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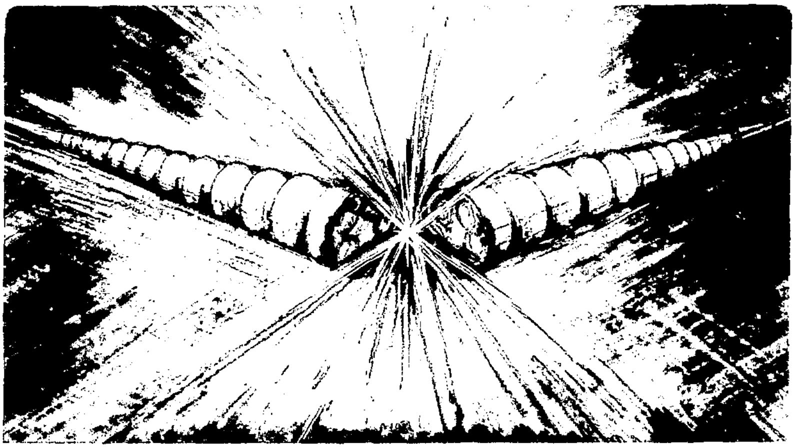

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Abstract

In the ten years that beams of intermediate energy ($\approx$50 MeV/amu $\leq E \leq \approx$2 GeV/amu) heavy ions ($Z \leq 92$) have been available, an increasing number of new research areas have been opened up. Pioneering work at the Bevalac at the Lawrence Berkeley Laboratory, still the world's only source of the heaviest beams in this energy range, has led to the establishment of active programs in nuclear physics, atomic physics, cosmic ray physics, as well as biology and medicine, and industrial applications. The great promise for growth of these research areas has led to serious planning for new facilities capable of delivering such beams; several such facilities are now in construction around the world.

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Introduction

Beams of the heaviest-mass ions in what is now called the intermediate energy range became available first in the early 80's when the Bevalac achieved the capability of accelerating them [1]. Without a clear picture of what such beams would be good for or even how to look for interesting new phenomena, a tentative experimental program was undertaken. In the intervening years this program has matured, has demonstrated many new interesting areas of research, and has in fact been the gateway for the blossoming of new accelerator projects and research programs both at these as well as much higher energies. As seen in Figure 1, this intermediate energy range spans several thresholds which hold interest for different scientific disciplines. In subsequent sections we will look at the highlights of research activities in nuclear physics, biology and medicine, atomic physics, and space sciences which are the direct outgrowth of Bevalac programs.

Nuclear Physics

Because the energy of the projectiles is so much higher than any of the characteristic nuclear energy thresholds, such as the Coulomb barrier or individual nucleon binding energy, the potential exists to study properties of nuclear matter in a very different environment from that available with lower energy accelerators. The energy available is all in the form of kinetic energy of the incident projectile, while the studies of nuclear matter deal with energy in the reacting system. In this energy range, the transfer of energy from kinetic to the reacting system is determined entirely by the impact parameter of the colliding nuclei; the greatest overlap between the nuclei leading to the highest energy transfer, while a grazing collision where the nuclear surfaces barely touch can leave the projectile and target almost undisturbed. This wide range of reaction energy offers great diversity of opportunities for studies across a great segment of the entire field of nuclear physics, as will be detailed below.

Central collisions: Experiments with the Plastic Ball [2] have demonstrated that the stopping power of nuclear matter is high enough that for central collisions in this energy range a projectile of even very modest mass (≥40) will totally stop in a target nucleus of like size. Thus there is no question but that all of the available kinetic energy of the projectile is involved in the reaction. This is different from the conditions existing when a proton of high energy strikes a nucleus: in this case reactions are more of a nucleon-nucleon nature and do not involve bulk nuclear matter. In the case of colliding heavy nuclei, the energy density and temperature of the reacting system become extremely high. Analysis of data indicates that densities as high as four times normal nuclear density have been observed in such reactions [3]. Theoretical analyses of this environment have led to the speculation that if high enough energy densities can be obtained it might be possible to break up nucleons into their constituent quarks, such deconfined quarks existing in what is now refered to as a "quark-gluon plasma" [4]. Although it is generally conceded that the projectile energy needed to achieve these conditions is more in the realm of the SPS or higher-still energy machines, studies at our energies are eminently suited to observations about the nuclear equation of state. Measurements of such thermodynamic properties as maximum density, temperature, entropy and compressibility are of very high relevance to models and theories of supernova explosions, neutron star formation, and even to cosmological theories of conditions existing at the creation of the universe. Determining these thermodynamical parameters is no mean feat, as seen in Figure 2, the reactions generally involve almost total breakup of both target and projectile nuclei leading to events with many hundreds of reaction products, and a very challenging analysis job. Experiments are concentrating on weakly-interacting probes such as photons or lepton pairs to probe the hot core of the reaction [5]; strongly-interacting pions to measure properties of the surface of the reacting nuclei [6]; proton-deuteron-alpha ratios in the emerging fragments to determine entropy of the systems [7]; and most recently the combined velocity vectors of reaction fragments which gives indications of non-axial flow of a hydrodynamic nature of the nuclear matter involved in the collision [8].

Peripheral collisions: On the other side of the spectrum, grazing collisions transfer very little energy to the reacting system. In the gentlest reactions a few nucleons may be removed from the projectile, but most of the kinetic energy remains with the now-modified projectile, which can be transported and separated through normal beamlines to an experimental area for further analysis or reaction studies [9]. At beam energies above several hundred MeV/amu, typical reaction products from grazing collisions can be formed into a secondary beam with very little difference in the beam emittance from that of the primary, so that transport efficiency is very high. Rigidity differences of the reaction products, from differing charge-to-mass ratios, allows for clean separations, so that secondary beams of high purity can be generated. Such beams have been used for basic exploration of nuclear stability; one noteworthy experiment with a 48-calcium primary beam produced twenty previously undiscovered isotopes in one 24 hour period of running [10]. Other studies have included systematic measurements of nuclear radii for very exotic light nuclei [11], as well as neutron-proton mass distributions [12] and nuclear moments [13].

Studies in nuclear physics with ions in this energy range have only begun, but have shown a wealth of interesting areas of research, enough to guarantee forefront science for many years to come.

Biology and Medicine

High energy charged particles offer considerable advantages for radiotherapy because of a highly favorable depth dose (or Bragg) curve [14]. As Figure 3 shows, the rate of deposition of energy increases as the particle slows down, with the largest amount of energy lost just as the particle stops at the end of its range. Thus, by adjusting the range of the beam so particles are made to stop inside the area to be treated, a large fraction of the total radiation dose can be delivered with high precision to this region, while sparing much of the normal tissue penetrated on the way to the treatment volume. This is in contrast to photon treatments now considered the state-of-the-art, where the dose falls off exponentially from the surface of the patient. An excellent example of this is shown in Figure 4, which shows a heavy ion treatment plan for a tumor totally surrounding the spinal cord; the tumor can be given a dose of over 600 Gy while the cord receives well under 100 Gy.

The importance of high energies in this application arises from the need to have sufficient penetration range of the beam to reach any part of the body. To achieve a depth of penetration of 30 cm, energies from 250 MeV for protons to over 600 MeV/amu for neon ions are required.

Although protons and helium ions offer good dose-localization characteristics, heavier ions, by virtue of less multiple scattering and range straggling are potentially superior for placing the dose precisely where desired. Heavy ions offer another advantage, that of high LET (Linear Energy Transfer), or ionization density. This increase in microscopic energy deposition can lead to much greater effectiveness in cell killing, and decreases the sensitivity of the response of tumors to such effects as cell type, stage in its reproductive cycle and oxygenation.

Nuclear reactions play a significant role in medical applications as well. On the negative side, beam particles penetrating 30 cm into a patient have a significant chance of undergoing a nuclear collision before stopping. Such reactions lead to a decrease in the height of the Bragg peak, and to the presence of a tail beyond the beam range due to the nuclear fragments produced. On the positive side, nuclear reactions can be used to great advantage. With proper targeting and analysis, a secondary beam can be produced and used for diagnostic purposes. For example, a neon 20 beam passed through a 1 cm thick beryllium target can be converted with high efficiency into a beam of neon 19. This secondary beam can be easily purified of all contaminants and delivered into a patient; a rate of about 1 μCi per second has been observed at the Bevalac [15]. Neon 19 is a 20 second positron emitter, so once deposited, to within a volume as small as a few mm^3, normal PET scanning technology can be utilized to determine the precise stopping point of the radiation, or to study the flow of the tracer from its sharply determined implantation point. Stopping-point localization is very important because of the uncertainties in determination of total tissue density along the incident path of the beam. This technique serves as a much-needed verification of treatment plans and patient alignment. The ability to deposit a dose with very sharp boundaries close to sensitive tissues, such as shown in Figure 4, heightens the importance of such a verification tool.

Patient treatments with charged particles have been underway for many years at numerous centers around the world; several thousand patients have been treated with protons and helium ions, and in the last ten years several hundred have received treatments with heavy ions at Berkeley. The advantages of superb dose localization with charged particles are plainly seen, demonstrating this modality as clearly superior where sparing of critical adjacent tissues is important. Heavy ion treatments have also shown good results, and although clear clinical advantages for the heaviest beams have not yet been demonstrated, techniques continue to be developed for exploiting the full potentials of the physical properties of these heavy beams. Expectations are that once optimized, heavy ion beams, with radioactive tracer verification and high LET, will be a superior modality for radiation therapy.

Atomic Physics

Energetic ions passing through thin foils will be stripped of electrons, the degree of stripping being related to the velocity of the ions. As the velocity increases it becomes possible to reach deeper into the electronic structure of the atom and pull off more tightly bound electrons. In this new energy range, it is possible for the first time to fully strip all elements. In fact bare uranium nuclei have been observed for proper stripping materials at Bevalac energies. Figure 5 shows that the selection of stripping material is quite important to achieve the highest charge states. Interestingly enough high Z strippers are more efficient at this energy, contrary to the case at lower energies [16]. From this figure, one can also surmise that by proper selection of stripping material and beam energy it is possible to produce an ion in any desired charge state, opening up essentially the entire array of ionic configurations of any nuclear species for study.

Perhaps the greatest interest in atomic physics with these ions lies in producing uranium ions with one or two electrons, and studying the level structure of these ions. Lamb shift experiments with these ions are being performed [17]; such measurements are viewed as extremely sensitive tests of QED.

Most interesting channeling studies have also been performed [18]. Ions are observed to suffer much less stripping when aligned along a crystal axis, demonstrating the importance of close nuclear collisions for stripping the more tightly bound electrons from an ion. Followup channeling experiments are planned using magnetized crystals, where interactions with oriented valence electrons in the channel may yield a polarized ion beam for hyperfine interaction studies.

Space Physics

With the exception of extreme tails of the distribution, energies and masses of beams available from such accelerators span essentially the full range of the Galactic Cosmic Ray spectrum. In addition, should it be desired, the normally mono-isotopic and mono-energetic beam from the accelerator can be converted into one more closely resembling the mass and energy spectrum of the space environment using nuclear fragmentation reactions, and properly designed energy modulators (nonuniform absorbing material placed in the beam, such as a brass plate with a deep spiral groove). Having an earth-side source of cosmic rays can be of very high value for disciplines associated with the environment outside our atmosphere. Cosmic ray physicists use these beams to test and calibrate instruments designed to fly in satellites [19]. Commercial firms with communications equipment in satellites test critical components in these beams to assess their vulnerability to impact by a highly ionizing heavy cosmic ray [20].

Of great interest to the manned space program is the effect of the radiation dose from cosmic rays on astronauts, whether in orbital platforms, on the lunar surface, or on long interplanetary missions. Experiments have demonstrated that for high LET radiations long exposures to very low levels of radiation are different, and in fact much more biologically damaging than the same doses given in a much shorter time. Much is still not known of the detailed biological response of tissues to such low levels of radiation, and having research facilities capable of simulating the space environment will play a key role in assessing risk factors, designing space vehicles which can mitigate the problem, and possibly in developing biological protectors to guard astronauts from the effects of cosmic rays.

Sources of Intermediate Energy Heavy Ions

With such varied research possibilities it is clear that the scientific community should have a convenient supply of these ions. Table I lists existing and planned facilities around the world. At the present time, only the Bevalac at Berkeley can deliver ions of all masses in this energy range. Other currently operating accelerators producing lighter ion beams are Saturne II at Saclay and the Synchrophasotron at Dubna. The SIS project at Darmstadt is nearing completion; beams of all elements will be available in 1989. An interesting aspect of this project is ESR, a storage ring which will greatly expand the research capabilities of this facility. HIMAC, at NIRS near Tokyo is in construction now, and will deliver beams up to silicon for medical applications in 1993. New accelerators in the Soviet Union are planned, the Nuclotron at Dubna is under construction now, and an upgrade of ITEP in Moscow for heavy ion capability is contemplated.

It is clear that the focus of activity in the field is moving away from the United States. The Bevalac, which pioneered this work and has provided the motivation and primary justification for much of the dynamic growth in the field, will not remain competitive with the new modern overseas facilities which will be coming on line in the next few years. Action to fund new or upgraded US facilities is urgently needed, and must be initiated in the very near future to not completely lose our leadership position in this field. Drive for this must originate from the national research community; it is essential that a concerted, unified call arise to direct government funding agencies to respond to this need.

Acknowledgements

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Table I

Sources of Intermediate Energy (E>500 MeV/amu) Heavy Ions

Accelerator	Location	Ions Accelerated	Year Operational	Mission
Existing or under construction				
Bevalac	Berkeley, USA	All elements	present	General purpose
Saturne II	Saclay, France	Light ion	present	Nuclear physics
Synchrophasotron	Dubna, USSR	Light ion	present	Nuclear physics
SIS-18	Darmstadt, Germany	All elements	1989	General purpose
HIMAC	Chiba, Japan	Light ion	1993	Medical
Nuclotron	Dubna, USSR	Mid mass	?	Nuclear physics
Proposals				
Bevalac Upgrade	Berkeley, USA	All elements		General purpose
EULIMA	Nice, France	Light ion		Medical
LIBRA	Oakland, USA	Light ion		Medical
ITEP	Moscow, USSR	Light ion		General purpose

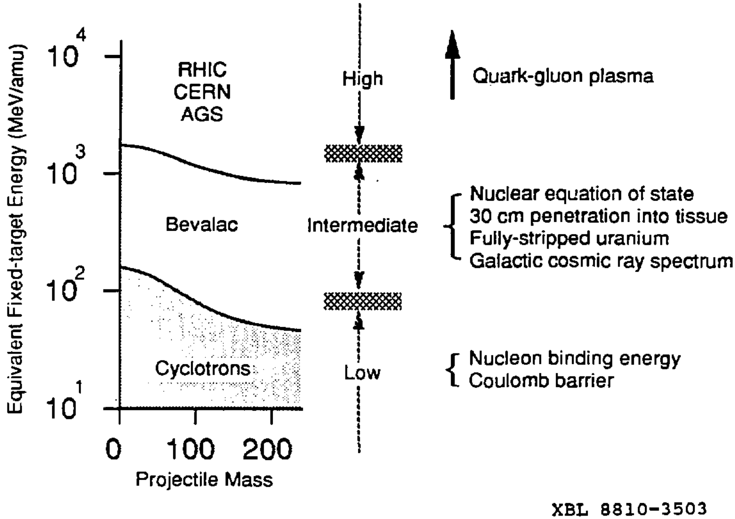

Fig 1. Spectrum of energy regimes for accelerated heavy ions, with facilities operating in these regions, and noteworthy research foci.

CBB 851-128

Fig. 2 Streamer chamber photograph of a U-U collision at the Bevalac indicating complexity of reactions. Analysis of this event includes particle and energy identification from the tracks, multiplicity counts and angular distributions of reaction products.

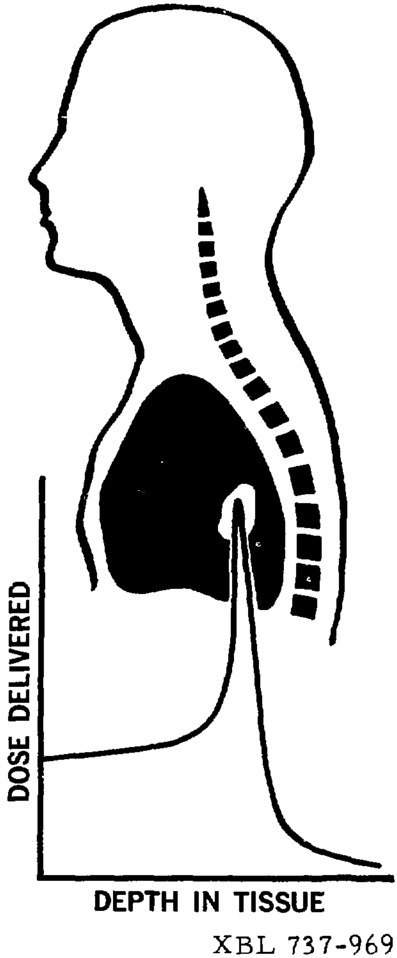

Fig. 3 Bragg curve depth dose profile for stopping heavy ions in a patient. Proper adjustment of beam energy and transverse profile can result in excellent dose-localization into a desired treatment volume with good sparing of surrounding normal tissue.

CBB 839-8412

Fig. 4 Treatment plan with heavy ions showing toroidally shaped target volume (outlined with small squares) designed to cover a tumor in a vertebral body surrounding the spinal cord. The treatment volume (denoted by dose-contour lines) provides excellent coverage of the target volume, with almost total avoidance of a good fraction of the cord.

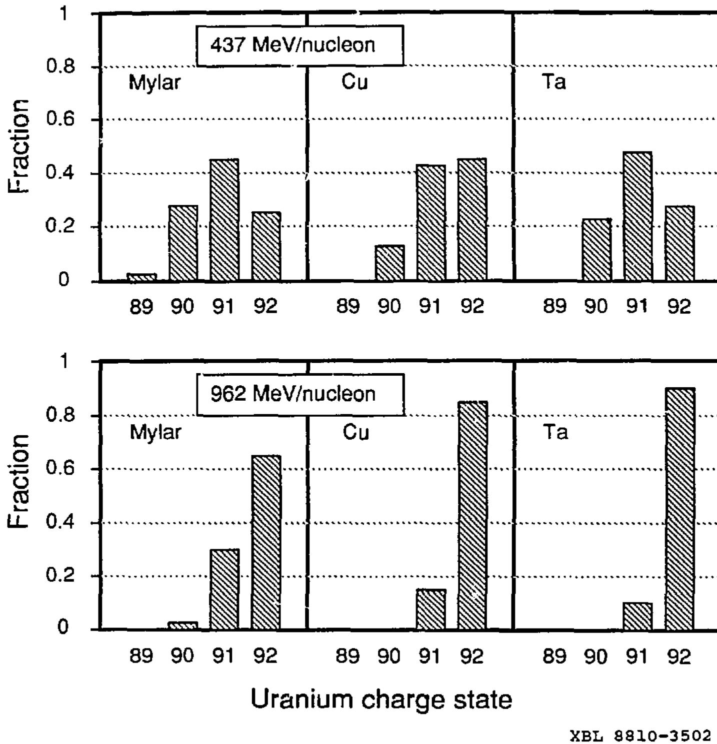

Fig. 5 Equilibrium charge state distributions for uranium ions stripped by different materials.