THE UNIVERSITY OF MANITOBA

A STUDY OF PROTON INDUCED X-RAY FLUORESCENCE AND MAGNETIC REGENERATION, THE CONSTRUCTION OF A HELICAL WIRE CHAMBER AND A MECHANISM FOR DIPROTON PRODUCTION IN THE SUN

by

C. P. RANDELL

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ABSTRACT

The details of 4 separate projects are reported and the results obtained prior to May 1976 are described. The first chapter gives the progress made towards the development of an on-line trace element analysis system using X-ray fluorescence excited by 20 - 50 MeV protons. A study of K shell X-rays from heavy elements has given results for the $K_\beta:K_\alpha$ and $K_{\alpha_2}:K_{\alpha_1}$ ratios and the K shell ionization cross section. The nature of a satellite peak on the high energy side of K_α and K_β groups is identified and preliminary results for the preparation of environmental samples are outlined.

The second chapter gives details of a program written to design a magnetic regenerator and to determine the extent to which the proton orbits in the cyclotron can be distorted by this regenerator and an electrostatic peeler. An increase in turn-to-turn separation from 0.2 mm to 4 mm is obtained. This should be sufficient to allow extraction of a proton beam using an electrostatic deflector which would enable the acceleration of positive rather than negative ions, resulting in increased beam intensity.

The third chapter describes the progress up to May 1976 in the design, construction and testing of a multiwire proportional counter with delay lines incorporated into both cathode and anode planes. The basis for the design has been the chamber described by Lee (1973, 1974).

The final chapter outlines the results from a study of diproton production in the reaction $^3He(^3He, 2_p)^4He$. The mechanism for this reaction was determined below the Coulomb barrier and the implication of our results along with those of Slobodrian (1975) has been considered in the hydrogen burning cycle.

ACKNOWLEDGEMENTS

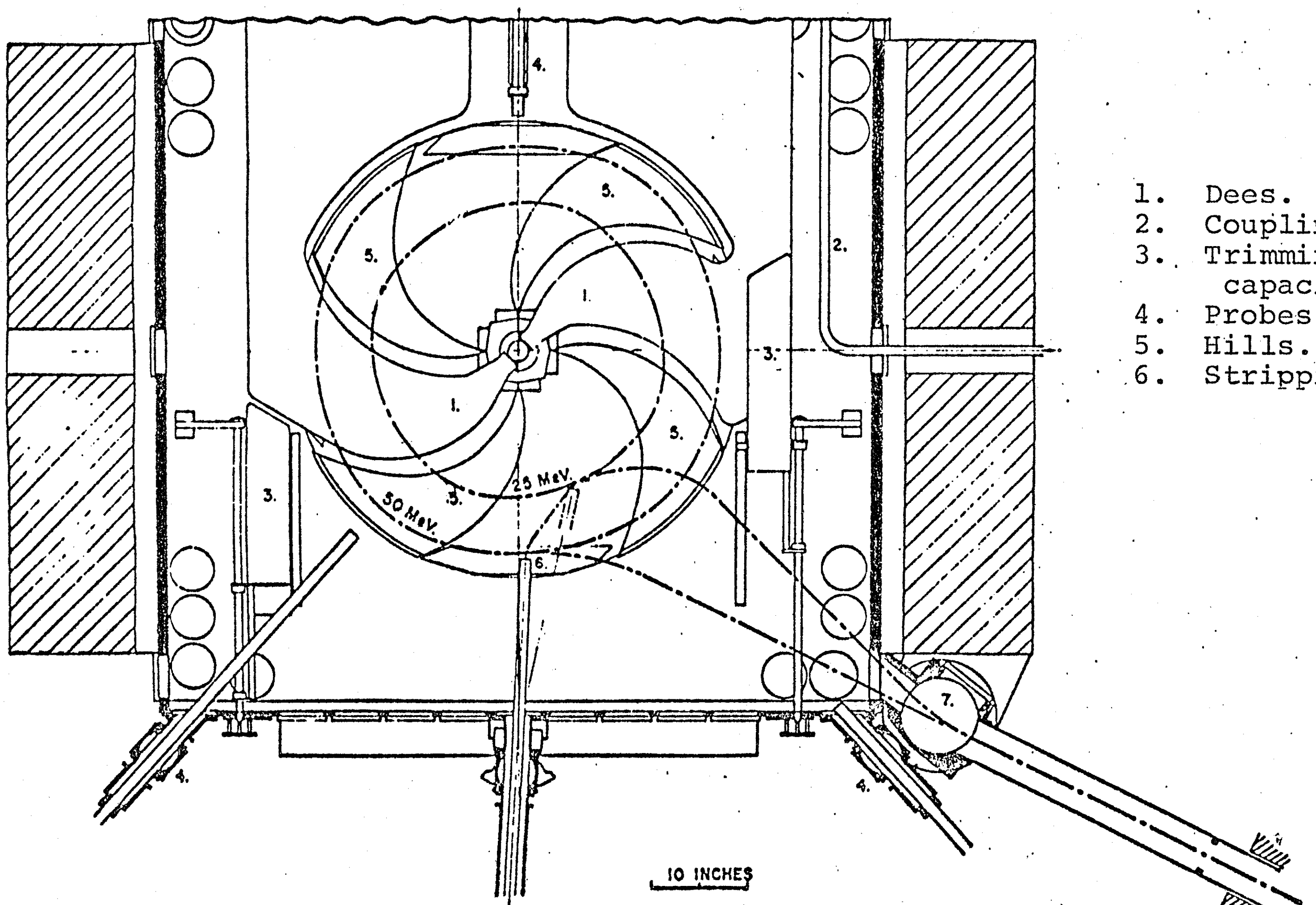
I wish to acknowledge the supervision of Dr. J.S.C. McKee throughout these projects, and that of Dr. S. Oh in the design of the magnetic regenerator. I would also like to thank all the cyclotron staff and graduate students for their help in each of these projects.

A COMMENT ON THE STRUCTURE OF THIS THESIS

This thesis is divided into 4 Chapters describing 4 separate projects I have undertaken with the cyclotron group at the University of Manitoba during the period between September 1974 and April 1976. The cyclotron group is supported by an A.E.C.B. grant, the machine is a sector focused cyclotron which is capable of producing proton beams in the energy range 20 - 50 MeV with typical intensities between 1 and 5 μA.

A recently installed axial injection system, see R.A. Batten (1976), injects a beam of negative hydrogen ions into the centre of the cyclotron at 11 keV. The ions are deflected into the median plane by an electrostatic mirror and accelerated by a 28 keV rf voltage. Extraction is achieved by stripping the two electrons from the negative hydrogen ions using a thin Aluminium foil, the magnetic force reverses, sweeping the beam out of the cyclotron field. Changing the stripping foil radius and angle and the use of a small exterior magnetic field (the combination magnet) allows extraction of proton beams varying from 20 to 50 MeV (see Fig. 1). The single main beam line serves 5 separate experimental lines by means of a switching magnet.

The first project involved the study of proton induced X-ray fluorescence, measuring production cross sections and intensity ratios of various X-ray components for heavy elements. This work was carried out with the aim of establishing an on-line trace element analysis system with a particular interest in heavy elements since it is felt that the use of higher proton energies than those used previously leads to several advantages in obtaining accurate values for heavy element concentrations in the order of 1 - 10 ppm. This topic forms the major part of my thesis, the research carried out up to April 1st, 1976 being described in Chapter I.



1. Dees.
2. Coupling loops.
3. Trimming capacitors.
4. Probes.
5. Hills.
6. Stripping foil.

Figure 1. The interior of the cyclotron.

The second project was a design study of a magnetic regerator which would enable the acceleration of protons rather than negative hydrogen ions in the cyclotron. Since the production rate of negative ions in a plasma is at least one order of magnitude below the rate for proton production a considerable increase in beam can be gained with a high extraction efficiency. However the turn-to-turn separation of orbits within the Manitoba cyclotron is only 0.2 mm which is too small for the normal extraction method of positive ions, that is to position an electrostatic deflector such that the protons are swept from the cyclotron field. With so small a turn-to-turn separation the beam would be lost into the deflector.

A magnetic regenerator and electrostatic peeler make up a system which perturbs the field in such a way as to distort the proton orbit, increasing the turn-to-turn separation sufficiently to enable the use of an electrostatic deflector with a high extraction efficiency. A program was written to design a suitable regenerator and to determine the maximum turn-to-turn separation that could be achieved. A summary of the program is given in Chapter II,the program is listed in Appendix II.

In the spring of 1975 a third project was undertaken, this was to design and construct a muliwire proportional counter using delay line readout in both anode and cathode planes as described by D. Lee (1973, 1974). This chamber was designed with the view to its use in a radiative captive experiment which is under preliminary study at the present time. In this project, with the assistance of A. Hathaway, a first chamber was built during the summer but proved unsuccessful. A second has recently been built and has given good results. Its basic principles, design features and the results of recent tests are described in Chapter III.

Finally during my first winter in Manitoba a theoretical project was undertaken to determine the effect of diproton production on the hydrogen burning cycle. Recent experimental results (Slobodrian 1975) have indicated that there exists a substantially higher branching ratio for $^3He + ^3He \rightarrow ^4He + d + e^- + \nu$ over $^3He + ^3He \rightarrow ^4He + p + p$ than expected, our calculations suggest that both these reactions proceed via an intermediate anti-bound state of two protons commonly called the diproton or ^2He for reaction energies below the Coulomb barrier. The effect of this high branching ratio on the equilibrium calculation for a main sequence star with a non-convective core (particularly the sun) has been considered. Results show that this would not help in an explanation of "the solar neutrino problem". The papers published on this topic make up Chapter IV.

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CHAPTER I

PROTON INDUCED X-RAY ANALYSIS OF HEAVY ELEMENTS AS AN ENVIRONMENTAL PROBE

INTRODUCTION

X-ray fluorescence is one of two de-excitation processes which follow the ionization of inner-shell electrons, the other being the emission of Auger electrons. The study of "characteristic X-rays" following ionization by heavy charged particles dates back 60 years. J. Chadwick (1912) observed this phenomenon by exposing elements to alpha particles emitted from a radioactive source. However, it is only in the last 15 to 20 years that a more thorough study has developed both theoretically and experimentally, the latter being encouraged by the recent development of solid state detectors with high efficiency and good resolution. In this time ionization cross sections have been measured for a wide range of elements induced by protons of energies up to 10 MeV, the results showing good agreement with theory. However for proton energies above 10 MeV results are scarce.

At the same time it has been realized that this phenomenon presents a powerful method for determining elemental concentrations within an unknown sample since the energy of the "characteristic" X-ray lines is a continuously varying function of Z. This technique is now a well established tool for trace element analysis of environmental, clinical and biological samples.

Proton energies commonly used for such a system are between 0.4 and 5 MeV using a Si(Li) detector to record the X-ray emission spectrum. The K X-ray series is normally used for elements in the range $15 < Z < 50$ and the L X-ray series for heavier elements (see Sec. 3).

Various authors have attempted to calculate the most suitable energies to gain the maximum possible sensitivity for specific elements.

Results are inconsistent. Folkmann (1974) suggests 1 - 10 MeV proton energies whereas Verba (1972) and Gordon (1972) suggests 10 - 40 MeV. The common use of low energies is probably due to the abundance of low energy accelerators rather than this being the optimum energy.

However there is one component in the X-ray background, the Compton scattering of gamma rays in the detector crystal (see Appendix I) which, it has been suggested, increases sufficiently to obscure the characteristic X-ray lines when the proton energy is increased from 3 to 40 MeV. A. Gervé and G. Schatz, in an invited paper to the Seventh Int. Conference on Cyclotrons and Their Applications (1975) states categorically that cyclotrons can find only limited application in ion-induced X-ray analysis and that there is no significant advantage in studying X-ray fluorescence at energies higher than a few MeV. W. Wolfli has expressed similar beliefs in a private communication.

Having obtained high resolution K X-ray spectra from lead following bombardment by 40 MeV protons, we have undertaken a study of the K X-ray emission spectra induced by 20 - 50 MeV protons, with a particular aim of establishing a trace element analysis system. With an increase in proton energy from 3 to 40 MeV the K shell ionization cross section increases by 3 orders of magnitude making possible the use of the K series for detection of heavy as well as light elements, the K series having considerable advantages in detecting trace elements over the L series, see Sec. 3.3.

2. X-RAY FLUORESCENCE - THEORY

2.1 Atomic Ionization

In the 60 years during which atomic ionization has been studied three formulations have been developed which now show good agreement with experimental observations. Two of these are "high energy" theories, that is they apply for projectile energies very much greater than the electron binding energies. These are the Born approximation (Henneberg, 1933; Merzbacher, 1958) and the impulse or binary encounter approximation (Gryzinski, 1965; Garcia, 1970). The third is applicable for low energies close to threshold, this is the impact parameter method (Bang, 1959). These theories are reviewed in detail by Garcia (1973).

The criterion given for the applicability of the Born approximation gives a quantitative interpretation of "high energy". This is,

$$\frac{zZe^2}{\hbar v} \gg 1$$

where z, Z are the charge of the projectile and target element and v is the relative velocity. This requires that in considering K shell ionization by proton impact the latter's energy E_p must fulfil the condition,

$$E_p/u_k \gg 24$$

where u_k is the K shell binding energy. This condition shows that the high energy formulations apply for protons with energy between 20 and 50 MeV.

Each formulation gives results which suggest that by scaling the ionization cross section σ_I by a factor u_x^2/Z^2 and plotting this function against the proton energy E_p scaled by $\frac{m_e}{m_p} \cdot \frac{1}{u_x}$ a single universal curve is followed by the data from all target atoms, where m_e, m_p are the electron and proton mass, u_x the electron binding energy.

In Garcia's paper (Garcia, 1973) the data from a variety of experiments are compared with the two high energy formulations on a universal plot. The various experiments show a significant distribution, the two theoretical curves lying within this distribution.

We have measured the cross section for lead and gold and compared our results with those of F. Bodart (1975) which were obtained through bombardment of elements from Ti to Cu with protons of energies in the range 0.4 to 2.3 MeV, and those from G.A. Bissinger (1972) which were obtained by bombarding Ag with 2 to 30 MeV protons.

2.2 De-excitation of Ionized Atoms

Following ionization of an inner-shell electron de-excitation proceeds through the transition of an electron from a higher orbital to the vacancy shell with the emission of either an X-ray or an Auger electron.

X-ray emission is dominated by one photon electric dipole radiation, thus the transitions are severely restricted by selection rules. However, Auger electron emission proceeds through a repulsive interaction proportional to e^2/r. The selection rules are

$\Delta L = \Delta J = \Delta S = \Delta(\text{parity}) = 0$ but since the emitted electron can have any angular momentum the number of accessible final states has considerably fewer restrictions.

This results in an X-ray spectrum which is very simple in comparison with the Auger electron spectrum. For this reason the study of inner shell vacancy production has been predominantly through the measurement of X-ray fluorescence spectrum, despite the fact that for