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NATIONAL INSTITUTE FOR RESEARCH IN NUCLEAR SCIENCE

GOVERNING BOARD

Proposals for Nuclear Structure Research

Covering note by the Secretary

02616

The attached report has been prepared by a D.S.I.R. working party under the chairmanship of Dr. J. B. Adams. It will be seen that the establishment of a national nuclear structure laboratory is recommended at an estimated initial capital cost of £4½ million.

While the report has not yet been considered by the D.S.I.R. Research Grants Committee, the D.S.I.R. have supplied copies for the information of the Institute.

Some provision for a possible new accelerator of the kind recommended was included in the Institute's recent five-year forecast of expenditure. The amount included was, however, £3.6 million and it must also be remembered that from the total forecast expenditure of £7.56 million over 5 years on this and other future major schemes, £2.29 million was deducted because some schemes might not be adopted and others might be delayed.

The notes in Appendix III of the paper were made available to the working party on an informal basis and should not be disclosed without the approval of D.S.I.R.

RESTRICTED

SECOND DRAFT

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

REPORT OF THE WORKING PARTY ON

NUCLEAR STRUCTURE RESEARCH

D.S.I.R.,
State House,
High Holborn,
London, W.C.1.

May, 1963.

REPORT OF THE WORKING PARTY ON NUCLEAR STRUCTURE RESEARCH.

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WORKING PARTY ON NUCLEAR STRUCTURE RESEARCH

Terms of Reference

To advise the Nuclear Physics Sub-Committee of the Research Grants Committee on the facilities which will be required in the future for nuclear structure research.

Membership

Chairman

Dr. J. B. Adams.

Members

Dr. K. W. Allen (Atomic Weapons Research Establishment, U.K.A.E.A.)

Professor W. E. Burcham (Birmingham University)

Dr. L. L. Green (Liverpool University)

Professor E. B. Paul (Manchester University)

Professor D. H. Wilkinson (Oxford University)

REPORT

Introduction.

1. The last 15 years have seen a spectacular advance in our understanding of the structure of the atomic nucleus. Until 1948 our knowledge of the nucleus had been largely empirical and our theory very scanty - chiefly a translation into the nuclear domain of universal thermodynamic and resonance concepts. The atomic weapons projects during the war had been little more than great technical achievements and had given only negligible insight into the workings of the nucleus itself. The great event of 1948 was the invention of the nuclear shell model, the starting point of which is the hypothesis that, to a first approximation, nucleons in the nucleus move independently of each other in an effective overall central potential. This brought order into chaos and showed how the ground states of the nuclei throughout the periodic table could be described within a single consistent scheme. The development in 1953 of the optical model for the nucleon-nucleus interaction showed how essentially a small extrapolation of the shell-model viewpoint could bring nuclear reactions within the same scheme. That the nucleus is also capable of displaying states of excitation that may be thought of as quasi-classical collective rotations and vibrations in which the bulk of its matter is involved - such as are familiar from molecular spectroscopy - was realized in the years following 1952. Since that time the two viewpoints, the shell model, dealing essentially with the motions of single particles within the nucleus, and the collective models, dealing with the correlated motions of many particles within the nucleus, have confronted each other. Both are models, extreme abstractions from the true situation, each with its own successes in its

own particular spheres of applicability, but neither giving the full picture.

2. There have been several rapprochements and, in particular, the shell model is improved if its starting point is taken as the motion of individual particles not within a spherical potential, but rather within the ellipsoidal potential specified by the collective model of nuclear rotations. There have been more fundamental attempts to understand how the nucleon-nucleon interactions within the nucleus can generate the collective models from the shell model. These attempts are potentially successful but are at an early stage. Some aspects of nuclear structure seem mostly simply understood through intermediate models in which the nucleus is described in terms of small interacting clusters of particles - quasi-alpha-particles, quasi-tritons, quasi-deuterons and so on. In some cases we can see how such clusters are already contained embryonically within the shell model, the nucleon-nucleon interaction then tightening them and making them more like the "real thing".

3. We are also making substantial progress in understanding how the empirically-determined free-space nucleon-nucleon interaction gives rise to models such as those to which reference has just been made, in particular how the strong and short-range nucleon-nucleon force is consistent with and can generate the superficially-contradictory quasi-atomic single-particle motion of the shell model. But our progress, experimental in revealing the regularities that suggest the models, and theoretical in relating and reconciling the models and making plausible their derivation from more fundamental interactions, has raised more questions than it has solved. We are still remote from a thorough-going theory of nuclear matter and have scarcely begun

to tackle the problem of finite nuclei from the standpoint of the nucleon-nucleon interaction. We have made much more progress in inventing and applying models of nuclear behaviour than we have in understanding or justifying them. We do not even know the relative importance of two-body and three-body or many-body forces between nucleons (there is as yet no demonstration that we can or cannot understand the properties of the three-nucleon systems, the triton and He^3, in terms of the two-body nucleon-nucleon interaction). We do not know the momentum distribution of nucleons in the nucleus. Despite intensive experimental and theoretical study we do not know the degree to which "closed shell" nuclei such as O^{16} and Pb^{208} in fact contain excited configurations - a question crucial to the advance of our understanding of the relationship between shell and collective models. We do not know the degree to which the hard core or strong velocity-dependence of the nucleon-nucleon interaction produces highly-excited configurations in the nucleus or the relationship of the free space nucleon-nucleon interaction to the residual nucleon-nucleon interactions effective after those highly-excited configurations have been defined away into the fictitious simple shell-model motions of resultant quasi-particles. We do not know the way in which, in a deformed nucleus, the nucleons distribute themselves among the various Ω-states belonging originally to a single j-value. We have very little idea about what happens at the nuclear surface, how the dense central regions of the nucleus match into outer space.

4. In our present understanding of nuclear structure we are, to make rather a close analogy, roughly at the same stage as we were in our understanding of the solid state when it was realized that electrons in metals do not simply uniformly fill a Fermi-sphere but display complicated structures in momentum-

space. Because the nucleon-nucleon interaction is so much more complicated than the electric interaction, and because nuclei are finite systems, we anticipate that the unfolding of the nuclear structure story will be more lengthy and complicated and fascinating than that of the solid state. The degree of understanding (perhaps familiarity would be a better word) so far achieved in terms of surprisingly simple models shows that the extra complexity of the nuclear case is not so great as to defy all hope of interpretation and that we are completely justified in going ahead with researches that we know will answer some of the crucial questions already raised and will perhaps reveal new types of regularity or new phenomena to be fitted into the expanding scheme.

5. The special role of nuclear structure research in the education and training of young physicists should also be mentioned since the equipment and techniques used in nuclear structure research are such that the research student can be given responsibility for a major part of an experiment and so can become familiar with a very broad range of concepts as well as with advanced equipment. For this reason we feel that continued full support for a lively programme of low energy nuclear physics is of great importance for the further supply of capable research physicists.

Existing facilities for nuclear structure research in the U.K.

6. In considering the experimental facilities which will be required over the next decade for a reasonable and well-balanced programme of research in nuclear structure, we have taken into account firstly the existing facilities in Universities and in the United Kingdom Atomic Energy Authority, and secondly the plans which, according to the latest information available to us, are being made in other countries, notably the U.S.A., for similar studies. In the case of the latter we were grateful to the National Science Foundation of the U.S.A. for providing copies of their report "Research Trends: Nuclear Structure Physics, 1962-67" (National Science Foundation Report NSF 62-45).

7. The present activity in nuclear structure research in the U.K. is centred in four Universities - Birmingham, Liverpool, Manchester and Oxford - in two United Kingdom Atomic Energy Authority laboratories - the Atomic Energy Research Establishment, Harwell, and the Atomic Weapons Research Establishment, Aldermaston - and in the Rutherford Laboratory of the National

Institute for Research in Nuclear Science. In addition relatively small programmes are in progress at a few other Universities and in one industrial laboratory, but these are not major interests of the respective Departments. The following table gives the machines which are at present in use (or are in the course of construction) in the U.K. The energy classification roughly defines the fields of interest. The facilities available at the seven main centres are also summarized in Appendix I.

Accelerator	Energy	Number	Sites
Cockcroft-Walton	<1 MeV	4	A.E.R.E., Glasgow, Durham and Edinburgh
Van de Graaff (one stage)	2-6 MeV	7	A.E.R.E. (2), A.W.R.E. (2), A.E.I. Ltd. and Manchester (2)
Tandem Van de Graaff (two stage)	12 MeV	3	A.E.R.E., A.W.R.E. and Liverpool
Cyclotrons	5-12 MeV/ nucleon	3	A.E.R.E. and Birmingham (2)
Heavy Ion Linac	10 MeV/ nucleon	1	Manchester
Electron Linac	28 MeV 100 MeV	1 1	A.E.R.E. Glasgow
Tandem Van de Graaff (three stage)	20 MeV	1	Oxford
Proton Linac	50 MeV	1	N.I.R.N.S. Rutherford Laboratory
Synchrocyclotrons	150 MeV 400 MeV	1 1	A.E.R.E. Liverpool

About one-half of these installations are more than five years old whilst some are more than ten years old. Furthermore they vary widely in their "supporting" facilities such as ancillary laboratories and offices, target-area layout, experimental equipment and technical support staff.

8. The facilities at the Atomic Energy Research Establishment, Harwell, and the Atomic Weapons Research Establishment, Aldermaston, have been provided primarily for the basic research requirements of the United Kingdom Atomic Energy Authority. These facilities are not national ones in the sense that they are generally available for potential users outside the U.K.A.E.A. although they have been used by some Universities. We understand that about 25-30 per cent of the running time of the A.E.R.E. synchrocyclotron and tandem Van de Graaff has been taken up by Universities whilst some use has also been made of the electron linear accelerator. The A.W.R.E. facilities, in particular the tandem Van de Graaff,

have also been used by some Universities and in the future will be more freely available now that the Nuclear Physics Division has been separated from the main site. We believe that these facilities at A.E.R.E. and A.W.R.E. may be valuable in meeting some specific programme requirements in individual Universities. Moreover, in the event that any of the present machines at the Atomic Energy Research Establishment or the Atomic Weapons Research Establishment should no longer be required by the U.K.A.E.A., it may well be that these could be put to good use if moved to a University site.

9. In considering the more advanced facilities which will be needed by Universities over the next decade we have not taken into account the future interests of the U.K.A.E.A. in nuclear structure research. However there are at present several groups at A.E.R.E. and A.W.R.E. actively engaged in nuclear structure research and we understand that these groups would also be interested in the use of the advanced facilities discussed later in the report.

10. The existing, or planned, facilities at the main University centres (including Glasgow where the recently approved 100 MeV electron linear accelerator will be useful for investigation of certain nuclear structure problems) have been financed

largely by grants from D.S.I.R. It is now a condition of these grants for large capital facilities that the machines should be regarded as "national assets" and made available for use by workers outside the particular Universities possessing the machines, but in fact this sharing of facilities has always taken place spontaneously as far as is practicable (for example teams from Manchester University and the Bradford Institute of Technology are using the recently installed tandem Van de Graaff at Liverpool). We therefore feel sure that the existing University facilities are being used, and will continue to be used, to maximum advantage in the national interest, although the sharing of these facilities may be limited by such factors as accommodation for additional experimental work. However, in the past, the provision of facilities for nuclear structure research in the Universities has been decided on the strength of proposals put forward by individual Universities related to their own requirements, and there has been no deliberate attempt to establish a rational policy based on the overall national requirement. This does not reflect any criticism of the several excellent schemes which have gone ahead in Universities in recent years - indeed we are very firmly of the view that strong "home" facilities must remain an integral part of the overall national resources - but we feel that with the new generation of machines now becoming available, in particular the advanced electrostatic generators, the time has come when the provision of these large and expensive machines must be considered on a national basis. We have therefore recognised that the most advanced facilities which will be needed in the future will almost certainly have to be provided through a national laboratory for nuclear structure research.

Proposed future facilities for nuclear structure research in the Universities

11. There are many ways in which nuclear structure research may be furthered but we are agreed that unquestionably the most general and powerful is by the extension to the highest possible energies, and for the greatest possible variety of projectiles, of electrostatic generators. The scientific need is for intense direct current beams of energetically-homogeneous particles with easily variable energy, high optical quality and good positional stability. Direct current beams are demanded because the great majority of experiments involve coincidences and so the rate of gathering data goes at least proportionally to the duty cycle for a given mean current. Easily variable energy is demanded so that excitation functions may be run and so that optimum conditions may easily be sought for a given experiment. High optical quality is demanded because many experiments, for example those using magnetic spectrometers, depend on current density rather than current and also require the smallest possible angular divergence; these considerations become the more pressing the higher the energy involved and so the better the percentage resolution needed to separate given states. Good positional stability, including easy and accurate reproducibility from day to day, is demanded by the need for precise geometrical definition, which itself becomes more and more important as the energy is increased because of the increasing complexity and shrinkage to smaller angles of the diffraction-like patterns associated with direct-interaction mechanisms. Energetic homogeneity is always demanded to permit the separation of closely-spaced states. Only electrostatic generators meet these requirements. In addition, only they are able to accelerate all types of ions. They are also the cleanest

accelerators in the sense that their background generated per microampere of useful accelerated beam is substantially lower than that of any other machine.

12. A possible competitor that we considered in the energy range in which an advanced electrostatic generator might operate is a spiral ridge cyclotron accelerating negative ions which are stripped and extracted with high efficiency as positives. However, in all significant respects, except for cost and magnitude of unresolved beam, such a machine is likely to be inferior in performance to an electrostatic accelerator, and in particular will probably not provide resolved beams of adequate homogeneity. In addition, the negative ion cyclotron is a relatively new project supported by little university or industrial experience, whereas the performance of a future tandem generator can be reliably extrapolated from the behaviour of many existing machines.

13. Other accelerators can achieve much higher energies than the electrostatic generator. There is a large and promising field of research into nuclear structure using projectiles of several hundred MeV. There is also special and considerable interest in electron excitations using energies of several hundred MeV. But this work is complementary to and does not replace the detailed structure studies that can only be carried out using lower energy beams of the quality detailed above. It must, in particular, be emphasized that the virtues of work at higher energies are only felt when those energies are so high that the quasi-free-particle pictures of the reaction mechanisms become valid and at the same time final state interactions are reduced to the level where they can be ignored or handled with confidence. We know by experience that this means energies of at least 200 MeV and preferably considerably more.

Until such energies are reached, there is little virtue in increase of energy above that attainable with electrostatic generators if, as must be the case, this increase is accompanied by a surrendering of the features of precision and control (see paragraph 11) belonging to the electrostatic machines. In particular it seems that the energy region 50-100 MeV has little to recommend it for nuclear structure work unless it can be attained with particle beams of electrostatic generator quality.

14. The present generation of tandem electrostatic generators (including those now under construction) will reach energies of certainly 20 MeV and very probably 25 MeV (for hydrogen isotopes). The case for taking the next step, towards 40 MeV, by the same means, is a strong one and some of the many reasons for this are given in Appendix II. When we come to consider the mechanism for achieving these objectives it is clear that the ideal machine is a single (presumably tandem) electrostatic generator. For hydrogen isotopes this brings the benefit of the highest possible currents and for heavy ions it enables us to attain the highest energies. At present no such tandem accelerator with a terminal voltage of 18-20 MV has been contemplated, but our objective in energy for hydrogen isotopes can, however, be reached through the double tandem concept which will permit the attainment of energies 3/2 times greater than those now anticipated from single tandems, viz. probably 37 MeV. We therefore recommend unanimously and very strongly the early purchase of a double tandem installation for the highest energy commercially available (at present the H.V.E.C. double 'Emperor' tandem which is guaranteed for 30 MeV and is likely to achieve nearer 40 MeV) unless the development of a single tandem for the same total (hydrogen

isotope) energy be declared feasible, in which case our recommendation would change in favour of the latter. In fact, in the light of discussions which have taken place since our meeting, it now seems possible that the present Emperor design could be scaled up by a factor of 1.5 with some additional development effort and this possibility should become clear during 1964 following the initial testing of the first Emperor machine. We also recommended very strongly that a national nuclear structure laboratory should be established for the machine, not only because of the extended scope and high cost of such an installation, but also because we believe that it would be undesirable for the management and operation of a project of this nature to be fully integrated with the work of any one University. We feel that it is of prime importance that an early decision should be reached on the establishment of such a laboratory with the most advanced facilities available; once this decision has been reached the final choice can be made between the single or double tandem installation in the light of the further information.

15. We have not attempted to forecast the likely requirements beyond this stage, partly because the next step will be a very big one in itself, and partly because the position will need to be reviewed periodically in relation to the latest developments in the design of electrostatic generators. However we have indicated in paragraph 13 the complementary interests in electron excitations using energies of several hundred MeV and we should therefore record that we considered very briefly (without reaching any conclusions) such possibilities as superconducting linacs, proton linacs with storage rings; or perhaps a complete rebuild of the Liverpool 450 MeV synchrocycltron for nuclear structure research.

16. We are also very strongly of the view that maximum advantage cannot be taken of advanced facilities available in a national laboratory unless adequate "home" facilities are also provided for the main centres of University interest, i.e. at Birmingham, Liverpool, Manchester and Oxford. These facilities will be needed not only to sustain the core of University research interest, without which a national laboratory would not become a viable establishment, but to provide the training ground for future generations of physicists versed in nuclear techniques (whether these are to be applied in the

low or high energy fields). However, much as we recognise this training function of the Universities, these "home" facilities should also be valuable research installations in their own right, although over a more limited field; we therefore favour the provision of smaller specialized machines at the four Universities which will offer facilities complementary to those available at a national laboratory.

17. From the reports which were made orally to us, the existing facilities at Liverpool University and those which are scheduled for completion next year at Oxford University, should provide adequately for the home-based programmes at these centres; however the representatives of Birmingham and Manchester Universities felt that new facilities would shortly be required at these centres. Professor Burcham informed us of proposals which have been prepared by Birmingham University for a 25-45 MeV variable energy cyclotron based on the axial injection of negative hydrogen ions into a three-sector spiral ridge system. This machine would replace the existing 60" Nuffield cyclotron which Birmingham University considered was now nearing the end of its useful life. Professor Paul informed us that Manchester University is considering a versatile accelerator in the 8-10 MeV range capable of very large beam intensity. Such a machine of advanced design is being discussed with the High Voltage Engineering Corporation and would be intended primarily for high resolution fast neutron spectroscopy. It would replace the present small Van de Graaffs,

which

Manchester University felt were inadequate for their home needs, and would offer facilities complementary to those available on the heavy ion linear accelerator which Manchester University regarded as rather too specialized for many domestic purposes. We have not considered these proposals in detail since individual submissions will have to be made by the Universities concerned. However we would again emphasize the importance of providing adequate home facilities for the main centres of University interest

Nuclear structure research outside the U.K.

18. It is appropriate at this stage, before considering the important questions of cost and siting which are associated with the proposals made in paragraphs 14 and 17, to establish how these proposals stand in relation to the facilities which will shortly be available (or are at present under consideration) for nuclear structure research in other countries.

(a) U.S.A. and Canada

The recent report published by the National Science Foundation surveys the current state of nuclear structure research in the U.S.A. and makes proposals for expansion of the work to take advantage of recent technological advances, notably in the design of accelerators.

The report states that out of a total of 529 doctoral dissertations in physics in the year 1959/60, 27 per cent were in nuclear structure, 16 per cent in cosmic rays and elementary particle physics, 28 per cent in solid state physics and 29 per cent in other branches of the subject. The ratio between nuclear structure and high energy physics has been essentially constant over the period 1951/61; and the absolute numbers have not changed significantly. The costs of research have increased substantially over the same period and for nuclear structure the report quotes an operating cost per graduate research worker increasing from 32,000 dollars in 1957/58 to 41,000 dollars in 1961/62. The report assumes that, as a result of developments in instrumentation and computers, operating costs will continue to increase rapidly, approaching 100,000 dollars per graduate research worker in 1968. As regards capital facilities, the report proposes an annual expenditure of 22 to 35 million dollars per year.

The many new tandem Van de Graaff generators installed or approved during the last two or three years is an indication of the rate of expansion of nuclear structure research in the U.S.A.: in fact the rate of installation of tandem generators is a useful measure of research activity in nuclear structure, since these accelerators, as the report points out, are particularly suitable for the majority of experiments. The first tandem generator manufactured by the High Voltage Engineering Corporation began operating in the Chalk River Laboratory of Atomic Energy of Canada in February, 1959 (and was followed two months later by the United Kingdom Atomic Energy Authority's machines at Aldermaston and Harwell). Following the success of the Chalk River accelerator, seven similar machines have been installed in U.S. laboratories (at the Universities of Wisconsin and Florida, California Institute of Technology, Rice Institute, Argonne and Oak Ridge National Laboratories and Keystone University) and two more (at the Universities of Texas and Pennsylvania) are in the construction stage. All these machines are guaranteed to operate with a 6 MV centre terminal and higher voltages have been achieved with the newer designs of accelerating tube.

Two larger versions of the tandem generator are now offered by the High Voltage Engineering Corporation: one of these, known as type FN or 'king size', will accelerate protons to at least 15 MeV, and the other, known as the type MP II or 'Emperor', is guaranteed for 20 MeV and is likely to achieve 25 MeV. Various combinations of these generators are possible if still higher energies are required.

The first 'king size' generator will begin operation at Los Alamos late in 1963, and will be used in conjunction with the laboratory's large single ended Van de Graaff to accelerate protons, deuterons and tritons to at least 23 MeV. The University of Washington (Seattle) is to have a combination of two 'king size' tandem generators and a single 'king size' machine is under construction for Rutgers University in association with Bell Telephone Laboratories. The University of Texas is installing a combination consisting of a standard tandem and a 6 MeV single ended machine and the University of Pittsburgh will have two standard tandems in 1963.

Four 'Emperor' machines have so far been ordered. These are for Yale University, the University of Minnesota, Chalk River, and the University of Rochester. A combination of two 'Emperors' is expected to be approved later in 1963 for Brookhaven National Laboratory and Princeton University is also known to be actively negotiating for similar support. Chalk River, in their proposal, have emphasized the role of heavy ion research with the 'Emperor'. They intend to develop a special iron free β ray spectrometer for conversion electron studies following heavy ion Coulomb excitation (the University of Rochester has included a similar proposal); and they also discuss the advantages of reversing the roles of the target and bombarding particle, e.g., studying the reaction $(Ne^{20}, \ )Mg^{24}$ instead of $Ne^{20} (\ , \ )Mg^{24}$. Yale University proposes to install a source of polarized ions in the terminal of its 'Emperor' tandem and it also intends to construct a scaled-up version of the Aldermaston multigap magnetic spectrograph for the study of charged particle reactions. Los Alamos intend to accelerate tritons in their three stage accelerator and propose to study fission through charged particle reactions such as ^{238} (dp) ^{239} fission.

(b) Europe

Excluding the United Kingdom, there are six standard tandem generators in Europe. Two of these are in France (Saçlay and Commissariat de l'Energic Atomique), two in Germany (Heidelberg and Erlangen), one in Denmark (Copenhagen and one in Switzerland (E.T.H., Zurich). One of the French machines is for military research; all the others are in well established centres of nuclear structure research.

(c) U.S.S.R.

There are known to be at least two tandem generators under construction in the U.S.S.R. - one at the Kurchatov Institute in Moscow and the other at the University of Kharkhov - but very little is known about the state of development of these machines. Nuclear structure research is expanding rapidly in Russia and an indication of the rate of expansion is the number of papers published annually in the Journal of Experimental and Theoretical Physics, which has increased sixfold in the period 1956 to 1960. As yet relatively little of the experimental work has been carried out with electrostatic generators.

(d) Other Countries

Australia has an active nuclear structure research school at the National University in Canberra. Her facilities include a tandem generator which was installed in 1960.

A standard tandem generator is being installed in 1963 at Rehovoth in Israel, another well established nuclear structure research centre.

The purchase of a tandem generator is also under consideration at the Nobel Institute in Stockholm.

19. From this short review it will be seen that the greatest effort in nuclear structure research over the next few years will unquestionably take place in the U.S.A. However, although our proposals appear modest in relation to the American plans, we feel that with the facilities proposed in paragraph 12 the U.K. can still play a leading part in nuclear structure research.

Estimates of cost related to electrostatic generators available commercially

20. A short description of the 'Emperor' tandems now offered by the High Voltage Engineering Corporation is given at Appendix III (Notes on Visit to High Voltage Engineering Corporation, 4th-5th March, 1963 by Professor E. B. Paul). Our recommendation in paragraph 14 would at present favour the purchase of the H.V.E.C. double 'Emperor' tandem, i.e. the three-stage system. The cost of such an installation, including purchase of site, housing and ancillary laboratories and offices, would be of the order of £3½ million, and at least a further £1 million should be allowed for initial experimental equipment. (The building must be of unusual size and flexibility just because the machine is intended to be a multipurpose flexible installation easily used by a variety of groups. It will have to provide for extensive target areas so that the two accelerators can either be used separately or combined into the 3-stage configuration, since for energies under 20 MeV it will be most advantageous to use the 2-stage configuration. Facilities for visiting teams from distant Universities will also have to be provided). We have not attempted to make any detailed estimate of the recurrent costs (including new experimental equipment) of such an establishment, but assuming an average of 10 graduate workers using the machine at any time, we believe that the figure would be in the region of £¼ million per annum. If budgetary considerations prevent the placing of an early order for the double 'Emperor' tandem, we would favour proceeding now with a single machine provided that a firm decision was taken that the second machine would be ordered later; but we would not support any proposal to limit the first order without a positive guarantee being

given on the second machine. In our opinion this would be false economy.

21. The cost of providing new "home" facilities for Birmingham and Manchester Universities (including the associated buildings and initial experimental equipment) would be of the order of £1 million for each. Recurrent costs would probably be around £50,000 per annum for each project.

22. We would however emphasize that these figures do not purport to be more than rough indications of the orders of cost. We did not consider it necessary to make fully costed proposals at this stage.

<u>The siting of the proposed national laboratory for nuclear structure research</u>

23. We have already mentioned (paragraph 14) that we are strongly in favour of the establishment of a national laboratory for the proposed double 'Emperor' tandem installation and we feel that there would be every advantage in siting this national laboratory on or near the campus of one of the present centres of University interest in nuclear structure research. We understand that suitable space could be made available at Birmingham University (which is situated centrally in relation to the interested Universities), whilst other possible locations are the Harwell area (near Oxford University) or the new N.I.R.N.S. site at Daresbury, Cheshire (near Liverpool and Manchester Universities). The management and operation of the national laboratory, with its own Director and permanent staff, would be quite independent of the particular University, but we nonetheless feel that for a project of this nature there are many mutual benefits which can be derived from a close association with one or more of the existing centres. We are unable to make more than this general recommendation on siting since the choice of the particular University must depend, not only on geographical considerations and on the availability of suitable sites, but on the collaboration which would be forthcoming from the respective Universities. The choice of site is not only important in itself but might determine the timing of the provision of future home-based facilities at the nearest Universities".

Summary of recommendations.

24. We recommend very strongly:-

(1) The early purchase of a double tandem electrostatic generator for the highest energy commercially available unless the development of a single tandem for the same total (hydrogen isotope) energy is declared feasible in which case our recommendation would change to the latter (paragraph 14)

(2) The establishment of a national nuclear structure laboratory for this installation which should be sited on or near the campus of one of the present centres of University interest in nuclear structure research (paragraphs 14 and 23)

(3) The provision of adequate "home" facilities for the main centres of University interest in nuclear structure research. These should be smaller specialized machines, although over a more limited field, which will offer facilities complementary to those available at the national laboratory (paragraph 16)

Appendix I

EXISTING FACILITIES FOR NUCLEAR STRUCTURE RESEARCH AT THE SEVEN MAIN CENTRES IN THE U.K.

1. Atomic Energy Research Establishment, Harwell.

This laboratory, set up in 1946, has for a long time been world renowned as a centre of low energy nuclear physics. It compares well with the national laboratories of the U.S.A. Its present and planned equipment suitable for nuclear structure research is as follows:-

0.5 MeV	Cockcroft-Walton accelerator (1947)
3 MeV	Pulsed Van de Graaff (1961) (one of the first in the world to produce fractional nanosecond beam pulses of several milliamperes)
5 MeV	Van de Graaff (1947)
12 MeV	2 stage tandem Van de Graaff (1959)
28 MeV	Electron Linear Accelerator (1960) (one of the first high intensity ELACs)
150 MeV	Synchrocyclotron (1950)
12 MeV/nucleon	Heavy ion cyclotron (under construction)

Although several of these accelerators were intended for purposes other than nuclear structure work, valuable contributions have been made with all of them. Examples are the recent giant resonance work using the electron accelerator and the inelastic proton scattering studies using the synchrocylotron.

2. Atomic Weapons Research Establishment, Aldermaston.

This laboratory, set up in 195 , has low energy nuclear physics facilities which are among the best in the world. It is particularly well equipped with large charged particle analysers and elaborate neutron detectors. The laboratory has considerable experience in accelerating tritons, He^{3} ions and heavy ions such as O^{16} and f^{19}. The accelerators which are available are as follows:

3 MeV	Van de Graaff (1957)
6 MeV	Pulsed Van de Graaff (1956)
15 MeV	2 stage tandem Van de Graaff (1959)

3. Rutherford Laboratory, National Institute for Research in Nuclear Science, Harwell.

The National Institute for Research in Nuclear Science provides facilities which are available for common use by Universities and similar institutions. Its 50 MeV proton linear accelerator at the Rutherford Laboratory (built in 1959) is being used by a number of teams from several universities for nuclear structure and dynamics research.

4. Birmingham University.

The nuclear structure work at Birmingham has been almost entirely connected with the 60" cyclotron (completed 1950) which produces 10 MeV/nucleon beams of protons, deuterons and other ions. Recently (1962) a 37" radial ridge cyclotron has been brought into operation. In addition, Birmingham uses the 50 MeV proton linear accelerator at the Rutherford Laboratory.

5. Liverpool University.

Liverpool is now equipped with a 12 MeV two stage tandem accelerator which came into operation in 1962. This replaced a 1 MeV Cockcroft-Walton set and a small cyclotron. The 400 MeV proton synchrocyclotron (completed 1954), though primarily used for high energy physics, is also suitable for certain nuclear structure work and such work is in active preparation.

6. Manchester University.

The work at Manchester has been almost entirely nuclear structure physics and has been centred around a 6 MeV single stage Van de Graaff and to a lesser extent around a 2 MeV Van de Graaff. Recently (1963) a 10 MeV/nucleon heavy ion linear accelerator has been brought into operation. Teams from Manchester are also using the Liverpool tandem and the Rutherford Laboratory machine.

7. Oxford University

Oxford has previously worked with two Cockcroft-Walton accelerators and a 125 MeV electron synchrotron. These are being replaced by a 3 stage tandem accelerator to produce 20 MeV protons. In recent years teams from Oxford have made major use of the facilities already mentioned at A.E.R.E., A.W.R.E. and the Rutherford Laboratory.

Appendix II

Some examples of nuclear structure programmes requiring more than 25 MeV

(i) Stripping in heavy elements. Our studies must be carried into the region of the heavy elements because it is there (in the rare earths and in the actinides) that the collective rotational model is best developed. Distorted wave calculations and experiment agree that unambiguous interpretation of stripping angular distributions (e.g. (d,p)) is unlikely unless the incident deuteron energy is of the order of twice the Coulomb barrier. This means that about 35 MeV are needed for the heaviest elements.

(ii) Pickup reactions for reduced widths. The safest way to measure reduced pickup widths is by (p,d). This is a strongly endothermic reaction and 35 MeV or more are needed both to reach interesting states in light nuclei where neutron binding energies are sometimes very high and also to give Coulomb-barrier clearance to as wide a range of Z-values as possible for the outgoing deuteron. (It may be hoped that the equivalent (He^3,α) reaction may be used for this purpose, but attempts to get direct-interaction fits, and so to extract reduced widths from the experimental data, are so far disappointing, and it is likely that the (p,d) reaction with its higher energy demands will remain the only reliable approach to this important problem).

(iii)(p,γ) giant resonance studies. To make a complete traverse of the ground state giant resonance (to 2 full widths above the peak) about 25 MeV are usually needed. An important problem is the relationship between the resonances to excited states and to the ground state. To investigate this situation to an excitation of 10 MeV above ground, 35 MeV are needed.

(iv) New collective states. Several predicted forms of collective excitation await discovery (e.g. T=1, $J=1^+$, T=0 $J=2^+$, T=1 $J=2^+$). Inelastic proton scattering should be a powerful tool for such searches. Typical expected energies are 10-20 MeV. The usual barrier arguments and the need to seek effects associated with excited states lead to the requirement of at least 35 MeV bombarding energy.

(v) (p,t) studies. Double pick-up is potentially a most powerful tool for discovering new nuclides, for investigating level structure and for determining double fractional parentage coefficients about which almost nothing is known. These reactions are strongly endothermic and the arguments in (ii) lead to a demand for more than 30 MeV.

(vi) (p,2p) reactions. Van de Graaff type resolution is needed to separate individual final stages. Although 35 MeV is too low an energy for confident direct interpretation of (p,2p) patterns it should be possible to some degree to calibrate the distortion effects by using levels of known properties. 35 MeV are essential to make accessible the states of interest and to take the reaction out of the range where distortion effects are hopelessly large.

(vii) Surface cluster studies. The texture of the nuclear surface is an important problem. The central question is whether it is rich in nucleon clusters such as alpha-particles. Reactions such as (p,α), (p,pα),(d,Li^6),(t,$Li^{6,7}$) etc. will throw important light on this matter. They should be carried out in heavy elements because only there is the surface of a nucleus sufficiently well differentiated from its volume. These studies demand the highest possible energies and also good resolution so that the associated parentage may be ascertained.

(viii)Reactions induced by helium isotopes are also important. Here the case for high energy is even stronger than for hydrogen isotopes because the Coulomb barriers are almost twice as high.

(ix) Heavy ion studies are occupying an increasingly-important part in our thinking about nuclear structure. They have a multitude of uses. They are the most powerful tool for Coulomb excitation studies, themselves of great and very widespread importance for probing nuclear dynamics. They also present a novel method of nuclear exploration, namely grazing surface encounters between complex nuclei during which nucleon or cluster transfer may take place or collective states may be excited or both. It is quite possible that qualitatively novel and unexpected results may be forthcoming from these latter studies. Since coincidence techniques are essential, the very poor duty cycle of a heavy ion linear accelerator cannot be tolerated; the highest possible energies are needed to facilitate transfer of the most sizeable clusters possible; and good energy resolution is needed to separate final states. An electrostatic generator is therefore demanded.

Appendix III

NOTES ON VISIT TO HIGH VOLTAGE ENGINEERING CORPORATION

BY PROFESSOR E. B. PAUL ON 4th-5th MARCH, 1963

1\. For clarity it is desirable to adhere to the HVEC nomenclature in which the accelerator system is identified by the number of acceleration stages. For example, "3 stage" is a two tank system, "2 stage" is a single tank tandem and "1 stage" is a Van de Graaff. Exotic systems of up to 5 stages have been discussed.

2\. Price Current prices for the 3 stage MP (Emperor) system are as follows:-

a)	MP Tandem including neutral negative ion source	$2,540,000
	Tank for above	308,000
b)	MP Tandem including negative ion source with inflector	2,540,000
	Tank for above	308,000
c)	Analysing magnet $\frac{ME}{Z^2}$ Product 120-90°	176,000
d)	7 position Switching Magnet Product 120-45° including 3 extensions and quadrupole sets	121,000
e)	Extra beam extensions and quadrupoles each	17,600
f)	Gas handling and Storage System	182,000
g)	Terminal Source and separate acc. tube with beam extension (this item is not recommended by HVEC)	253,000
h)	Estimated Installation Costs (to serve as a guide only as these will vary widely with location) This item does not include parts of the building such as crane, pipe sleeves through concrete ducts, trenches, water system, heat, air conditioning, cost of water, power, etc.	104,750

Thus the total installed cost of a 3 stage MP is the sum of a,b,c,d,4 x e,f and h, and comes to $6,350,150 or £2,260,000. Of this, the tanks and installation and possibly the gas handling item would be obtained locally amounting to $902,750 or £322,000.

3. Delivery etc.

There are at present four orders for 2 stage MP machines. These are Yale, Minnesota, Chalk River and Rochester. The order is as shown with Yale and Minnesota equal first. The Brookhaven 3 stage MP system is expected to be approved this fall. Three European proposals are at present current of which one may be approved soon. This would bring the list of MP's to seven. A complete 3 stage system with two tanks is at present under construction at the HVEC plant so that two MP stacks can be commissioned at a time before transfer to the site.

The delivery period from order placement to machine acceptance would extend over three years. Tank fabrication on site would begin approximately one year from order date. Building and tank would be complete on or before 2 years from order. Installation would then begin and last six months. Commissioning would then take a further six months. These estimates refer to a single two stage facility. The third stage would be 4-6 months later.

4. Voltage Stability

Guarantees call for 10 MV on terminal but 15 MV is expected. Guaranteed currents are 25 μ amp to 15 MeV and 10 μ a to 20 MeV. (2 stage operation.) Guarantees on 3 stage operation are very cautious at present and is 0.5 μ amp positive for 30 MeV.

Guaranteed stability for 3 stage operation is ± 1 kv on the positive terminal and 3kv on the negative terminal. One would expect better than 2kv on a 2 stage beam and better than 5 kev on 3 stage beam. The usual slit-corona stabilisation system will be supplied but in addition capacitative pick-ups, and generating volt meter voltage stabilisers will be used and a partial liner at a few kv for fine control may be tried. Some of these will be optional. For 3 stage operation the negative terminal will be held constant via G.V. or pick up and stabilisation system applied to the positive terminal. These ideas are motivated by the need to use less abundant charge states of heavy ions which are not suitable for stabilising on. The idea of a separate proton source on a separate tube for stabilisation in this case is not favoured at present.

5. Ion Source

The MP negative source is a completely different design from the standard EN source. The whole source will be on a 300 kev set and also on another 80 kev set. The exchange canal will be at earth and close to the tank. However for bunching the canal would be moved back and a separate lens added. The inflection magnet will accept beams from 30° on either side of zero and so two sources can be used. This is a Product 20 magnet. This source is now bench tested.

The experience on neutral-negative injection is as follows: This is being supplied for the Pittsburgh 3 stage EN system. 3 μamp of negative from the first tank and 2 μamp of analysed positive is guaranteed. The machine will be delivered by the end of 1963. It is also being supplied for the Washington 3 stage FN system. The guarantee is 0.5 μamp of analysed positive beam.

6. Analyser

This is a product 120 magnet, i.e. $\frac{ME}{Z^2} = 120$ at 12kgauss. Max. kilogauss is 14.5. For heavy ion work Chalk River is specifying also a 70° port and this will likely be standard. This gives an equivalent product of about 250. It is considered that this is adequate for 3 stage MP and no larger magnet is being considered.

7. 3 Stage System.

It is likely that the injector tank would be a mirror reflection of the stripper tank, i.e. the belt would be in the neutral stage. For single stage use of one of the tanks with a terminal source a separate tube in another of the three tube positions available could be used. However, this is not recommended as Pennsylvania has such a system in their EN machine and performance has been very poor both as regards current and voltage. A better system would be to run the 'injector' tank positive, inject neutrals and get single stage positives which are removed via say a product 36-90° magnet between the tanks. This should give more than 20 μ amp positive.

For independent use of the two tanks as two 2 stage MP tandems one would use separate negative sources both inflecting between the tanks and target areas at both ends of the installation. One more 90° analysing magnet would be required (item (c))

These alternatives leading to extreme flexibility will require clarification at an early stage but affect mainly building design and target areas since the tanks and stacks are completely symmetric or almost so.

A site plan with the two tanks at right angles is to be avoided as another large magnet is required and there are other problems.

8. Building

For the 3 stage system a hall 300 ft long by 40 ft wide is needed with the machine centre line 12 ft from one wall. A complete basement under all this is strongly recommended. A minimum of a 6 ft wide trench 10 ft high is required. Many of the services e.g. generators and gas handling can be sited in the basement if provided, otherwise will require extra building area. The sources are also designed as 2 story structures and require a pit underneath. Complete coverage by a 6 ton crane is required.

The tank will be constructed outside on a 100 ft by 50 ft area. An access road to this area for 30 ton lorries is required and temporary power and water. If a hydrostatic test is required (as in the U.S.) the water filled weight of one tank is 515 tons and provision for disposal of the 11,250 cu.ft of water. The road from construction site to building must take the 140 ton weight of the empty tank.

The average acceleration building in the U.S. costs about $30-40/sq.ft. Floor loading on the machine room floor will be less than 200 lbs/sq.ft. Local strengthening will be required for one or two units. Temporary shoring up will be used for tank installation. The tank actually rests on four columns and is lightly keyed to the building.

9. Power

For three stage system:-

Acceleration and magnets

175kva, 440v. 3ph.

90kva,120/208v.

Gas Handling

200 kva.

A transformer to give correct voltages would be needed (not included). The gas handling is mostly a 150 mva motor for the compressor which could be got locally.

10. Water

For 3 stage system:

at 50° F max. likely requiring a separate chiller 100 g.p.m.

at 85° F max. requiring a heat exchanger 100 g.p.m.

11. Liquid Nitrogen

For 3 stage system: 290 litres per day.

A trap monitoring and filling system will need to be supplied by customer.

12. Air conditioning

For the accelerator this is not critical: 65-75° F, 50% humidity but temperature should be controlled to 5°F change or better. The ion source is critical and will likely be cocooned in plexiglass with hot air blowers for dryness and to keep dust free.

Blowers to clear tank during maintenance will be required. The above does not provide air changes which may be required for radioactivity hazards as these are somewhat unknown.

13. Shielding

HVEC are not prepared to advise on this until they have some experience. They will shortly quote maximum values of misaligned beams striking specified materials at particular points along the machine. The customer must then base shielding design on this.

14. Stack

As stated there is space for three tubes in the stack. As well as much additional space. The stack sections are 8ft long with 6ft of insulation. The tube sections are similar. Hence there are three 2 ft blank sections in each stack in which strippers etc. can be inserted.

The whole stack is installed through one end of the tank. The other end is solid. There is an internal hoist running the length of the tank on a demountable monorail. The drive motor (100 hp) is inserted via a special port on the side of the tank.

Access to the tank is via manholes at side and bottom. A large 42" flange opposite terminal for major terminal modifications is optional.

15. Future Developments

These were ideas put forward by Proffesor R.J. Van de Graaff and do not represent systems which HVEC is yet prepared to supply.

a) Multistripper heavy ion application In this configuration the first tank would be run positive with negative injection as in a normal tandem. Further stripping would be done during the positive stage in the 2 ft sections of the tubes and at ground. This heavily stripped beam would be put into the second tank run negative and with further stripping would strike targets in the negative terminal. Experiments in the terminal would be aided by the low radiation background expected in the MP, by solid state devices telemetering information, by terminal capsule extraction without depressurization and fast target removal by a similar method. The larger access ports to be provided opposite the terminal are intended for these devices.

With this configuration Professor Van de Graaff believes that essentially all nuclides can be reached and the uranium on uranium potential barrier could be exceeded.

b) Multiple Independent Beams

Inclined field tubes with substantial sized slots (6" x 1") could be used to accelerate four or five separate beams from different ion sources of different ions. These would each have separate stripping canals. The voltage of each of these could be independently varied using a 300 kv. insulating core transformer for which there is room in the terminal. Hence the beams could be independently varied with fixed terminal voltage. The beams could then be directed into separate target rooms. With many different groups using an Emperor this might be attractive.

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