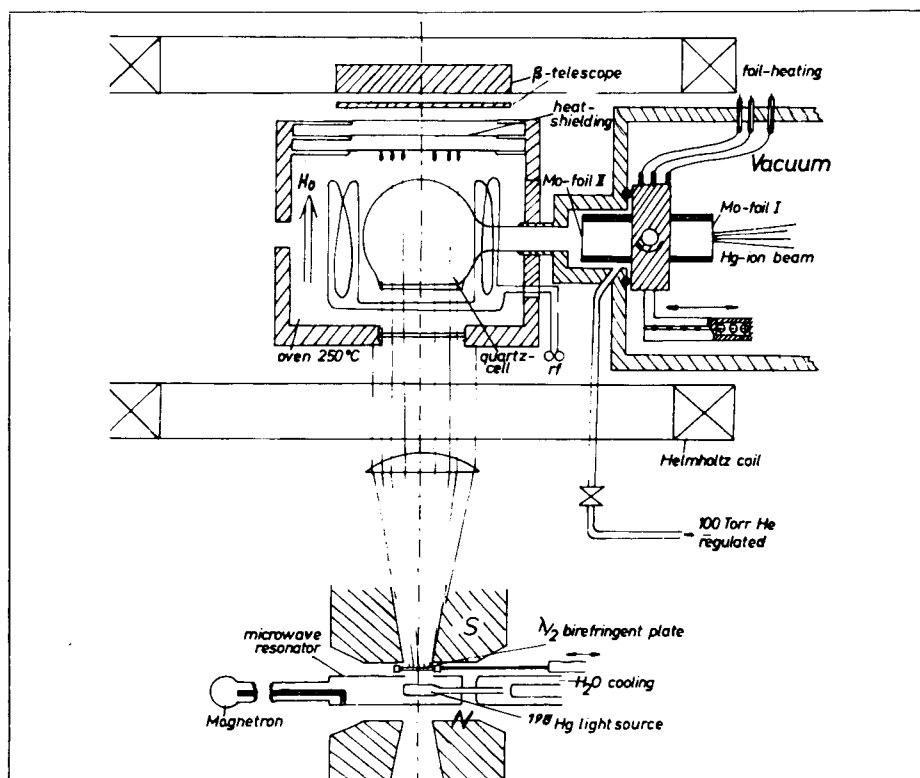


Diagram of the layout of the apparatus for the optical pumping experiment of the visiting team from Heidelberg. Mercury ions come in from ISOLDE and are collected on a molybdenum foil which can be swivelled round to feed the ions in the bulb (top centre of diagram). The bulb is surrounded by a magnetic field and an r.f. coil. Circularly polarized light from a mercury lamp is illustrated as coming in from the bottom in the diagram. The beta telescope which observes the decay of the ions is indicated on top.



length some ten times greater. Finally, the reliability may decide between the use of a plane of parallel wires or of foil for the septum. CERN preferred foil for the first tests. Batavia and Brookhaven are trying wires, thus both approaches will be tested.

Optical pumping

One of the most intricate experiments ever carried out at CERN is under way at the isotope separator on-line, ISOLDE, fed by the 600 MeV synchrocyclotron. It is concerned with nuclear structure studies — measuring nuclear spins, nuclear moments and nuclear shapes. When such measurements are carried out with nuclei far from the stability line (nuclei which have neutrons or protons over and above what is normally a stable configuration), such as can be produced and examined at ISOLDE, new know-

ledge can be gathered about how the nuclei are built up. Work at ISOLDE can be compared to work on superheavy elements in the sense that we are testing whether our existing knowledge of nuclear matter can be extended to unexplored regions.

These studies are often difficult because so few nuclei of isotopes far from the stability line can be isolated for examination that only extremely sensitive methods can hope to study their properties. A visiting team from Heidelberg (J. Bonn, G. Huber, H. J. Kluge, U. Köpf, L. Kugler and E. W. Otten) working at ISOLDE have employed techniques (including 'optical pumping' which has become particularly associated with their experiment) which run through a great deal of our knowledge of atomic and nuclear physics en route to unearthing new information about the nucleus. Indeed, when their experiment was first proposed, Professor Preiswerk remarked

that it contained so much beautiful physics that it was worth doing even if it failed.

They have studied a series of short-lived mercury isotopes obtained from ISOLDE. An isotope is collected on a molybdenum foil which can be swivelled round (after a collection time of about 1 half-life) to point into a bulb containing an inert gas (helium). The foil is heated and the mercury atoms evaporate off; the gas helps to preserve them as 'free' atoms (keeping them away from the walls where they might interact) which is necessary for the subsequent spectroscopy stage of the experiment. While this stage is under way another foil, at the opposite end of the swivelled unit, is collecting more mercury atoms.

Only something like a million of the short-lived mercury atoms are likely to be in the bulb for investigation at any one time and this is far from adequate for normal optical spectroscopy. Hence the series of manoeuvres which we will now attempt to describe in simplified form.

Optical pumping is a technique discovered by A. Kastler (earning him the 1966 Nobel Prize for Physics) which enables us to have many atoms existing in an identical energy state with their spins lined up in one direction. The technique is an essential part of the operation of the laser.

If we consider a mercury atom, it consists of a nucleus (whose properties we wish to study) with eighty electrons swirling around it. This configuration can exist in many energy states depending on the orbital angular momenta of the electrons, and on the spins of the electrons and of the nucleus. Specific amounts of energy can be absorbed or emitted by the atom as it hops between energy states. Like most of us, atoms, after being excited, will fall back to their lowest energy state. Optical

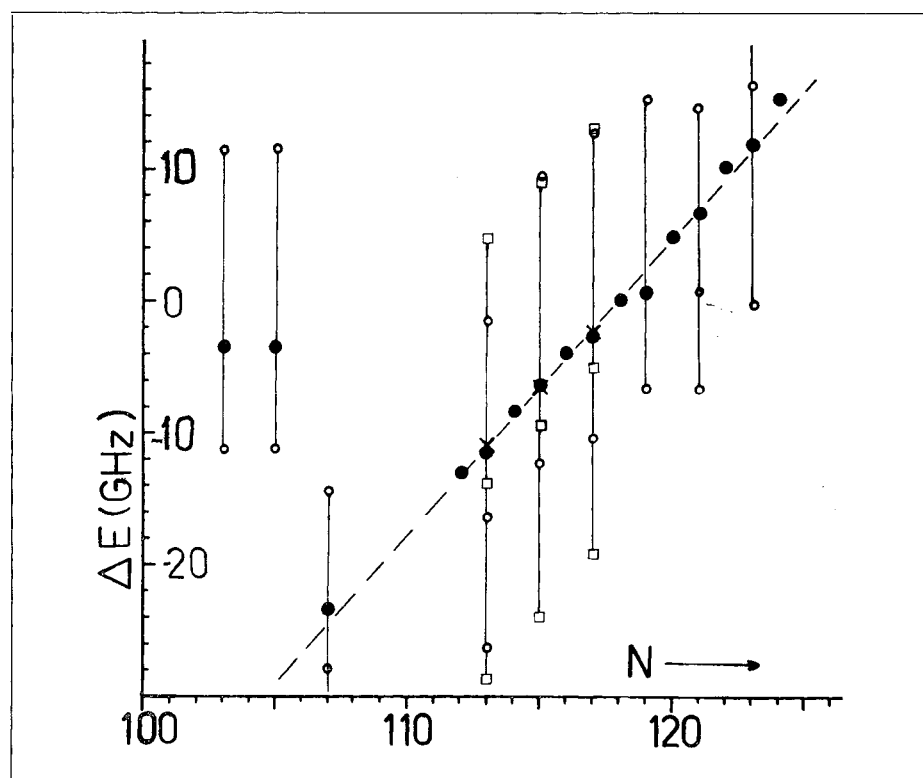
Energy level differences for a chain of mercury isotopes (the x-axis counts the number of neutrons in the nucleus; the y-axis counts the energy difference by comparison with the ^{198}Hg isotope). The difference as we move down the isotopic chain follows the straight line predicted by calculation until the isotopes with 105 and 103 neutrons when the difference changes abruptly. This indicates that the nuclear shape has changed radically for these two isotopes compared with the others.

pumping is used to manoeuvre the atoms into a particular energy state where their nuclei are polarized.

The polarization of nuclei, so that their spins line up in one direction, is quite common in the field of high energy physics. In polarized targets it is achieved by the use of high magnetic fields and low temperatures. With optical pumping it is achieved by directing circularly polarized light, where the photon spins are all aligned in one direction onto the atoms. The polarization can be transferred to the atoms by the absorption of the light quanta — conservation of angular momentum then requires that the spins of the atoms are polarized after absorption. Coupling between the electron spins and the nuclear spins completes the desired polarization of the nuclei.

Absorption can only take place when the incoming light quantum matches the difference between two energy levels in the atom. This condition can be covered by adjusting a magnetic field applied around a mercury lamp (Zeeman effect) shining on the bulb containing the radioactive mercury atoms. The light quanta can be varied over a range of values which are known when the field at the lamp is known. But without being clever we would never know that we had hit the particular values at which absorption, and thus atomic and nuclear polarization, takes place since there are too few atoms in the bulb to give us discernable light signals. However, the values can be identified when the nucleus decays sending out an electron (beta decay).

Beta decay is a weak interaction and does not conserve parity — as found in the famous experiment of C. S. Wu, the direction at which the electron emerges depends upon the direction in which the nucleus is spinning. There will be an asymmetry in the distribution of the electrons



emerging from our bulb when we hit the right values because they then come from polarized nuclei.

When we can see that we have produced polarized nuclei we can measure the nuclear magnetic moment using the usual r.f. resonance technique. R.f. energy is fed to the atoms, via loops wrapped around the bulb, and, as the r.f. frequency is varied, the polarization (the asymmetry in emitted electron direction) will disappear when the r.f. frequency reaches the value corresponding to the energy needed to swing the nuclear spin round from one direction (relative to the magnetic field) to the other. The magnetic moment can be calculated knowing this r.f. frequency.

Another way of estimating the nuclear magnetic moment comes from the way in which energy levels split into several levels when in a magnetic field due to the 'hyperfine' coupling between the magnetic moments of the electrons and of the nuclei. As described above, we sweep over a range of frequencies with the ingoing light. This will produce polarization at several values (because there are more energy levels between which the atoms can hop), the number of which yields the nuclear spin and the separation of which is a measure of the nuclear magnetic moment.

The most surprising results have come from a third item of information which is drawn from knowing the fre-

quency of the light needed to achieve the optical pumping. The energy level difference to which this corresponds is related to the nuclear shape (to be more precise — the mean squared radius of the nucleus). This is because the electrons passing close to the nuclear surface act as a probe of the nuclear charge distribution. The work with mesic atoms (see, for example, vol. 10, page 251) is based on the same principle.

The way the nuclear shape changes as we go along a very long chain of isotopes has never been studied so extensively before. ISOLDE makes over twenty mercury isotopes available for investigation.

The difference between levels by comparison with that of the stable isotope ^{198}Hg (118 neutrons, 80 protons) follows the straight line anticipated by calculation as the number of neutrons varies from 125 to 107 (^{205}Hg to ^{187}Hg). Then with 105 and 103 neutrons the difference departs radically from the predicted value — in other words the nuclear shape changes abruptly (probably from a spherical to a deformed shape).

Why this sudden deformation of the nucleus takes place is unknown. It is certainly not expected to take place for an element like mercury which has an almost closed shell of protons. This very intricate experiment has succeeded not only in carrying out the difficult measurements it set out

A DISC counter specially designed to identify charged hyperons. The optics are housed in the cylindrical sections. The photomultipliers with their magnetic shielding are shaded black.

Alongside is a diagram of the same instrument.

to do but also in revealing some very unexpected features of nuclear structure.

DISC counters

When a fast-moving charged particle passes through a transparent medium such as air, water or glass, it can emit light by the Cherenkov effect. The mechanism of this effect is often compared to that of an aeroplane travelling through air. When the plane travels through the air faster than the speed of sound, a supersonic bang is produced; when a particle travels through a transparent medium at a speed faster than that of light in the medium, Cherenkov light is produced. The light wave is conical, like the shock wave of a supersonic plane, and the angle of the cone depends on the relationship between the speed of the particle and that of

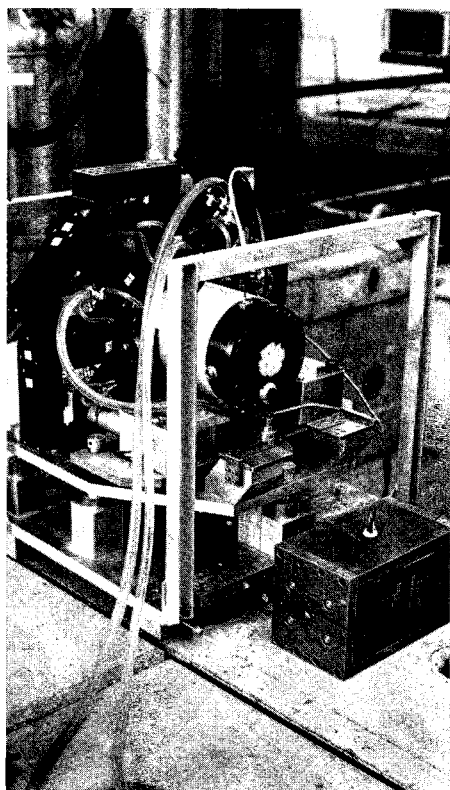
light in the medium — this is the basis for the measurement of the speed of charged particles in Cherenkov counters.

A special optical system picks up the light produced and focuses it into a ring. The speed of the particle is determined from the diameter of the ring of light. If particles of different mass such as pions, kaons and anti-protons are sorted magnetically in a beam-line so that they all have the same momentum, their velocity will depend on their mass (the heaviest being the slowest). A Cherenkov counter will record for each type of particle a ring of different diameter which can be distinguished by means of a combination of screens and photomultipliers. The measurement of the particle velocities can then be calculated knowing the refractive index of the medium

$$\frac{v}{c} = \frac{1}{n \cos \theta}$$

The first counters of this type were in use long before physicists had access to accelerators of even 1 GeV. Their performance was limited by the quality of the photomultipliers then available and by their relatively simple optics. From 1959 studies were undertaken at CERN to perfect an optical system. The main difficulty in the optics is that there is a chromatic dispersion of the Cherenkov light which limits the ultimate velocity resolution of the instrument. A counter was finally developed in which chromatism was corrected, using a doublet of axicons. The resolution was greatly improved.

The first models of this type of counter, known as Differential Isochronous Self Collimating (DISC) counters, which were liquid-filled, were used on the 600 MeV synchrocyclotron for a variety of experiments with pions and were then tested without modification on the 28 GeV



CERN 21.5.71

