece of equipment used to test individual parts of this antenna.

The Physics Department offers programs leading to the degrees of Master of Science in Physics, Doctor of Philosophy, and Doctor of Science.

Candidates for Doctoral degrees are expected to enroll in those basic graduate courses that will prepare them for the General Examination, which must be passed no later than in the sixth term after initial enrollment. This examination demonstrates the student's background in advanced physics and depth of understanding in some particular branch of physics. No specific subjects of study are required, apart from the "breadth requirement " of two courses outside the candidate's field of specialization. A wide selection of courses in physics is available. In addition, students may attend classes at Harvard University when no comparable courses are offered at MIT.

Students are able to start their research programs early in their graduate careers and thereby come under the individual guidance of members of the staff. This high degree of personal contact between students and faculty at the beginning of studies is one of the most valuable aspects of graduate work at MIT.

Regular weekly colloquia and numerous seminars in all areas of physics are offered by visiting physicists and by MIT staff members. In addition, the proximity of MIT to other colleges and universities in the Boston area makes colloquia at these institutions readily accessible.

Financial aid is available in the form of fellowships, research assistantships, and teaching assistantships. The Karl Taylor Compton Fellowships were initiated in 1967 to attract the most promising physics graduate students, irrespective of area of interest, to study with our faculty. The fellowship is renewable for three years and carries a 12-month stipend. About five K. T. Compton fellowships are offered each year to incoming students of outstanding ability.

The large majority of incoming graduate students in physics at MIT are supported by research assistantships, which involve duties amounting to approximately 20 hours per week. These positions aid students substantially in progress toward their degrees. The particular assignment of a research assistant depends, insofar as is practical, on the interests and desires of the students.

The Physics Department has a relatively small number of graduate teaching assistants. These assistantships are generally offered to students who have particular ability and interest in teaching, or are truly undecided as to their field of specialization, or are in the process of changing fields of specialization.

Photographs have been collected with the cooperation of the faculty and laboratories associated with the MIT Physics Department.

Design: MIT Design Services

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The Institute has adopted an affirmative action plan expressing its continuing commitment to the principle of equal opportunity in education.

Inquiries concerning the Institute's policies and compliance with applicable laws, statutes, and regulations (such as Title IX and Section 504) may be directed to Dr. Clarence G. Williams, Special Assistant to the President and Assistant Equal Opportunity Officer, Room 3-221, (617) 253-5446. Inquiries about the laws and about compliance may also be directed to the Assistant Secretary for Civil Rights, US Department of Education.