REPORT BY THE ISC ON THE WORKSHOP ON FUTURE EXPERIMENTS AT ISOLDE

LEY SIN, Switzerland, May 29 - June 1, 1991

SYNOPSIS

The purpose of the Workshop was to provide the ISOLDE Committee with a basis for making recommendations on the future experimental programme at the PSB ISOLDE. These recommendations may be summarized as follows:

- The transfer of the ISOLDE facility to the extracted beam at the PS Booster will result in vastly improved conditions for experiment. The installation with two modern isotope separators (one for general purposes and the other especially designed to give very high mass resolution) will improve the beam quality. The 1 GeV pulsed beam is expected to give higher production yields, better background conditions and also prospects of developing new radioactive beams.

- Broad systematic studies of nuclear ground state properties with laser techniques and ion traps should continue to be a major part of the programme in the next five years at least.

- Programmes on exotic nuclear decay modes and nuclear structure at the limits of stability should be strongly supported. ISOLDE has played a pioneering role in this field and the new facility at the PSB will certainly make it possible to keep the leading position for several years to come.

- Experiments on nuclei which are important for the understanding of astrophysical phenomena such as the r- and s- processes, and the low-energy studies of fundamental interactions on the interface between particle-, nuclear- and atomic physics should become prime elements of the future experimental programme.
- Solid state physics programmes have in recent years used about one third of the total beamtime available at ISOLDE. These programmes should continue to receive strong support. The key points in the future programme will be in the field of surface physics and in investigations of impurities and defects and their interactions in semiconductors. In the field of materials science a technically oriented programme for studies of wear and corrosion resistance of materials could be an interesting future development.

- In the case medical physics, ISOLDE produced isotopes should be used for developments both for diagnostics and therapy. These studies should be given a higher priority in the programme than earlier. Biophysics experiments, giving information on structure of complex molecules like enzymes, hormones etc., are an interesting future possibility that should be investigated.

- The ISOLDE beam development programme has been and remains of paramount importance for the future of the facility. This is one area where a relatively small additional effort can give handsome dividends in the research output. We recommend that CERN strengthen its support of this activity.

- On the three to five year term ISOLDE might be the prime site for building a unique world facility for radioactive beams, providing exotic beams up to 6 - 10 MeV/u for astrophysics and nuclear physics studies. We recommend that this option be actively studied.
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1. INTRODUCTION

The ISOLDE (Isotope Separator On-line) programme is among those diversified scientific programmes at CERN which have been pursued over extended periods of time. Its uniqueness, high quality and competitiveness have long been recognized. Following the closure of the SC machine which provided ISOLDE with its 600 MeV proton beam, CERN has decided to move the ISOLDE facility to the PS Booster which can supply protons of more than 1 GeV with intensities similar to those of the SC. The increase in beam energy will lead to higher production rates of radioactive isotopes while the pulsed operation of the Booster will mean better background conditions.

With the new ISOLDE building, the separators and beam-lines still underway, the ISOLDE Committee called a special meeting in Leysin from May 29 to June 1, 1991 in order to look into the future programmes at the new facility. At this meeting the ISOLDE users - old and potential new ones - together with a few invited speakers from outside the existing ISOLDE community presented their views in six topical sessions each chaired by a member of the ISOLDE Committee. From those sessions and the ample time allowed for discussions, a thorough review of the past ISOLDE programme emerged in addition to a picture of possible future extensions, improvements, new projects and ideas.

In the six sessions the following topics were covered:

SESSION A: Investigations of Nuclear Ground State Properties (Traps, Lasers and other Techniques); Chairman: E.W. Otten

SESSION B: Nuclear Spectroscopy; Chairman N. Stone

SESSION C: Astrophysics and Fundamental Symmetries; Chairman: A. Richter

SESSION D: Exotic Decays; Chairman: A. Poves

SESSION E: Solid State Physics; Chairman: J.W. Petersen

SESSION F: Layout and Facilities; Chairman: B. Jonson

The presentations and the lively discussions indicated that many of the programmes envisaged for the immediate future (i.e. for about the next four years) at the new ISOLDE are in general of the quality, uniqueness and competitiveness which characterize the high standards expected of CERN. In the future, however, priorities have to be better defined concerning the availability
of adequate beam time and will also need to be focussed somewhat better than has previously been the case. Clearly, the Leysin-Workshop has provided a guideline for the future work and decisions of the ISOLDE Committee concerning the forthcoming proposals for experiments.

As is often the case at a new facility with a diverse research programme (ranging in the PSB-ISOLDE case from the study of fundamental phenomena to very practical applications) the longer term future is less clear. It would, therefore, be appropriate to review the ISOLDE programmes in a similar Workshop in about three years time. Until then it is mandatory for the ISOLDE community to maintain its image of high quality research within the wider physics community.

2. IMMEDIATE FUTURE

The prime experiments for the immediate future (< 4 years) will be executed in the fields of nuclear ground state properties, nuclear spectroscopy, astrophysics and fundamental phenomena, exotic decays and solid state physics.

2.1 Atomic physics and nuclear ground state properties

Atomic physics experiments have been a tradition at ISOLDE from its earliest days. Some of them were devoted to pure atomic physics questions, like the first determination of the atomic spectrum of the element francium by various laser spectroscopic methods; but the majority of them were linked to nuclear physics problems, namely the investigation of nuclear binding energies, radii, shapes, spins and moments, which have been derived from precision measurements of atomic masses and of the isotope shift and hyperfine structure in atomic spectra. In the following we will try to describe the interplay of the two sides of this coin, on the one hand the implementation of new experimental techniques at ISOLDE, (the modern "magic" of manipulating a handful of atoms by lasers, traps, etc.), and on the other the rôle of the scientific results within the general strategy of nuclear structure physics.

2.1.1 Laser spectroscopy

The fruitfulness of atomic spectroscopy at ISOL-facilities is documented by more than 500 nuclei which have been measured this way for the first time. The vast majority of these data were obtained at the CERN ISOLDE, clearly the leader of the field, but with essential contributions from the on-line-facilities at Gatchina, GSI and Orsay. This voluminous output resulted from the continuous and many-sided methodological development work over the last twenty years. The typical problems involved, adaptation to on-line-conditions, achievement of high accuracy while in the main measuring from a neutron deficient isotope,
development reflects the revolution of atomic spectroscopy that took place with the transition from spectral lamps to tunable lasers. Some of the methods specially developed for ISOL purposes have produced spin off in other areas of precision spectroscopy and trace analysis.

The present state of affairs is approximately as follows: the isotopic chains of volatile elements are mostly measured down to yields of $10^2$ atoms/s in favourable cases and $10^6$ in unfavourable ones. The dominant methods by now are collinear laser spectroscopy and resonance ionization spectroscopy. Both include a number of variants, sometimes hybridized with other techniques like NMR, radioactive detection, collisional charge exchange, laser desorption, time-of-flight analysis, sometimes with each other.

Current laser spectroscopic techniques make full use of this methodological freedom and aim to extend the scope of measurements towards:

- light elements, requiring higher spectroscopic precision
- refractory elements, requiring appropriate separation and handling techniques
- nuclei near the drip lines, requiring improved sensitivity or separation yields.

The pulsed operation of the booster ISOLDE could greatly improve the situation for the two latter items provided that appropriate target ion-source combinations are developed. The proposed intermediate storage of the ISOLDE beam in an ion trap would also be instrumental in this respect.

Another proposal for the booster ISOLDE leads to a new field of laser spectroscopy and to quite different physics questions as well. The experimental technique concerns laser cooling, by which a dense cloud of atoms is trapped by the fields of six orthogonal, intersecting lasers, within which the atoms come practically to rest ($T \approx 10^{-4}$ K). It seems possible to trap efficiently ISOLDE isotopes from a vapour or an atomic beam this way and to prepare a sample dense enough to allow the extremely interesting but demanding parity violation experiments in atomic transitions to be done. This is discussed in a separate section below.

2.1.2 On-line-nuclear orientation

ISOLDE's NICOLE facility is a powerful on-line dilution refrigerator by which implanted nuclei can be polarized within their lifetime by the hyperfine fields of the host lattice. The NICOLE collaboration plans to continue its multi-faceted physics programme, which includes determination of nuclear spins and moments, investigations of problems in solid state physics and studies of $\alpha, \beta$, and $\gamma$ angular correlations from polarized nuclei including proposals for symmetry tests of the weak interactions.
The NICOLE and related techniques offer a large variety of experimental approaches to the problem. Since not only the hyperfine splittings but also the relaxation times and equilibrium polarization depend on the nuclear moments, the latter may be deduced from NMR measurements as well as from the time dependence and the strength of angular correlations. Experience has shown that NMR is to be preferred whenever possible. As an alternative to low temperature polarization in the host, various techniques to polarize the mass separated beam while still in flight (before implantation) are in use at ISOLDE or are being proposed. This can be done by optical pumping with lasers, by passage through optically pumped gases or by scattering from or passage through tilted foils.

During its short time of operation at ISOLDE, NICOLE has been able to exploit only a small fraction of its scientific potential and has a good future ahead. In measuring spins and moments it is complementary to laser spectroscopy, addressing refractory elements or daughter elements which are not available as primary beams.

2.1.3 Mass spectrometry

Nuclear binding energies far off stability may be determined either by a network of Q-values derived from nuclear reactions and decays or by weighing the nuclear mass directly, which requires atomic physics techniques again. This field has also a long tradition at CERN starting with a Mattauch-Herzog spectrometer at ISOLDE II in the middle of the seventies. These measurements provided absolute masses and thus neutron separation energies along isotopic chains of alkalies over a wide range of mass numbers connecting regions of completely different nuclear structure. In the Rb-chain, for instance, the measurements extended from deformed isotopes on the neutron deficient side through closed shell nuclei at stability up to another deformed region at the very highest mass numbers. Also the extremely low 2n-separation-energy of the famous "halo nucleus" $^{11}$Li was measured in this way. These data served for a long time as mass standards far off stability. In recent years a subtle technique of storing ISOLDE isotopes in a Penning trap has been developed. By cooling off the random motion in the trap with the help of rf-fields the cyclotron frequency could be measured with a resolving power of $10^6$, yielding binding energies with an accuracy of about 10 keV. Thus the previous limits of error could be improved by up to two orders of magnitude. Since the method works with only a few ions at a time, it promises extremely high sensitivity once the project of storing and cooling the ISOLDE beam directly and efficiently in an intermediate Paul trap has been realized.
2.1.4 The physics of surveying nuclear ground state properties

The maturing of experimental methods has enabled us to proceed from punctual to systematic measurements, or to choose the case in the context of specific physics questions rather than of experimental limitations. The importance of systematics is most easily explained from the cases of nuclear masses and radii, which follow to first order the Bethe-Weizsäcker-formula and the droplet model. The interesting features of nuclear structure and its typical many-body-effects, like shell structure and symmetry breaking, are seen only by a synopsis of these data, that is by the local deviations from the first order gross structure. Even such an exotic and isolated case, like $^{11}$Li, with its neutron halo cannot be properly interpreted without knowing the masses, spins and moments of its neighbourhood as well. These data strengthen and stabilize the conclusions on this problem drawn directly from nuclear reactions and decay. Another interesting problem from recent years concerns the occurrence of a stable octupole deformation in radium isotopes. The phenomenon manifests itself in characteristic features of the nuclear excitation spectrum. Again an investigation of the mass surface in the region corroborated the corresponding theories on octupole deformation. Moreover the spins and magnetic moments showed how the single particle wave function reacts on the asymmetric potential with the breaking of its intrinsic parity.

Bearing in mind the wealth of experimental data obtained in recent years we stress the necessity of more theoretical work at every level - on the side of phenomenological models surveying and characterizing the data, as well as on the side of microscopic calculations. The phenomenon of coexisting shapes has attracted many theoreticians in the past and one clearly sees progress in understanding these phenomena. But there are many other clear-cut and striking observations in nuclear structure which still await a satisfactory explanation within or beyond the present frame of theories.

2.2 Structure of highly unstable nuclei and exotic decay modes (Sessions B & D)

2.2.1 Spectroscopic investigations of nuclear structure

Nuclear phenomena studied through investigations of excited states and their interlinking transitions have been fundamental to the ISOLDE programme since its beginning. Indeed the exploration of the interplay of different excitation modes, and their separate and joint variation over the N, Z surface, form the very substance of nuclear structure study at low excitation. Phenomena elucidated by systematic sophisticated spectroscopic study include nuclear deformation (with associated sub-shell structure and including octupole and higher terms), shape co-existence, cross shell excitations (intruder states) and scissors modes.
Although measurement of the first excited state of mirror nuclei above \( Z = 80 \) is of immediate interest, modern spectroscopic study of nuclear structure at low excitation does not mean building up ever more complex decay schemes. Secure spin/parity assignments, half-lives, electro-magnetic moments and transition probabilities are among the sophisticated parameters required if level structures are to yield physical understanding. This is particularly true of the high \( Q \) decays far from stability with attendant interwoven excitation structures. Only rarely will particular excitation modes stand out strongly. Complexity however does not imply lack of interest but is a challenge to both experiment and theory. Current theoretical approaches clearly struggle to describe the complex structures that occur, nevertheless it is equally obvious that only precise experimental study in appropriately chosen nuclei can show the way to theoretical development.

At the new ISOLDE spectroscopic studies focussing upon specific questions and utilizing methods yielding detailed level properties will continue to be supported. Adequate theoretical involvement is essential to extract the maximum insight from the measurements.

The study of nuclear deformation, both symmetric and asymmetric, has been, and will continue to be, a strong theme of excited state nuclear structure investigation at ISOLDE. The well-known large array studies of superdeformation and fission isomers have their direct equivalent in lower lying excitations in specific regions of nuclei far from stability. Shape-coexistence and intruder states have cast light on nuclear structure in many areas and are of continuing interest, particularly where systematics can go through mid-shell and beyond. Moving from \(^{90}\text{Zr} \) - doubly magic towards the neutron drip line one can reach extreme deformation around \(^{102}\text{Zr} \) whilst towards the proton drip line the same happens at \(^{80}\text{Zr} \). Echoes of twin bands in superdeformed nuclei has been suggested in the low-lying excitations of n-rich Sr isotopes, for example.

Octupole deformation has been an active topic at ISOLDE. A clear spectroscopic signal for static octupole deformation has been established and further exploration of this phenomenon in the actinides, with possible short-term extension to n-rich rare earths, is well justified.

With increased energy and with isobaric separation the ISOLDE booster will access nuclei close to the proton drip line up to yttrium. Yields of other proton rich isotopes will be increased in the \( A = 50-100 \) region. In these nuclei, of direct astrophysical interest, active studies which should be encouraged include:

1. Nuclei with both \( n,p \) in the \( f_{7/2} \) subshell, open to full shell model calculation
2. Mirror nuclei with \( N > 30 \) to extend knowledge of the residual \( n-p \) interaction
3. Extended isospin multiplets (to \( T=2 \)).
Among technical developments, in the short term new $\beta$, $\gamma$, $\gamma$ coincidence methods to establish lifetimes in the 10-1000 ps range will provide stringent model tests. In the longer term Doppler width measurements with crystal spectrometers may give entry to the fs-ps range but difficulty of high precision operation and the low efficiency of such devices will pose problems.

Despite the advent of new trap-based methods of nuclear mass measurement, the programme of mass surface investigation though $Q_\beta$ study continues to be the best available for heavier nuclei and for half-lives less than one second. Experiments are focussed in the complex $A = 100$ region.

Recent studies of alpha particle anisotropy from oriented nuclei have stimulated a revival of theoretical interest in the mechanism of alpha decay and the influence of nuclear shape, dormant since pioneering orientation work in the 50's and 60's. Other results on beta particle asymmetry show the future for such studies yielding electro-magnetic moments and beta matrix elements bearing on isospin conservation nuclei. It is clear that much new physics is accessible on details of alpha and beta decay modes and on interaction strengths. Well focussed proposals in these areas should form part of the future ISOLDE programme.

2.2.2 Exotic decays

The study of the beta decay of nuclei far off stability is one of the main lines of the ISOLDE programme. Nuclei involved in these decays are rarely produced and short lived. Moreover, their decays are associated with a variety of complex de-excitations of the state fed in the daughter nuclei. In addition to $p$, $2p$ and alpha decay, these decays include $2n$, $3n$, triton and deuteron emissions. The latter four were actually discovered at ISOLDE. The information that can be extracted from the analysis of these experiments is manifold and relates to fundamental problems; new nuclear structure physics, weak interaction physics, charge symmetry effects and the importance of non nucleonic degrees of freedom in nuclei. In many cases the unveiling of new physical phenomena relies on the comparison of the experimental results with fully microscopic nuclear structure calculations (now available for many light and medium-light nuclei and even for some heavier ones). It is natural to divide the topic "Exotic Decays" into four main items:

(a) $\beta^+$ decay of proton rich nuclei
(b) $\beta^-$ decay of neutron rich nuclei ($Z<<N$)
(c) $\beta^+$ decay of neutron deficient nuclei ($Z<N$)
(d) prompt radioactivities
a) The proton rich nuclei have the unique property that a large fraction of the $\beta^+$ strength sum-rule lies within the Q-window of the decay. For example in the case of the decay of the $T_2 = -3/2$ nucleus $^{37}$Ca about 30% of this strength can be observed. The experiments should be pushed to more proton-rich nuclei, where more of this strength is expected to fall within the Q-window. A very interesting case would be $^{31}$Ar, whose decay energy is as high as 18.7 MeV. This exotic nucleus will be readily available as a unique ion beam in the new ISOLDE facility, possibly together with a number of other exotic beams of sd shell nuclei close to the proton drip line. Most of the giant GT-resonance would be then accessible.

Recently a carefully tailored experiment on the $\beta^+$ decay of $^{37}$Ca has been conducted at ISOLDE. This experiment exemplifies the kind of physics that these measurements may convey:

(i) The results of the experiment are relevant to other branches of physics. The $^{37}$Ca $\beta^+$ decay is equivalent to the $^{37}$Cl $\nu$ capture by isospin symmetry arguments, and therefore can be used to calibrate the $^{37}$Cl solar neutrino detector.

(ii) The results for the total $\beta^+$ strength question the accepted status of the Gamow-Teller quenching in sd shell nuclei and the extraction of the GT strength from $(n,p)$ and $(p,n)$ reactions.

(iii) The large $Q_{\beta}$, $\beta^+$ decays may serve as a calibration for them. The importance of this calibration is enhanced by the fact that theoretical approaches to 2 $\nu$ $\beta\beta$ decay have as ingredients the $\beta^+$ and $\beta^-$ strength functions relying on comparison with $(n,p)$ and $(p,n)$ data.

The beta decay of $^{31}$Ar is also associated with the emission of a proton pair, a decay mode discovered in Berkeley in 1983. This mode seems to become a dominant decay mode for very proton rich nuclei and it is largely expected in the decays of very proton rich fp shell nuclei. It offers an interesting possibility to study the p-p correlation and the $^2$He system.

b) The experimental programme at the PSB-ISOLDE must contribute to the improvement of our knowledge of the changes in the behaviour of nuclei at the neutron drip line. Given the wealth of new phenomena found already (neutron halos, superallowed $\beta^-$ decays, etc.) it is clear that a continuation of the programme in order to cover a wider range of nuclei as well as to improve the existing data is highly desirable.

As was the case in the proton-rich side, the discovery of regions of deformation was one of the 'aces' of the past ISOLDE programme. The continuation of the
study of nuclei of the N=20 region in order to get as close as possible to the n-drip line (while obtaining the maximum of spectroscopic information) is a fundamental goal. For example, the extension of the half-life measurements to very n-rich Ne isotopes would be desirable. The proposal that the anomaly in the β half life of $^{29}\text{Ne}$, suggesting the "second valley of stability", is due to an intruder from the fp-shell is very interesting and deserves increased attention in the future.

The study of the structure of the Gamow-Teller strength function near threshold via β delayed emissions is a promising way of studying exotic structures at the neutron drip line. Precise measurements of first forbidden beta decays have been recently advocated as one of the best ways to study the effect of meson exchange currents in nuclei with special emphasis in the $0^- \rightarrow 0^+$ decays.

c) Suggestions on possible nuclear orientation measurements of the β delayed particle decays are certainly interesting. The scientific interest of studying the delayed particle decays of heavy nuclei (A > 60) is in statistical phenomena and quantum chaos and should consequently be supported.

d) There are no really good candidates of p-, 2p-, or n- radioactivities worth looking for at ISOLDE. Heavy cluster radioactivity programmes should be continued on the same level as in the past. Fine structure studies and the search for new cluster emissions definitely add to our understanding of this phenomenon.

2.3 Astrophysics and fundamental symmetries

The production of exotic nuclei at ISOLDE offers excellent possibilities to study the nuclear physics of fast-burning astrophysical environments of which a prime example is the r-process. One of the main issues at present is the understanding of the so called isotopic anomalies in meteorites. Astrophysical models have difficulties in explaining the solar abundance ratio of $^{48}\text{Ca}/^{46}\text{Ca}$ and the correlated Ca-Ti-Cr-Fe-Ni-Zn isotopic anomalies in certain meteorites which point to a large overabundance in the most neutron-rich isotopes of each element. From those anomalies important questions on the conditions in the early solar system and on mechanisms taking place at the stellar origin of such anomalous matter can be answered. For this some key experiments are necessary (and have been proposed) that study via on-line high resolution β-delayed neutron and γ-spectroscopy the nuclear structure of highly exotic nuclei which are at the extreme borderlines of production at the new PSB-ISOLDE facility. Those nuclei are the "progenitors" of the stable isotopes for which the isotopic anomalies have been found.
Still another very exciting astrophysical problem which might be partially solved with the help of the new ISOLDE concerns the s-process nucleosynthesis. In particular, the abundance patterns of s-process branchings carry important information on the physical conditions of the stellar site. They allow for example the determination of the neutron- and the mass density as well as the temperature and their study thus yields information on the reliability of stellar s-process models. The function of ISOLDE in this programme lies in the preparation of radioactive samples by implantation techniques which are then transported to an off-line facility (at Karlsruhe/Germany) where radiative neutron capture will be performed. About 30 radioactive branch points need to be measured with priorities on the radioactive isotopes $^{90}$Sr, $^{135,136}$Cs, $^{147}$Pm, $^{155}$Eu, $^{163}$Ho and $^{179}$Ta which have half-lives ranging from 1.8 to 4570 years.

A third class of experiment in which radioactive ion beams could become important in nuclear astrophysics, (e.g. to study processes in the CNO cycle as recently shown on the radioactive beam facility at Louvain-La-Neuve/Belgium through the process $^{13}$N(p,$\gamma$)${}^{14}$O) would require a postaccelerator after ISOLDE. This, however, is a much longer term project, which should have clearly focussed and well defined physics aims.

The ISOLDE nuclear astrophysics programme must be therefore viewed as a coherent and important effort and given priorities accordingly.

While the nuclear astrophysics experiments at ISOLDE are relatively 'straightforward' and probably easy and fast to integrate within the planned facility, the envisaged experiments in the field of more fundamental phenomena partly call for rather sophisticated equipment. This is particularly true for a very exciting class of experiments in which the measurement of parity nonconservation in optically trapped radioactive isotopes is attempted. Precision experiments on the tiny parity nonconservation effects in atoms require relatively high densities of atoms. The new ISOLDE, in conjunction with laser trapping and cooling techniques to collect and hold radioactive isotopes of rubidium, cesium, francium and other alkali atoms efficiently, will make such measurements feasible. Due to the fact that atomic structure effects are safely removed by comparison of isotopes, the proposed parity nonconservation measurements will provide potentially the most precise test of the standard model. Also, measurements on different isotopes (or ratios of differences) would allow the first independent determination of the electron-quark neutral coupling constants. At the level of precision aimed for, the experiment requires detailed knowledge of nuclear structure far off stability since the change of neutron and proton distribution within the nucleus along the isotopic chain enters the analysis at the percent level. In addition to this motivation, measurements of the nuclear anapole moments in a number of
isotopes would greatly improve our understanding of parity nonconservation in nuclear physics.

Another topic of current interest in elementary particle physics which will continue to be studied at the PSB-ISOLDE as at the old one, is the sensitive search for particles which are either feebly produced or weakly interacting (massive neutrinos, axions or other elusive scalar bosons). Those experiments utilize the important property of ISOLDE that very strong sources (of the order of 1 Curie) can be produced which are simultaneously very clean with respect to contaminating radioactivities. Significant upper limits from a $^{125}$I source have been derived concerning the existence of a massive keV neutrino. This would show up in the internal bremsstrahlung spectra from electron capture decay, and from the same source for the branching ratio of axion to gamma emission in a Mössbauer transition. This approach has shown that significant progress can be expected in the future using highly efficient, low-background detectors.

Like the astrophysics programme, low-energy studies in the atomic and nuclear sector of fundamental interactions should be an integral part of the ISOLDE programme and should be pursued. "New" physics is being probed on the interface of particle-, nuclear- and atomic physics.

Experimental studies of time reversal and parity violation in nuclear $\gamma$-decay using linear polarization of $\gamma$-rays from nuclei oriented by the hyperfine interaction at low temperature have also been reviewed. If the observed CP-violation in the $K^0\bar{K}^0$ system (explained in the Standard Model by an imaginary phase in the Kobayashi-Maskawa quark mixing-matrix) involves mostly quarks of higher generations, T-violation can only be sensitively investigated at high energies. However, alternative scenarios exist in which CP-violation is due to other sectors, encouraging low-energy searches in nuclei for which certain enhancement factors could be effective. Since all symmetry tests in $\gamma$-decay so far were performed on long-lived radioactive nuclei, the on-line nuclear orientation facility NICOLE at ISOLDE allows a search for suitable candidates further from stability, on which in principle T- and P-violation effects could be studied. However before such experiments are accepted at ISOLDE the physics case needs to be worked out on a suitable nucleus. It should also be kept in mind that the experiments are rather time consuming and require coherent action and collaboration of experts in the various fields of source producing mechanisms, cryogenic methods, polarized photons and nuclear physics. Thus, such studies will for the moment have a lower priority.

Finally, ISOLDE will provide nuclei distant from the valley of stability for which magnetic moments can be determined by the combination of their subsequent polarization with the tilted-foil method and then the measurement of the g-factor using the $\beta$-NMR technique. In particular, the measurement of g-
and differences of such moments will provide direct information on the isovector and isoscalar parts of the nuclear current, which is composed primarily of nucleonic and mesonic pieces. Such studies on symmetries on the nuclear level should certainly be pursued at the PSB-ISOLDE for a few selected and interesting cases which would help to pin down the effective magnetic operator in the s-d and f-p shells.

In conclusion, the study of astrophysical phenomena involving the r- and s-process and the low-energy studies of fundamental interactions on the interface of particle-, nuclear- and atomic physics should become prime elements of the research programme at ISOLDE in the immediate future.

2.4 The Solid State Physics Programme
The solid state physics programme at ISOLDE started in 1976 with experiments using Perturbed Angular Correlation (PAC) to investigate the local electronic structure at impurities in metals. The new feature of these experiments was that the implantation of short lived parent isotopes allowed investigation of completely immiscible systems where conventional techniques could not have been used.

Soon afterwards a project was started to investigate implantation processes into metals, a topic of very high technological importance, via Mössbauer spectroscopy. Combined with data from PAC and electron Emission Channeling, (a further nuclear solid state technique initiated at ISOLDE), a very complete picture could be given of the microscopic environment of the primary implant. Other techniques that have been used for solid state research in recent years are tracer diffusion, electron-gamma PAC, beta-NMR and Tracer Deep Level Transient Spectroscopy (TDLTS). In particular the new technique of Conversion Electron Spectroscopy of Valence Electron Configurations (CESVEC) used a modern magnetic spectrometer originally built for a neutrino mass measurement. The close collaboration between groups using different techniques and isotopes has become a characteristic of the ISOLDE solid state programme which at the end of 1990 had expanded to a level of one third of the total ISOLDE beam-time.

During the last year of SC-ISOLDE operation five new projects, i.e. diffusion in amorphous semiconductors, tilted foil nuclear polarization, laser polarization in semiconductors, and PAC in enzymes were allocated test beam time.

We expect that investigation of metallic systems with nuclear techniques will continue on a moderate scale. Some essential problems concerning magnetism in particular remain to be solved. The great successes of the semiconductor physics programme in recent years imply on the other hand that this activity will probably still grow and diversify.
It is typical for solid state research as well as for other applied work with radioisotopes that a regular availability of beamtime is an essential ingredient for success. Once fully completed the new PSB-ISOLDE facility with its various possibilities for parallel beam usage will be ideally suited for this purpose. In the following the strong points of the future solid state programme as they appear at the moment will be outlined.

2.4.1 **Semiconductors**

Characteristic properties of semiconductors like charge carrier densities or optical absorption are governed by the chemical nature and concentration of impurity atoms. Therefore semiconductor physics at ISOLDE has been focussed on the investigation of impurities and defects by nuclear techniques. In contrast to most methods conventionally applied in semiconductor physics, the nuclear methods overcome the bottleneck of "chemical blindness" by using radioactive ions whose specific decay unambiguously labels the investigated impurities. In semiconductors, many diffusion mechanisms are still not completely understood, especially those concerning self diffusion and fast diffusers like transition metals. A combination of radiotracer diffusion and emission channeling experiments should be a powerful tool to determine migration energies of the impurities and the involved diffusion mechanism.

Radiation induced defects and the lattice sites of impurities after ion implantation has been successfully investigated by Emission Channeling. This method determines the lattice location of radioactive ions as well as their dislocation due to the interaction with defects. Antisite defects in III-V compounds can be investigated by means of site-selective doping, e.g. implanting two suited probe isotopes, one can populate lattice sites of group V elements by group III elements and vice versa, creating well defined antisite defects. The Coulomb driven impurity-impurity interaction has been investigated by PAC, yielding information about the formation of acceptor-donor complexes and the trapping of hydrogen at acceptors in Si, Ge and III-V compounds. In future this topic will be extended and combined with complementary techniques like TDLTS to determine also the energy levels of impurities.

The programme concerned with the semiconductors of today like Si and III-V compounds has a strong prospect for the first four years at the new ISOLDE facility. During this period the programme will probably turn its attention towards the semiconductors of the future, thin diamond films, silicongermanium and GaAs-GaAlAs alloys. This will then provide a long term perspective for this research.
2.4.2 Surface Physics
A very promising activity has recently developed at ISOLDE in the field of surface physics. Here the combination of the nuclear methods (PAC, Mössbauer spectroscopy, channeling) with state of the art ultra high vacuum and standard surface analysis equipment (including eventually a tunneling microscope) enables unique studies of the geometric and electronic structure of even very dilute impurities at surfaces. The problems of interest range from mere lattice location over diffusion mechanisms to more complex processes such as catalysis. Here ISOLDE can play a dominating role due to the broad range of (short-lived) isotopes and the quality of the beams available. The programme can safely be assumed to be very productive in the first four year period of PSB-ISOLDE operation and probably shows a perspective well beyond that limit.

2.4.3. Future Projects
The broad range of radioisotopes available at ISOLDE would be a great advantage for a technology oriented programme to study the corrosion and wear resistance of materials. In this field considerable progress has been made recently with the application of implantation techniques using empirical methods of analysis. Nuclear tracer methods as well as the more sophisticated microscopic techniques could lead to a deeper understanding of the underlying physics of this industrially important process.

A completely new field in ISOLDE's future would be applications in biophysics. Here some of the techniques developed in the solid state programme could be used to obtain information concerning the structure and dynamics of complex molecules like enzymes. Again the high specific activity available generally from ISOLDE is of central importance for biophysics experiments, as recently successfully demonstrated in a parasitic test experiment.

2.5 Nuclear Medicine
Since the ISOLDE technique allows the production of almost all radionuclei it has a large potential to deliver high purity radioisotopes for medical research. The ISOLDE medical programme has during the past years been small but active. The aim has been to develop new methods for both diagnostics and therapy as well as methods for isotope production. These methods have received commercial attention for routine applications outside CERN. We recommend a continuation of the medical research programme aiming at new developments on a similar or slightly increased level to the one at the SC ISOLDE.
2.6 The ISOLDE beam development programme
The ISOLDE beam development programme, often referred to as target-ion-source development, is the basis for the physics programme. Only by continuously monitoring and improving the performance of the target and the ion-source it is possible to maintain and match the needs for each individual experiment. One reason for the success of ISOLDE in the past has been that CERN has kept a strong group of specialists on the spot to work on developments of new beams and improvements in intensity and purity of the existing beams. The increasing complexity and sophistication of the target-ion-source systems has gradually changed the development work from a local affair, at CERN and a limited number of other laboratories, into a new research field of its own. ISOLDE will clearly benefit from this development and the increasing interest in the field of far-unstable isotopes and radioactive beams at present will surely add many contributions from scientists outside CERN to the development work.

The following programmes should be carried out:

2.6.1. Developments aiming at an optimal use of the PSB beam
a) The increase in beam energy to 1 GeV at the PSB would for a number of targets make it profitable to increase the target length to 40 cm, which corresponds to about one interaction length of beam range in the target.

b) The pulsed beam structure offers an interesting possibility to reduce the delay times. By studying the delay-time distribution cases of radiation enhanced diffusion may be found. For very short-lived species this could mean a shorter optimal target than at present.

c) For the experiments in laser spectroscopy and ion traps it would be valuable to study the possibility of bunching the radioactive ion-beams from ISOLDE. In the long term a bunched structure is also of extreme interest for the development of a post accelerator project.

2.6.2 Selectivity
The laser ionization scheme, which recently has proven to be both an element-selective and efficient ionization technique, may now be implemented at the PSB-ISOLDE. This pulsed ion-source which is very important in studies of elements in the rare earth region where no chemical method can separate the isobaric contaminants is now ready for use. The present work to extend it to other elements should continue. Tuning the selectivity to isotope separation is less efficient but might also become of interest in some cases.

Some elements which are refractory or which form refractive compounds can be brought to the ion source in the form of a volatile chemical compound. At the
An example of this is the case of the element calcium, which is produced with strong contamination of isobaric potassium masses. By forming \( \text{Ca}^{19}\text{F}^+ \) one can shift the \( \text{Ca} \) isotopes 19 mass units away from the \( \text{K} \) contaminants which cannot form such an ion.

The other solution, which was used for the \( ^{37}\text{Ca} \) experiment mentioned in Section 2.2.2 is to use the high resolution separator to reduce the mass doublets, in this case \( ^{37}\text{Ca} \) and \( ^{37}\text{K} \), the latter being produced at \( \times 10^4 \) times higher yield.

2.6.3 Specially requested new or improved beams

The beams of many of the elements produced at ISOLDE may be improved by applying the new techniques mentioned above. This is especially true for elements between \( \text{He} \) (\( Z=2 \)) to \( \text{Ne} \) (\( Z=10 \)). We clearly recommend a continuation of this development. As before the target group should work in close contact with users. The ISOLDE Committee should set the time priorities for these improvements.

2.6.4 New technologies

1) In addition to the already existing ion-source techniques, ideas to combine an ECR (Electron Cyclotron Resonance) source with the ISOLDE target are being pursued. Tests have already shown that a number of advantages will be gained with such a source: It will have a considerably higher efficiency for production of singly charged ions of the lightest elements, it can be pulsed and has the possibility of efficient production of high charge states which is an important advantage in all post-acceleration schemes.

2) The IGISOL technique (developed in Jyväskylä, Finland) which essentially replaces the ion source with a He gas filled chamber, in which the recoiling ions stop, is an interesting alternative to conventional ion-sources. After thermalization and charge exchange to the single charge state in the He gas the ions are directly extracted into the separator. This technique has the advantage of being free from any dependence on the chemical properties of the produced ions and is very fast. The adaptation of this new technique to the ISOLDE facility should be studied in detail. The main question related with the time structure of the pulsed high voltage should be investigated. It may also become necessary to conduct a series of pilot experiments on thin targets to gain more knowledge on fragment energy and angular distributions needed in the construction of an efficient ion guide system for spallation and fragmentation products.
3. POST-ACCELERATION OF EXOTIC NUCLEAR BEAMS

In the last few years there has been a strong increase in the interest in exploring the boundaries of the nuclear chart. It has become clear that experiments of this kind cast new light on nuclear structure and that novel and entirely unexpected features appear. Progress in this field requires powerful accelerators and very sophisticated spectrometers and detection systems; within the heavy ion sector several types of new facilities are at the moment being commissioned or constructed in Europe and clear ideas are beginning to emerge as to developments in the near future. It seems clear that radioactive beams with high energy ( > 20 MeV/u ) can best be made via heavy-ion fragmentation, if necessary in combination with an additional cooler-storage-ring. For the lowest energies ( <6 MeV/u ) it seems better to accelerate the intense, slow beams available from a facility such as ISOLDE.

In a report to appear in the autumn 1991 on the future directions in nuclear physics in Europe, The Nuclear Physics European Collaboration Committee (NuPECC) will recommend investigating the possibility of building a large-scale exotic beam facility somewhere in Europe. We note that there are several competing projects in the US and in Canada, but in view of the long lead that Europe has held in this field, we expect that the next step too will be European.

In 1989 ISOLDE started an investigation of the possibility to couple a postaccelerator, PRIMA, to the ISOLDE beam. (This document is available in draft form). The prime scientific motivation was to study nuclear reactions occurring in fast burning astrophysical environments. An energy range of 0.2 to 1.4 MeV/u was envisaged.

The improved conditions now available at the new installation at the PS Booster clearly change the frame of reference of the PRIMA proposal drastically. Even at the SC, ISOLDE was unique in the world in its diversity of radioactive beams. The pulsed beam structure at the ISOLDE PSB and the higher yields will improve the situation further. Since ISOLDE has all the technological bases for injection of a radioactive beam in a post accelerator it would be the logical site for such a machine. The energy in the first phase could range from 0.2 MeV/u up to 6 - 10 MeV/u permitting not only astrophysics but also nuclear experiments at and below the Coulomb barrier (e.g. Coulomb excitation). We suggest, that CERN invite the interested parties, and of course the ISOLDE Committee, to hold a dedicated workshop to make a detailed investigation of the feasibility of such a project as soon as possible. Since everything exists at CERN except the post-accelerator (possibly an RFQ + Linac structure), the time scale for the realization of such a project could be as short as 2 - 3 years, which would give CERN an irresistible advantage over other laboratories.
For the longer term future the energy could be increased to the Fermi energy. One could also imagine at an appropriate moment to transfer the elements of such an installation to a high intensity accelerator, as for instance the ISIS at the Rutherford Appleton Laboratory, after an initial phase at CERN.