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MESON FACTORIES

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INTRODUCTION

Technological improvements in accelerator design in the 1960's resulted in the capability to develop medium-energy proton accelerators with beam intensities of almost 1 mA. These beams are able to produce fluxes of secondary particles, including pions, muons, neutrinos, and neutrons, which are as much as 10,000 times as intense as those previously available. Those machines built for optimum meson production are commonly called meson factories. The purpose of this paper is to briefly review the characteristics of these facilities, the present programs in applied research, and some potential areas of future work.

FACILITIES

There are three meson factories now in operation. These are the LAMPF linear accelerator [1] in Los Alamos, New Mexico, the SIN cyclotron [2] in Villigen, Switzerland, and the TRIUMF [3] cyclotron in Vancouver, British Columbia. The characteristics of these accelerators are listed in Table I.

TABLE I

Characteristics of Present Meson Physics Facilities

Facility	Max. Energy (MeV)	Design Average Current (μA)	Present Operating Current (μA)	Duty Cycle	Biomed. Facility	Present Pion Dose Rate in a liter (rad/min)	Type
LAMPF	800	900	500	7.5%	Yes	15	linac
SIN	590	100	100	cw[1]	Yes	~1[2]	cyclotron
TRIUMF	525	100[3]	100	cw[1]	Yes	4	cyclotron

[1] continuous wave

[2] existing channel. New channel with pion therapy applicator near completion.

[3] 400 μA at 450 MeV.

The synchrocyclotron at JINR, Dubna, USSR, is being modified to produce higher intensity [4] and should be operational in 1981. There is also a proton linac similar to LAMPF under construction. The construction of a sixth facility in Japan is under consideration [5,6].

PRACTICAL APPLICATIONS

The advent of meson-producing accelerators has resulted in much work which has practical application, ranging from the development of improved megavoltage therapy machines [7] to the treatment of cow-eye tumors with hyperthermia [8]. This paper reviews some of the more promising programs which are related solely to the existence of these specific accelerators.

PROTONS: RADIOISOTOPES

Generally, about one-half of the primary beam remains after passing through the production targets with a relatively small decrease in energy. The high energy and intensity are ideally suited for producing large quantities of neutron deficient isotopes of small cross sections and/or short lifetimes. Table II lists some radioisotopes being produced along with their applications. Many other radioisotopes can also be produced in useful quantities.

TABLE II

Some Radioisotopes Presently Under Production

Product	Half-Life	Use
^{22}Na	(2.6 y)	Positronium Studies
^{26}Al	(7.3 x 10^5 y)	Geochemical Tracer
^{44}Ti → ^{44}Sc	(4 h)	Bone-Scanning Agent
^{52}Fe	(8 h)	Brain Scan
^{52}Fe → ^{52}Mn	(21 min)	Myocardial Studies
^{77}Br	(57 h)	Pharmaceutical Labeling
^{77}Br → ^{77m}Se	(17 sec)	Infant Blood Flow
^{82}Sr → ^{82}Rb	(75 sec)	Blood Dynamics, Infarct Studies, Renal Function
^{123}Xe → ^{123}I	(13 h)	Thyroid Imaging
^{127}Xe	(36 days)	Pulmonary Studies

PIONS: RADIATION THERAPY

The potential advantages of negative pions in cancer therapy include a reduced oxygen effect and better dose localization as compared to x rays. Programs to investigate these advantages are now in progress at all facilities. This includes the physical [9] and biological [10] characterization of the interaction of pions in tissue. Only at Los Alamos is the dose rate (~15 rad/min in a liter) sufficient at this time for human studies. Kligerman et al. [11] began clinical studies of metastatic skin nodules in 1974. As of May 1979, 93 patients have been treated. The locations of the tumors included, in addition to the skin metastases, brain, head and neck, breast, lung, prostate, and pancreas [12]. Stage III randomized trials will begin shortly.

MUONS

Muonic X-Ray Analysis (MXA) - Negative muons, in the same manner as negative pions, can be captured by a nucleus to form a muonic atom; x-rays are emitted as the muon cascades to lower energy levels. The practical applications group at LAMPF is studying muonic x-ray measurements for the nondestructive elemental analysis of bulk materials [13]. Some analyses have been done with samples containing carbon, nitrogen, and oxygen [14]. The MXA technique has a fairly high detection limit of a few tenths of a percent by weight, but it is unique in that it is sensitive to all elements except hydrogen and is applicable to large samples without special preparation. Because of the low doses required, it could be applied to living organisms.

Muon Spin Rotation (μSR) - Muons are leptons of spin 1/2 which decay into $e^{\pm}$ (for $\mu^{\pm}$) plus a neutrino and an antineutrino. The behavior of muons in matter can be studied by observing the e^+ or e^- emitted from a sample. Such processes as diffusion of radicals, trapping, and chemical reaction rates can be studied [15] in a manner analogous to nuclear magnetic resonance (NMR). The use of μ^-SR is similar to NMR with an impurity of (Z-1) atomic number, except that it can be implanted in the sample nondestructively and it has a different size and magnetic moment distribution [16]. The use of μ^+SR is comparable to investigations with a hydrogen isotope with a mass one-ninth that of a proton [16]. One unique application, then, may be substituting μ^+ for hydrogen in biological materials (e.g., DNA molecules)[17].

NEUTRONS

These proton accelerators are potentially the most intense source of neutrons except for thermonuclear explosions. The neutron facility (WNR) at LAMPF [18] provides yields of 5×10^{14} n/s (tantalum target) which will increase to about 1.5×10^{15} n/sec in 1979. A storage ring,which is a device for storing and bunching proton pulses, will increase the instantaneous flux (but not the average) by a factor of 100.

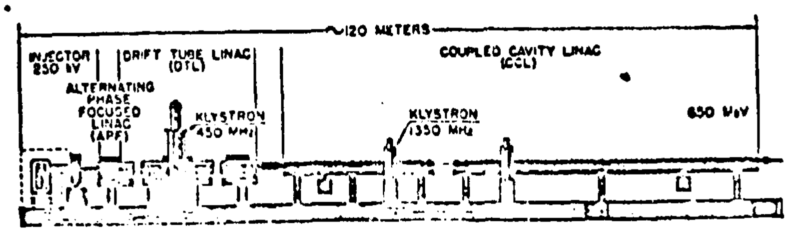
By a suitable choice of target and moderator materials, neutron spectra from the ultra-cold region (< 5 meV) through the high energy region ($\lesssim$ 800 MeV) are available.

These facilities are ideally suited for materials analyses and radiation damage studies including, for example, neutron scattering from polymers and chromatin [19].

ACCELERATOR DEVELOPMENT

Typical costs for construction of a medium energy physics facility have been in excess of $50 million; however, all of these machines were built primarily for basic research in physics. Recent research in accelerator design [20] has lead to considerable improvement in reliability and efficiency. A biomedically dedicated accelerator incorporating these innovations should cost considerably less than previous machines.

Figure 1 shows a schematic representation of the PIGMI accelerator, under development at Los Alamos. Such an accelerator for producing pions would cost approximately $10 million. A less energetic version could be used as a neutron source at much less cost.



MAJOR TECHNICAL INNOVATIONS

Higher Frequency	Permanent-Magnetic Quadrupoles
Higher Gradient	Disk & Washer Linac Structure
Alternating Phase Focusing	RF Manifold Power Distribution
Lower Injection Energy	Distributed Microprocessor Control
Double Harmonic Buncher	

Fig. 1 A schematic representation of the PIGMI linear accelerator.

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