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CYCLOTRON LABORATORY

Department of Physics

The University of Michigan

Annual Report

May 1, 1972 - June 15, 1973

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INTRODUCTION

This report contains a summary of the research and technical development carried on in the Cyclotron Laboratory of the Department of Physics at The University of Michigan during the period May 1, 1972 to June 15, 1973.

Much of the effort of the laboratory this past year was devoted to completing the new beam line and neutron tunnel, to completing a program of cyclotron modification and orbit studies, to continuing the investigations of the spectroscopy of the rare-earth region and in-beam γ -spectroscopy, and to the development of the neutron time-of-flight system. One obvious omission from the activities this year is research using heavy ions. This is not due to lack of interest but rather to the present ion source which does not produce a sufficient yield of high charge states. This part of the program will receive considerable attention in the months immediately ahead.

Again it is a pleasure for the research staff to acknowledge their indebtedness to Professor K. T. Hecht and Dr. J. P. Draayer for their theoretical help and guidance this past year.

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A EXPERIMENTAL PROGRAMA1 The Reaction $^{16}\text{O}(d, ^3\text{He})^{15}\text{N}$ at 29.0 MeV

M. A. Firestone and J. Janecke

Angular distributions for this reaction were reported last year. As indicated at that time, the angular distributions for the $1/2^-$ ground state and the $3/2^-$ state at 6.32 MeV, by far, the two strongest lines in the entire spectrum, were well described by distorted wave calculations and gave reasonable spectroscopic factors. Certain low lying "weak" transitions did not show obvious direct reaction characteristics, and the possibility that the formation of these states involves a two-step mechanism was considered. A study to predict angular distributions from such a mechanism is currently being carried out.

Another possible explanation for these weak transitions is that they are the product of the breakup of the compound nucleus ^{18}F . Compound nucleus contributions are generally not considered in this energy region, but since the cross sections are so small it was decided to obtain estimates.

A computer code was written to calculate angular distributions for the $(d, ^3\text{He})$ reaction as well as level densities and level widths as a function of J of the compound nucleus based on the Hauser-Feshbach statistical compound nucleus theory. A simplified expression evaluated by Eberhard¹⁾ was used for the level width and the Hauser-Feshbach denominator. A major problem in these calculations is that the level densities are not well known

and are difficult to determine in light nuclei so that the choice of level density parameters is not unique. Not only is there little experimental evidence to go on, there is also some question as to the proper form for the level density near closed shells ^{2,3,6)} even at high excitation energies.

Angular distributions were calculated using both a constant temperature, and a Fermi gas model for the level densities. ⁴⁾ The parameters for the constant temperature model were obtained by fitting known low energy levels. The parameters for the Fermi gas model were first obtained from the Cameron prescription. ^{4,5)} These were then adjusted to give values of the level width of ^{18}F in agreement with experiment and to produce a smooth transition between the constant temperature form and the Fermi gas model around 10 MeV. The constant temperature form is also in agreement with experimentally determined level widths. ⁶⁾

A comparison between the calculations and the experimental angular distributions leads to incompatible results for the estimates based on level densities from the Fermi gas model. The calculated cross sections are too big. Figure A1-1 shows the results of the calculations based on level densities of the constant temperature form. The comparison with the experimental values shows that even these estimates must be considered as upper limits. These findings are in agreement with those of Grimes et al. ²⁾ who found that level densities of nuclei near the doubly magic nucleus ^{208}Pb follow the constant temperature form while those of nuclei further away are better described with the Fermi gas model.

The estimated compound nucleus cross sections decrease with decreasing J of the final nucleus. Therefore, such contributions should be at most about 30% for the transition to the $7/2^+$ state at 7.57 MeV but only at most 10% for the transitions to the $1/2^+$ states.

Fig. A1-1

Tentative conclusions for the various 'weak' transitions are as follows. All transitions of Fig. A1-1 must contain significant contributions from direct reaction mechanisms. A regular one-step mechanism will contribute to the transitions to states with $1/2^+$, $5/2^+$, possibly $3/2^+$, but not $7/2^+$. A two-step mechanism is likely to contribute to the transitions to states with $7/2^+$, $5/2^+$ and $3/2^+$. Thus the transition to the $7/2^+$ state at 7.57 MeV, which shows an irregular experimental angular distribution, should be mostly due to a two-step mechanism with some compound-nucleus contributions. The transitions to the $1/2^+$ states should be mostly due to a regular one-step mechanism, and the other transitions are probably mixed. Indeed, the angular distribution shown in Fig. A1-1 for the $1/2^+$ state at 8.31 MeV denoted by $l=0$ (based on the computer code DWUCK) shows good agreement with the measured distribution. The spectroscopic factor is $C^2S \approx 0.04$.

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A2. Nuclear Structure in the N=50 Isotones

G. Neff and W.S. Gray

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A study of the $^{87}\text{Rb}(d,^3\text{He})^{86}\text{Kr}$ reaction, initiated last year as part of the program for determining the important proton excitations in the N=50 isotones, is nearing completion. Differential cross sections have been measured at $E_d = 29$ MeV for transitions to eight levels in ^{86}Kr , and values of ℓ_p and spectroscopic factors obtained using the DWBA code DWUCK. A spectrum taken with the array of position sensitive detectors at the focal surface of the first analyzing magnet is shown in Fig. A2-1. It consists of two separate but overlapping exposures (with slightly different spectrograph excitations) covering approximately three MeV of excitation in the ^{86}Kr residual nucleus. The target material, $^{87}\text{RbOH}$, was sandwiched between layers of carbon to avoid deterioration due to adsorbed water. As a result, the resolution was approximately 50 keV (FWHM).

The measured angular distributions are shown in Fig. A2-2. The transitions to the ground-state and to the 1.56, 2.35, 2.72, and 2.85 MeV states in ^{86}Kr proceed by $\ell_p = 1$ while those to the 2.24 and 2.92 MeV levels are more consistent with $\ell_p = 3$. Since the transitions to the 2^+ states in ^{86}Kr can be either $\ell_p = 1$ or 3, mixtures of varying $\ell_p = 1$ and 3 strength were tried but no significant improvement in the fit to the DWBA predictions was obtained. The results are consistent with recent (t, α) work by Tucker,¹⁾ Together with the decay work by Achterberg²⁾ and Talbert³⁾ and the (p,p') work by Hollis,⁴⁾ they allow assignments of 2^+ to the 1.56 and 2.35 MeV levels and limit the possible spins for the other observed levels in ^{86}Kr . A summary of spectroscopic information is given in Table A2-1.

Fig. A2-1

$^{87}\text{Rb}(d,h)^{86}\text{Kr}$
ANGULAR DISTRIBUTIONS

CENTER OF MASS ANGLE (degrees)

Fig. A2-2

TABLE A2-1

Summary of Results for the $^{87}\text{Rb}(d, ^3\text{He})^{86}\text{Kr}$ Reaction

<u>Energy</u>	<u>l_p</u>	<u>C^2S (relative)*</u>	<u>For the Assumed $(j)^\pi$</u>
0.0	1	0.8	$3/2^-$
1.54	1	1.2	$3/2^-$
2.24	3	2.5	$5/2^-$
2.35	1	1.0	$3/2^-$
2.72	1	0.1	$3/2^-$
2.85	1	0.4	$3/2^-$
2.92	3	3.0	$5/2^-$

*Normalized to give $\sum C^2S = 9.0$ .References

- 1) A.B. Tucker, K.E. Apt, J.D. Knight, and C.J. Orth, Phys. Rev. C6, 2075 (1972).
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A3. Spectroscopy of the Rare-Earth Region

A.S. Broad, D.A. Lewis, J.A. Splett, W.S. Gray,

J. Bardwick and W.C. Parkinson

The investigation of the spectroscopy of the rare-earth region continues. It is perhaps the most challenging of all the regions of the periodic table, both experimentally and theoretically. Considerable progress has been made not only in the measurement of reaction data, but also in the reduction and analysis of the data. The various aspects of the problem are summarized briefly.

The scientific justification has been detailed in an earlier report (1970). The aim of the experimental phase of the program is to determine 1) the energy systematics of the intrinsic proton excitations, 2) the pair-occupation probabilities near the Fermi levels, and 3) the intrinsic particle wave functions. With this basic information in hand, one can begin to unravel the complex spectra which are observed and to test some of the more complicated aspects of the collective model, such as the various band-mixing effects which can occur in these nuclei.

The experimental problem requires beams of sufficiently high energy and intensity with well-defined energy, development of target preparation and monitoring techniques, good ion-optical resolution, and an understanding of the effects of energy loss and straggling in the target on the experimental line shape. An understanding of the line shape is an important ingredient in optimizing the experimental resolution and in the reduction of the data.

Apart from experimental considerations, the extraction of reliable nuclear structure information from stripping and pickup reactions requires

an adequate description of the reaction. The conventional distorted-wave calculations which are generally used to analyze such data are based on assumptions which may not be justified for reactions on deformed nuclei. This subject is presently under investigation. Some preliminary conclusions are reported in Section A3-g.

a) Experimental Data

Preliminary data were reported last year on the reactions $^{158}\text{Gd}(\alpha, t)^{159}\text{Tb}$ and $^{162}\text{Dy}(\alpha, t)^{163}\text{Ho}$ both at $E_\alpha = 45$ MeV and $^{162}\text{Dy}(d, ^3\text{He})^{161}\text{Tb}$ at $E_d = 29$ MeV. Since that time, data have been obtained for $^{165}\text{Ho}(d, d)^{165}\text{Ho}$ at $E_d = 29$ MeV, $^{166}\text{Er}(d, d)^{166}\text{Er}$ at $E_d = 35$ MeV, $^{162}\text{Dy}(^3\text{He}, d)^{163}\text{Ho}$, $^{164}\text{Dy}(^3\text{He}, d)^{165}\text{Ho}$, $^{162}\text{Dy}(^3\text{He}, ^3\text{He})^{162}\text{Dy}$ and $^{159}\text{Gd}(^3\text{He}, d)^{159}\text{Tb}$, all at a ^3He energy of 46 MeV, and for the $^{166}\text{Er}(d, ^3\text{He})^{165}\text{Ho}$ reaction at $E_d = 35$ MeV. The results to date are summarized briefly here.

The measurements on the $^{162}\text{Dy}(^3\text{He}, d)^{163}\text{Ho}$ reaction have been completed, angular distributions having been obtained from 0° to 30° in steps of 2.5° . A sample spectrum is shown in Fig. A3-1 and selected angular distributions in Fig. A3-2. The final analysis of the data will not be complete for some months.

^{165}Ho is one of the few odd-even rare-earth nuclei that can be reached by both the $(^3\text{He}, d)$ and the $(d, ^3\text{He})$ reactions. The measurements on the $(^3\text{He}, d)$ reaction are complete with angular distributions in steps of 2.5° from 0° to 35° . The spectrum at 15° scattering angle is shown in Fig. A3-3. Measurements of the corresponding $(d, ^3\text{He})$ angular distributions at $E_d = 35$ MeV are in progress.

Angular distributions for the $^{158}\text{Gd}(^3\text{He}, d)^{159}\text{Tb}$ reaction have been obtained as a supplement to the $^{158}(\alpha, t)^{159}\text{Tb}$ data previously reported. The

DY162 (HE3, D) H0163

Fig. A3-1

Fig. A3-2

Fig. A3-3

15-keV resolution observed for the measured spectra (Fig. A3-4) represents a significant improvement over the 20-25 keV obtained earlier for the (α ,t) reaction for reasons discussed below.

The elastic scattering data are shown in Fig. A3-5. The purpose in obtaining these data is to determine the optical parameters used in the DWBA analysis of the reaction data. It is clear, however, that the usual analysis does not predict in the rare-earth region the correct magnitude of the elastic scattering cross sections, and it is concluded that the contribution from the 2^+ inelastic state must be included. Attempts to fit only the elastic cross sections with DWBA have yielded completely unreasonable sets of optical parameters. Therefore, the intrinsic deformation of the nucleus must be accounted for and all future reaction calculations should be done in a coupled channels basis.

b) Target Preparation and Monitoring

The solution of the target preparation problem was described last year. The great majority of targets are prepared by evaporation of the (enriched) rare-earth oxide onto carbon backings to thicknesses of 50 to 150 $\mu\text{g}/\text{cm}^2$. Because changes in target thickness are often observed during the course of a run, the thickness must be monitored and the spectra normalized. This is done by measuring the integrated yield of the elastically scattered incident particles (d, ^3He , or α) during the exposure by means of a specially constructed scintillation detector. (Thick solid-state silicon detectors were used but because of their high cost and short life they have been replaced with Na-I detectors.) Na-I crystals, 1/2" in diameter and of thickness matched to the range of the particular species of elastic scattered particle, are mounted on a RCA 4516 phototube, and together with suitable preamp and integrating circuits, provide a normalization factor for each exposure.

Fig. A3-4

Fig. A3-5

c) The Resolution Problem

The resolution obtained in any given measurement requires a trade off between available beam intensity, target thickness, and the cross section to be measured. In the rare-earth region the cross sections for the reactions of interest are of the order of 50 $\mu\text{b/sr}$ and the energy levels are closely spaced; the problem then is to optimize the beam intensity on target, consistent with the required resolution. Procedures for the determination of the line shape and energy spread of the beam on the target, and the use of the dispersion cancelling properties of the analysis system, together with optimum target angle, have been described before. The relation between straggling, ion optics, and resolution at the image surface of the reaction products analysis system has now been investigated and the results are discussed in the next section. The conclusions are that for proton-transfer reactions on typical rare-earth targets the width of the energy defining slits with ion-optical system can be increased as much as a factor of 8 without degrading the resolution, thereby reducing the exposure time by a factor of 8. This requires that the effective source be relatively small (≈ 1 mm) and stable, that at least two of the three magnets of the reaction products spectrometer be used, and that the target angle be properly chosen. The 15-20 keV resolution obtained for the $(^3\text{He},d)$ spectra of Figs. A3-3 and A3-4 is consistent with the predictions.

It should be noted that for reactions involving charge transfer, that is when the charge of the incident and outgoing particle differs by one unit as in the $(^3\text{He},d)$ or $(d,^3\text{He})$ reactions, the resolution is determined primarily by straggling in the target, with little contribution from the ion-optics. Resolutions for zero charge transfer reactions such as (d,t) would be approximately a factor of two better.

d) Straggling, Ion-Optics and Resolution

(D.A. Lewis)

The following paragraphs briefly describe how scattering from atomic electrons in the target and the ion optics system determine the experimental line shape.

1. Energy Loss in the Target

As a charged particle traverses the target, it loses energy by electron scattering. The fluctuations in the energy imparted to these electrons is called energy straggling. Landau ¹⁾ derived the basic equation describing this phenomenon in thin targets and solved it for very thin targets. Seltzer and Berger ²⁾ have tabulated solutions using the approximations first suggested by Vavilov. ³⁾ Maccabee ⁴⁾ has shown that these solutions are in excellent agreement with experiment.

In a reaction (a,b) the situation is more complicated because a and b have different straggling curves. If $f_a(\Delta, s)$ is the probability that particle a loses energy Δ in traversing a target of thickness s, and similarly, $f_b(\Delta, s)$, for particle b, then

$$\frac{1}{s} \int_0^s ds \int_0^\infty dE f_a(E, X) f_b(\Delta - E, s - X) = F_R(\Delta, s)$$

is the probability that the total energy loss will be Δ for the reaction (a,b) taking place in the target. This can be evaluated numerically.

One useful property of the straggling curve $f_a(\Delta, s)$ is that

$$\int_0^\infty f_a(\Delta, s) (\Delta - \bar{\Delta})^2 d\Delta = (\text{Constant}) \cdot z_a^2 \cdot s$$

where z_a is the charge of particle a. Also

$$\int_0^\infty f_a(\Delta, s) \Delta d\Delta = \bar{\Delta} = SP_a s$$

where SP_a is the stopping power. These expressions allow one to calculate the average energy loss and the mean square deviation σ_s^2 for the reaction (a,b). If θ is the scattering angle and α the angle between the normal to the plane of the target and the incoming beam direction, then

$$\bar{\Delta} = s \left(\frac{1}{2} \left[\frac{SP_a}{\cos(\alpha)} + \frac{SP_b}{\cos(\theta-\alpha)} \right] \right)$$

and

$$\sigma_s^2 = 156 \frac{Z}{A} \left[\frac{z_a^2}{\cos(\alpha)} + \frac{z_b^2}{\cos(\theta-\alpha)} \right] \left(\frac{s}{2} \right) + \frac{1}{12} \left[\frac{SP_a}{\cos(\alpha)} - \frac{SP_b}{\cos(\theta-\alpha)} \right] s^2$$

in keV^2 , where Z, A = atomic number and weight of target; z_a, z_b = charge states of particles a and b; SP_a, SP_b = stopping powers of particles a and b in keV per mg/cm^2 ; and s = target thickness in mg/cm^2 . The second term of this expression is often called the target thickness effect.

ii. Beam Optics With Target and Scattering Angles

The Michigan ion-optical system uses two beam preparation magnets with the primary energy defining slit placed at the focus between them. For most beams the source is incoherent with a finite width S .⁵⁾ The particles coming from the source can be described as occupying a region in phase space. Each point in this space undergoes a linear transformation as it passes through a magnet or the target. The particles that strike the target occupy a phase space region bounded by a parallelogram.⁵⁾ Therefore the particles that reach the image surface of the reaction products analysis system must also occupy a region in phase space bounded by a parallelogram. If the source has uniform intensity, then the line shape must be a trapezoid whose width at the base is $B = C_W W + C_S S$, and width at the top is $A = |C_W W - C_S S|$. In the preceding expressions $C_W = \left| T \frac{D}{D_a} - 2 \frac{\cos(\theta-\alpha)}{\cos(\alpha)} \right|$ and $C_S = \left| T \frac{D}{D_a} - \frac{\cos(\theta-\alpha)}{\cos(\alpha)} \right|$, W = the beam defining slit width, S = the source width, $T = \partial E_{\text{outgoing}} / \partial E_{\text{incoming}}$,

θ = the scattering angle, α = the target angle, D = the dispersion of one of the beam preparation magnets, and D_a = the net dispersion of all of the reaction products analysis magnets used. Note that α can be chosen to make $C_s = 0$ or $C_w = 0$, but not both. Choosing α to make $C_w = 0$ is usually called beam spot cancellation. The mean square deviation associated with this line shape is

$$\sigma_o^2 = \frac{2}{3} \left[\frac{A^3}{A+B} + \frac{1}{(B-A)(B+A)} (B[B^3-A^3] - \frac{3}{4} [B^4-A^4]) \right].$$

iii. Conclusions

Assuming only that a) the target is relatively uniform, b) magnet aberrations are small, and c) the source is uniform and incoherent, it is straightforward to calculate a theoretical line shape. Further, since the contributions from ion optics and energy loss in the target are independent, $\sigma^2 = \sigma_o^2 + D_a^2$ is an exact expression for the mean square deviation. As an aid to maximizing count rate while maintaining good resolution, a computer program has been written which minimizes the RMS deviation as a function of α for different source sizes, slit widths, and target thicknesses.

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e) Reduction of Data

With the exception of elastic scattering for which the position-sensitive detectors (PSD) are ideally suited, the reaction products are recorded in nuclear emulsions because of the small cross sections, hence long exposures, and the fact that the PSD require a double exposure to obtain overlapping

spectra. The trade-off is the long read-out time required by the hand scanning. Automatic plate scanning, while much faster, does not provide the required accuracy. (This was the reason the Michigan scanner was discontinued some years ago. Recent trials using the Argonne scanner were not satisfactory for the same reasons. This is in no way intended to imply that the Argonne scanner is not a high quality instrument, well suited for certain applications. We are grateful for the cooperation and help of the Argonne group in making test scans.)

In spite of the 12-20 keV resolution obtained for charge transfer reactions, the rare-earth spectra are often congested because different rotational bands fall at about the same excitation energies. The spectrum shown in Fig. A3-1 is typical. Knowledge of the theoretical and experimental line shapes, together with a peak fitting program such as AUTOFIT,¹⁾ permits the extraction of much more information than might be expected at first sight. Analysis of the spectrum of Fig. A3-1 yields the level structure shown in Fig. A3-6. The x's are the actual data points, while the deduced spectral lines are indicated by the full curves. In the analysis the experimental line shape was derived from a well resolved peak. The accuracy with which the intensity of the lines can be determined is considerably improved if, as is often the case, there is some prior knowledge of the location of the levels.

To complete the data reduction, a calibration of the beam and reaction-products analysis systems is required. This problem, and the methods used, have been discussed in detail in publication No. 4.

Reference

- 1) We are grateful to J.R. Comfort, Argonne National Laboratory, for supplying us with the AUTOFIT program.

Fig. A3-6

f) Reaction Calculations

It was pointed out in the introduction to Section A3 that the conventional DWBA, in the form which is generally used for treating stripping and pickup reactions, may not give an adequate description of reactions for rare-earth nuclei. Two aspects of this question are being investigated. The first has to do with the form factor (the radial wave function of the transferred proton) which is usually taken to be the eigenfunction of a spherical potential. The computer code BOUND, which was described in last year's progress report, computes the eigenfunction of a deformed potential well as an expansion which includes contributions from higher major shells and the continuum. This code has been used to analyze the results of neutron-transfer experiments in the actinide region, as discussed below, with a resulting improvement in the agreement between theory and experiment. Since the predicted cross sections differ significantly from those obtained with the less realistic "spherical" form factor, the form factors used in the analysis of the proton-transfer experiments will be generated using BOUND.

A second question being studied is that of the applicability of the distorted-wave approximation itself to reactions on deformed nuclei. Because of the large deformations occurring in rare-earth nuclei, there is strong coupling between the elastic and inelastic channels which can give rise to "two-step" processes, e.g., inelastic scattering followed by stripping, which are ignored in the conventional DWBA. A preliminary analysis of deuteron elastic scattering from ^{165}Ho at $E_d = 29$ MeV and ^3He elastic scattering from ^{162}Dy at a ^3He energy of 45 MeV indicates that the coupling is strong enough that the elastic scattering cannot be reproduced by an optical model potential with reasonable parameters. Consequently, further measurements of the inelastic scattering to the first few members of the ground state rotational band

will begin shortly, and coupled-channels calculations will be made in order to determine the optical potentials which describe the (elastic and inelastic) scattering problem. These potentials will then be used in a coupled-channels calculation of the stripping cross sections, which will be made with the Oxford two-step code. ¹⁾ The results of the coupled-channel calculations will be compared with those of the DWBA (using the modified form factors from BOUND) in order to assess the significance of contributions from two-step processes to the cross sections.

Reference

1) With the assistance of P.J. Ellis.

g) Calculation of Bound State Wave Functions

(A.S. Broad)

Recent work by Erskine ¹⁾ with neutron-transfer experiments in the actinide region has revealed several large discrepancies between experimental and theoretical spectroscopic factors. In the $1/2^+[631]$ band of ^{237}U some spectroscopic factors were off by a factor of two or more, while the $9/2^+$ state of the $5/2^+[622]$ orbital agreed well with theory. Since the reaction was done at sub-Coulomb energies, the experiment was insensitive to the optical parameters but depended critically on the tail of the bound state wave function. It therefore seemed likely that the problem was in the calculation of the bound state wave function, and that contributions from higher shells and the continuum could be important. New wave functions were calculated using computer code BOUND ²⁾ and the resultant DWBA cross sections were compared with experiment. The $1/2^+[631]$ band showed an improvement for all members except the $11/2^+$. The spectroscopic factors for the $1/2^+$, $3/2^+$ and $5/2^+$ members were reduced to reasonable values and the $7/2^+$ and $9/2^+$ states were also reduced, but not enough. The $11/2^+$ spectroscopic factor which experimentally was off by a

factor of 3 from the theoretical value was not reduced at all, and when a β_{40} of 0.08 was included the difference became even greater. The $9/2^+$ member of $5/2^+[622]$ which agreed well with theory showed no difference between the spherical and coupled-channels calculation.

The conclusion of the analysis is that contributions from the continuum and higher shells are important and should be included. Also, there seems to be some mechanism affecting the higher spin states which has some Ω dependence. This analysis will be carried on into the $^{162}\text{Dy}(^3\text{He},d)^{163}\text{Ho}$ reaction to see if the same discrepancies appear.

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h) Determination of Occupation Probabilities

The determination of occupation probabilities can be illustrated using the $^{158}\text{Gd}(^3\text{He},d)^{159}\text{Tb}$ reaction. Assuming the normalization factor for the $(^3\text{He},d)$ reaction is moderately well-known, the spectroscopic factor for a sharply-defined intense level such as the $5/2^+[413]$ level at 57 keV can be extracted. This in turn yields a normalization factor for the (α,t) angular distributions, and spectroscopic factors for the remaining levels can be extracted using for example DWBA analysis. Since the proton-stripping spectroscopic factor assumes the form $2C_{\alpha}^2 U_{\alpha}^2 C_{j\alpha}^2$ (where C_{α} is the Soloviev single-quasi-particle admixture coefficient, U_{α}^2 is the usual pairing emptiness probability, and $C_{j\alpha}$ is the usual Nilsson coefficient), a supplementary reaction is required to disentangle the C_{α}^2 , U_{α}^2 , and $C_{j\alpha}^2$. The proton pickup reaction $^{160}\text{Dy}(d,^3\text{He})^{159}\text{Tb}$ yields spectroscopic factors of the form $2C_{\alpha}^2 V_{\alpha}^2 C_{j\alpha}^2$ (where V_{α}^2 is the pairing occupation probability), hence a direct comparison of the two reactions yields U_{α}^2 and V_{α}^2 . (This reaction has yet to be measured.)

Fig. A4-1

The sum rule $\sum_j (C_{\alpha j \alpha})^2 = C_{\alpha}^2$ permits the determination of C_{α}^2 and $C_{j \alpha}^2$. It should be noted that this method is feasible because of the small number of Coriolis-coupled states.

A4. In-Beam γ -ray Spectroscopy

J. Bardwick, H.C. Griffin, K.L. Hull, and Robert S. Tickle

The in-beam γ -ray program was detailed at some length in last year's report. Since then, the completion of the beam line into the new experimental area has provided greatly improved facilities for in-beam γ -ray spectroscopic studies. All of the measurements discussed in this report were obtained using the new beam line.

Beginning in April of this year, emphasis has been given to developing techniques for measuring a broad range of half lives of isomeric states produced in (particle,xn) reactions. Previous work with isomers was limited to those with half lives substantially less than one rf period (~ 100 nsec). Now the capability of gating the cyclotron ion source permits the measurement of any half life greater than the resolving time of the γ -ray detector (several nanoseconds). The following examples illustrate some of the measurements which can be made with relative ease. In fact, none of the measurements described required more than approximately 30 minutes of beam time.

Treyth, Hyde, and Yamazaki¹⁾ have reported a 380-nsec isomer in ^{208}Po (see decay scheme in Fig. A4-1). This state is produced with a good yield in the $^{206}\text{Pb}(\alpha,2n)$ reaction as well as in the $^{208}\text{Pb}(\alpha,4n)$ and $^{209}\text{Bi}(p,2n)$ reactions. In the present case a target of ^{206}Pb was bombarded with 27-MeV $^4\text{He}^{++}$ ions. The cyclotron rf was 6409 kHz (156 nsec period) and the ion

6 ⁺	2212
4 ⁺	2104
2 ⁺	528
	1576

4 ⁺	2193
3 ⁺	1814
2 ⁺	1660

Fig. A4-2

source was gated "on" for 1 beam burst in every 13 rf cycles (or one beam burst every 2 microseconds). Times were measured with a time-to-amplitude converter (TAC) which was started with a pulse derived from the rf and stopped by γ -rays in the desired energy range. Time and γ -ray energy were recorded in 2-dimensional mode in the PDP-15 computer. Decay curves were obtained from net peak areas versus time. The results for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow \text{g.s.}$ transitions (see Fig. A4-1) imply a half life of the isomeric state of 350 ± 20 nsec.

A one-dimensional measurement also was made by selecting the 177-keV γ -ray with a timing single-channel analyzer and recording the time relative to the beam burst. A similar result was obtained, but this method cannot provide the accurate correction for the γ -ray continuum which can be obtained from the 2-dimensional data.

The N=82 nuclides include several cases of isomeric states with half lives in the μsec region.²⁾ Our results for three of these states are presented in Fig. A4-1 [$^{138}\text{Ba}(\alpha, 2n)^{140}\text{Ce}$] and Fig. A4-2 [$^{140}\text{Ce}(\alpha, 2n)^{142}\text{Nd}$ and $^{142}\text{Nd}(\alpha, 2n)^{144}\text{Sm}$]. The decay schemes in those figures include $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions observed in previous work in this laboratory and $6^+ \rightarrow 4^+$ transitions from ref. 2. The measurements were performed as follows. The ion source was gated on for an interval comparable to the half life of the state being populated and then turned off for a suitable measurement interval. The TAC was started near the end of the "on" interval and stopped by a γ -ray in the selected energy range. Again, data were stored in a 2-dimensional array.

The TAC module has a maximum range of 80 μsec . In order to test a method suitable for longer times, one of the measurements of the 18- μsec state in ^{142}Nd was made using a voltage ramp started by a signal derived from the rf and sampled at the time of the γ -ray event. This method can be used for any half lives greater than about 10 μsec and has the advantage of permitting

multiple stops (important for decay periods long compared with the ADC analysis time).

Accurate time calibrations are very important for these measurements and can be made quite easily. For short periods (such as measurements with ^{208}Po shown in Fig. A4-1) start time is obtained from a frequency scaled down from the cyclotron rf and stop times are obtained from prompt γ -rays randomly selected from individual beam bursts (ion source not gated). For longer time periods the output of the ion source is chopped with an external square wave generator the frequency of which can be measured accurately with a frequency counter. Examples of the calibration data obtained for the 80- μsec TAC range and 130- μsec ramp range are given in Figs. A4-1 (^{140}Ce) and A4-2 (^{142}Nd), respectively.

Although some of the data have poor statistics (from the short measurement times), our half-life values are comparable to those in the literature. The 350 ± 20 nsec result for ^{208}Po is in reasonable agreement with the 380 nsec (no error quoted) reported by Treyth et al. ¹⁾ Our 890 ± 60 nsec for ^{144}Sm suffers from poor statistics but is consistent with the value of 880 ± 20 nsec given in ref. 2. The reported value of 6.5 ± 1.5 μsec for ^{140}Ce has a large uncertainty and should probably be considered less accurate than our result of 7.90 ± 0.3 μsec . Finally our results for ^{142}Nd obtained with the TAC (18.1 ± 0.7 μsec) and ramp generator (19.4 ± 2 μsec) are internally consistent but are slightly above the value in the literature (16.5 ± 0.5 μsec). We expect to extend this work, particularly to longer half lives, and to give more careful consideration to possible systematic errors.

Preliminary measurements with the $^{232}\text{Th}(\alpha, 2n)^{234}\text{U}$ reaction have been made at ^4He energies of 22 and 27 MeV. Attempts to observe the 33- μsec isomeric state were unsuccessful, and the only transition in ^{234}U tentatively

identified is the 153-keV ($6^+ \rightarrow 4^+$) γ -ray. These measurements were attempted with a thick target, which stopped essentially all of the fission fragments and thus increased the background for delayed γ -rays. Although this is the most favorable trans-bismuth target in terms of low activity of the target and high spallation-to-fission ratio, it is clear that measurements will be substantially more difficult than is the case with lighter targets. Additional measurements under improved conditions are planned.

γ - γ coincidence data for the decay of ^{101}Mo - ^{101}Tc were obtained in order to develop techniques for recording and sorting such data. About 700,000 two-parameter events (4096×4096) were recorded on magnetic tape. Background corrected slices corresponding to several prominent γ -rays were extracted by a sorting program written for the IBM 360/67 computer. These data indicate that the method is satisfactory, although several million events will be required for characterization of less prominent transitions.

References

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- 2) Data for the half lives of $6^+ \rightarrow 4^+$ transitions in even-even $N=82$ nuclides are summarized by A. Filevich, J. Kownacki, and H. Ryde, Nucl. Phys. A176, 155 (1971).

A5. Neutron Spectroscopy by Time-of-Flight

The essential features of the neutron time-of-flight spectrometer are described and the results to date summarized.

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a) The Beam Optics

(J.F. Petersen, J. Bardwick and W.C. Parkinson)

The low resolution beam line, described in previous reports, was designed to accommodate a variety of experiments, including neutron spectroscopy by time-of-flight. Because the target area for the time-of-flight spectrometer is some 23 meters from the exit of the cyclotron, it is important to insure that the ion-optics do not introduce unacceptably large time spreads in the beam bursts on the target. In the design of the system the ion-optics computer program was modified to calculate flight times for ions following different paths through the configuration under study. The ion optical elements and the location of foci were adjusted to minimize the time spread while maintaining the resolving power and the beam size at the target position. This last requirement is critical since the scattering angle in the time-of-flight measurements is varied by moving the target in azimuth through the "neutron" magnet.

Measurements of the time spread at the entrance to the beam line and at the target were made using the beam diagnostics phase probe which has a time resolution of 300 picoseconds. The measured increase was in agreement with the calculated value. For 11-MeV deuterons, with all the beam extracted from the cyclotron brought to the target, the increase is approximately two nanoseconds. While for some spectroscopic measurements this is acceptable value, the important point is that the time spread can be reduced by limiting the angular divergence of the beam with slits at the entrance to the system. For 25% of the available beam the increase is less than half a nanosecond. The 11-MeV deuteron beam, because of the relatively low ion velocity, provides a good test of the system since other beams to be used will have higher ion velocities. The results are quite acceptable.

The energy resolution of the system, measured by comparing the width of

the image of the cyclotron source at the energy slits in the new beam line with the width of the image of the same beam in the scattering chamber of the high resolution beam line, was in agreement with the calculated value, indicated that a resolution of $E/\Delta E = 2000$ is available.

Thus, measurements of the ion optical properties of the new beam line are in agreement with the design calculations and indicate that the system is entirely adequate for our needs in neutron spectroscopy by time-of-flight.

b) The Gated Ion Source

(R.H. Day and W.C. Parkinson)

The gated ion source, in routine use for neutron time-of-flight and other measurements, has been described in detail in a paper now in press (Nuclear Instruments and Methods), thus only the essential features are described here. Ions of any charge state can be gated with 100% efficiency, and for reasons described below the current injected into the dee is essentially independent of the dee voltage and is greater than that obtained for the normal ion source-puller geometry. For these reasons it is often used in normal operation.

The electrode structure is shown in Fig. A5-b1. It consists of the conventional ungated ion source and puller with two plane parallel electrodes, the control "grid" and screen "grid", interposed between them. The "grids" consist of 0.010" thick tantalum sheets, each with a 0.500" high slit of width 0.020" and 0.040", respectively. These are aligned with the 0.040" slits in the ion source (cathode) and puller. The grid spacings are: 0.031" control grid to cathode, 0.031" control grid to screen grid, and 0.312" screen grid to puller. In DC operation negative bias voltages are applied to both the control and screen grids while the puller is at the rf dee potential. In the gated mode the control grid is operated with either zero or

Fig. A5-b1

Fig. A5-b2

Fig. A5-b3

positive bias on top of which is applied a negative pulse synchronized with the rf dee voltage and adjustable in relative phase.

The measured "static" grid-puller transfer characteristics for constant screen voltage and constant amplitude of the rf dee voltage for 11.2-MeV deuterons and 22-MeV $^3\text{He}^{++}$ are plotted in Figs. A5-b2 and A5-b3, respectively, with screen voltage as a parameter. The beam current was measured on the "centerline" probe in the median plane of the cyclotron after being accelerated through several turns.

Two important features emerge. First, the current extracted from the plasma and injected into the dee is space charge limited (Childs' Law) and second, the current injected into the dee is independent of dee voltage. Both features have some interesting consequences.

For the plane parallel gated source, with a grid-cathode spacing d_g , the ratio of control grid potential to the dee voltage required to give the same beam current as the normal ion source (cathode-puller spacing d_n) is reduced in the ratio $(d_g/d_n)^{4/3}$. Because relatively large voltages can be applied to the control grids, the current injected into the dee is enhanced. It also follows that a simple measurement of the beam current allows one to make rough estimates of the population of other charge states in the ion plasma. For a single ion species of charge e_i and mass m_i the current density given by Childs' Law is

$$J = \frac{4}{9} \left(2 \frac{e_i}{m_i} \right)^{1/2} \epsilon_0 V^{3/2} / d^2 \quad \text{amps/m}^2$$

where ϵ_0 is the permittivity of free space. It can be shown that for a mixture of charge states in the plasma, the current density of one of the species is

$$J_1 = \frac{4}{9} \cdot \epsilon_0 \cdot \frac{2 \left(\frac{e_1}{m_1} \right) \frac{v^{3/2}}{d^2}}{\left[1 + \sum_{i=2}^k \frac{n_i e_i}{n_1 e_1} \right]}$$

where n_i is the charge density in the plasma of ions of species i . This follows from the fact that $\text{div } J_i + \frac{\partial \rho_i}{\partial t} = 0$ for each ion species i . For the gated source with 100% ${}^3\text{He}^{++}$ and with $d = 0.040''$, $V = 2.0\text{-kV}$, control grid slit area $= 6.45 \times 10^{-6} \text{ m}^2$ and phase width of 20° the expected (DC) current is 1.39 ma, while the measured current is only 5 μA . This large discrepancy results from two factors. Because of the rf puller voltage, the ions are fanned out across the puller slit. This is estimated to account for a factor of 5, which leaves a factor of 55 to be accounted for by contributions to the space charge by other charge states of ${}^3\text{He}$. Assuming the only other charge state is ${}^3\text{He}^+$, the relative population of ${}^3\text{He}^{++}$ in the discharge is about 2%. This is consistent with the measurements of yields of hooded type arc sources by Papineau et al. ¹⁾ The important fact that emerges is that our present ion source (hot filament discharge tube) is not a suitable design for the production of He^{++} or heavy ions. The dominant charge states for a deuterium arc are D_1^+ and the molecule ions D_2^+ and D_3^+ . The measured yield of D_1^+ is consistent with a relative population density of 1:2:1.5 measured for hydrogen for a similar ion source. ¹⁾

The second feature, that the current injected into the dee is independent of dee voltage, permits the selection of a narrow phase group for acceleration in the cyclotron. This is a useful feature in obtaining high quality extracted beams, and is discussed further in Section B6.

In the "gated" mode of operation, a voltage pulse is applied to the grid. The voltage is manufactured by picking an rf reference signal from the dee, passing it through a variable time delay, and counting down to the desired

mode ($f/2$, $f/3$, ---) with standard TTL circuitry. The resulting square wave is clipped, amplified and applied to the control grid through a transmission line incorporated on the ion source tube (see Section C). The flexibility in pulsed operation is unlimited. As a single example, for measurement of short lifetimes of nuclear states the beam can be gated on for any number of rf pulses and off for any number.

The gating efficiency was determined by observing with the phase probe the prompt γ -rays produced by the gated beam striking a target in the scattering chamber. It is difficult to determine the gating efficiency with the internal circulating beam since all the beam in one turn must be intercepted on that turn. Otherwise, the fraction that misses the probe can make an additional turn before striking the probe, giving rise to γ -ray pulses that appear to be due to successive turns.

The spectrum of prompt γ -rays and neutrons resulting from the gated deuteron beam and single turn extraction is shown in Fig. A5-b4. The gating efficiency is essentially 100%. The rejection ratio is at least $10^3:1$, the limit being determined by the statistics of the background of low energy neutrons produced by the beam pulses on the target. The spectrum of γ -rays and neutrons from $^3\text{He}^{++}$ shown in Fig. A5-b5 illustrates that a properly gated ion source is an excellent diagnostic tool for studying the time and space structure of the extracted beam. The three peaks in the ungated spectrum are different slices of the internal beam that meet the criteria for extraction. Peaks b and c are extracted in a single turn with a gating efficiency of at least $4 \times 10^3:1$, the limit again being determined by the background statistics. Peak a, however, is extracted in two turns resulting in counts on every rf cycle.

Fig. A5-b4

Fig. A5-b5

Reference

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c) Detectors

(P.F. Julien, R.M. Polichar and W.C. Parkinson)

-----The neutron detector array, its associated electronics, and the method used for time synchronization of the ten counters was described in detail last year. A picture of the array is reproduced as Fig. A5-c1. It contains 10 liters of NE213m liquid scintillator, subtends a solid angle of 2.5×10^{-4} str at 40 meters and has a theoretical detection efficiency of 7% for 15-MeV neutrons.

The time resolution capabilities of the array have been studied using the $^{12}\text{C}(^3\text{He},n)^{14}\text{O}$ reaction with the geometry described previously, namely the target placed inside the second beam preparation magnet and the detectors located in the tunnel separating the analyzer room and control room 23 meters from the target. The spectrum obtained at $\theta_{\text{cm}} = 8^\circ$ with a ^3He energy of 20.3 MeV is shown in Fig. A5-c2, and that obtained for $\theta_{\text{cm}} = 4^\circ$ and with a ^3He energy of 19.5 MeV is shown in Fig. A5-c3. The time spread of the beam on target was 1.3 and 1.7 nsec FWHM, respectively, as determined with a small volume high resolution scintillation detector. It should be noted that the beam on target was not gated in taking these data. In Fig. A5-c2 the ground state and states at 6.3, 6.6, and 7.78 MeV excitation can be identified. The widths of the ground, 6.3 and 6.6 MeV states are 250, 170 and 145 keV FWHM, respectively, corresponding to overall time widths of 2.8, 3.1 and 3.6 nsec FWHM, respectively. Pulse shape discrimination was used to eliminate prompt gamma rays. The calibration is 0.54 nsec/channel. In Fig. A5-c3 the states at 6.6 and 6.3 MeV excitation show widths of 95 and

Fig. A5-cl

Fig. A5-c2

Fig. A5-c3

145 keV, respectively, and the calibration is 0.48 nsec/channel. For these data the pulse shape discrimination gate was not used. Comparison of the two figures gives a measure of its effectiveness. The neutron component in the background comes from the thick tungsten backing used to support the large area carbon target. The effective target thickness, after rotation to correct for kinematic time spread, was about $350 \mu\text{g}/\text{cm}^2$ and the energy spread in the beam was 40 keV.

The three sources of time spread were subtracted by quadrature from the observed widths to give the contribution from the detectors, which was determined to be 1.2 nsec. Prior to recording these data the counters had been synchronized to a summed width of 1.1 nsec. Thus the time resolution of the array for neutrons was measured to be essentially the same as for gamma rays. This suggests however that more careful synchronization of the array is required since the time resolution of the individual detectors for gamma rays has been measured many times to be 0.8 to 0.9 nsec.

The time resolution (FWHM) of the individual detectors was expected to be less than 0.5 nsec from the known speed of light in the liquid and the tank radius. (The traversal time for light across the radius is 0.5 nsec. The resolution as measured by the full width at half maximum should be substantially less than this since there is more scintillator at the outer radii and so the inner radii contribute fewer events to the average pulse shape. The increase in light collection efficiency for the central region is ignorable in these considerations and the timing electronics is designed to trigger low on the leading edge of the incoming pulse.) The measured value of 0.8 to 0.9 nsec therefore presented a puzzle.

To gain a better understanding of the inherent resolution, a computer code was written to perform a Monte Carlo calculation of the response of the system to a real event occurring at an arbitrary point P in the liquid tank.

By moving the point P across the tank radius, the shift in triggering time can be estimated.

The program "emits" a large number of photons isotropically into three dimensions from the point P inside a cylindrical tank containing a photocathode surface at the center. The program calculates the impact location on the tank wall of each photon, and the photon is reflected in a random direction (θ, ϕ) determined by a random number generator. The generator reflects according to a cosine distribution to simulate the known diffuseness of the white tank coating in the real detectors. The photon thus travels randomly about the interior of the tank, reflecting repeatedly until it is either absorbed in the paint, absorbed in the liquid, or strikes the photocathode surface and is "captured". If captured, its total time of flight is recorded in a multichannel analyzer from which plots of collected photons versus time are obtained. Since all the photons are emitted from P simultaneously, the "pulse" $G(t)$ is the response of the tank to a delta function input of light. Having determined $G(t)$, the program then calculates the anode current pulse which would result when the spreading action of the dynode structure is folded in.

The calculation was repeated for six points $P_1 \dots P_6$ ($P_6 > P_1$) across the face of the detector. The resulting six anode pulses are shown in Fig. A5-c4. The external electronics is designed to trigger at the 20% point of the pulse amplitude, thus from Fig. A5-c4 the spread in this triggering time between P_1 and P_6 is about 1.8 nsec. This surprisingly large time spread originates from two sources, the finite transit time across the tank radius of the photons contributing to the leading edge of the pulse, 0.5 nsec, and a distortion of the pulse shape for events occurring at larger radii. When the time response is weighted according to volume, the calculated time spread for the detector is 0.9 nsec, in good agreement with the measured value.

Fig. A5-d4

d) The $^{12}\text{C}(d,n)^{13}\text{N}$, $^{16}\text{O}(d,n)^{17}\text{F}$, and $^{40}\text{Ca}(d,n)^{41}\text{Sc}$ Reactions

(J.F. Petersen, R.H. Day, and W.C. Parkinson)

The above reactions have been measured at $E_d = 11$ MeV as a test of the neutron time-of-flight system and to obtain preliminary data on the reaction mechanisms.

Sample spectra obtained with a $40\text{ }\mu\text{g}/\text{cm}^2$ carbon foil and a $0.00015''$ Mylar foil ($\text{C}_{10}\text{H}_8\text{O}_4$) are shown in Fig. A5-d1. A spectrum of ^{13}N taken with higher resolution (but poorer statistics) and plotted on an expanded scale is shown in Fig. A5-d2. Angular distributions from -10° to $+80^\circ$ have been obtained for all the levels shown in the spectra. Those for the ground and 2.367 MeV states in ^{13}N and for the ground and 0.500 MeV states in ^{17}F are shown in Fig. A5-d3. The solid lines are the results of a DWBA calculation using reasonable optical model parameters. No attempt has been made as yet to improve the fit.

The spectrum obtained with a $375\text{ }\mu\text{g}/\text{cm}^2$ natural ^{40}Ca target on a $30\text{ }\mu\text{g}/\text{cm}^2$ carbon backing is shown in Fig. A5-d4.

The data were taken with a flight path of 37.5 meters and the beam was gated on each eighth rf cycle. The time spread of the beam on the target was typically 2 nsec FWHM. The data were taken without collimation of the scattered beam and with essentially no shielding against background neutrons. This accounts for the relatively high background in the spectra.

It is crucial that the beam not strike the target frame during the measurements. To monitor this an empty target frame connected to read current is permanently mounted 1 cm in front of the actual target. The target holder is designed to carry a second target which can be interchanged quickly without breaking vacuum or changing the target position in the "neutron" magnet. With the second target blank, background measurements can be made quickly

Fig. A5-d1

Fig. A5-d2

Fig. A5-d3

Fig. A5-c4

and easily. The spectra of Figs. A5-d1 and A5-d2 have not been corrected for background, but measurements indicated that the background is not associated with the target.

In these measurements the time-to-amplitude converter (TAC) received a "start" pulse from the detector array and a "stop" pulse synchronized from the cyclotron rf system. Some improvement in resolution is expected when the "stop" pulse is manufactured from the beam burst on the target, since any drift of the phase of the extracted beam with respect to the rf will be eliminated. The instrumentation for this is under construction.

e) The ($^3\text{He},n$) Reaction

(J.F. Petersen, R.H. Day and W.C. Parkinson)

The two-proton transfer reaction on middle-weight and heavy nuclei continues to hold considerable research interest. The ($^3\text{He},n$) reaction is one of the cleanest two-proton transfer reactions for obtaining spectroscopic information. The desire to study this properly was one of the motivating factors in developing the time-of-flight system. As indicated in Section A5-b the present ion source is inefficient in the production of ions of charge states greater than one, and the present yield of $^3\text{He}^{++}$ is marginal for ($^3\text{He},n$) measurements. To circumvent waiting the development of a new ion source, singly ionized $^3\text{He}^+$ has been accelerated to 21 MeV, extracted, and stripped to $^3\text{He}^{++}$ by sending the beam through a $20 \mu\text{g}/\text{cm}^2$ carbon foil placed at the first focus of the low resolution beam line. The current available at the target, using this scheme for $^3\text{He}^{++}$, is comparable to currents obtained for deuterons. It should be noted that singly ionized $^3\text{He}^+$ is not suitable for ($^3\text{He},n$) studies with our system because it strips in the target and the change in magnetic rigidity causes the resulting $^3\text{He}^{++}$ beam to deflect and strike the vacuum chamber, increasing the background and preventing

accurate monitoring of the beam intensity.

The disadvantages of accelerating ${}^3\text{He}^+$ as compared to ${}^3\text{He}^{++}$ is that the stability requirements placed on the cyclotron are more stringent because the ions must make twice the number of turns to extraction. The increase in time spread of the stripped beam, if any, is small.

Using this method, preliminary data have been obtained for the $({}^3\text{He},n)$ reaction at a scattering angle of -10° on targets of carbon (Fig. A5-e1), Mylar (Fig. A5-e2a), and ${}^{40}\text{Ca}$ on carbon backing (Fig. A5-e2b). Known levels in the residual nuclei are indicated on the figures. In each case the flight path was 37.5 meters and the time width of the beam was slightly less than 2 nsec FWHM. The energy of the beam was 21.7 MeV with the rf being 6.4 MHz. In taking these preliminary data no effort was made to collimate the scattered neutrons or to shield against background. The time scale for the spectrum of Fig. A5-e1 is compressed to 2 channels per nsec to show the relative position of the prompt γ -rays. This spectrum was taken with the beam gated at $f/9$. The remaining spectra were taken with a higher resolution of one channel per nsec and the folding technique was used, with the gating frequency set at $f/4$. This accounts for the appearance of the prompt γ -ray group among the neutron groups. No attempt has been made to identify all the levels in the spectrum taken with the calcium target; in addition to levels in ${}^{42}\text{Ti}$, it also includes levels in ${}^{14}\text{O}$ (from the carbon backing) and ${}^{18}\text{Ne}$ from the ${}^{16}\text{O}$ from oxidized calcium.

Perhaps the most significant point of these data is they prove that the study of the $({}^3\text{He},n)$ reaction on a variety of nuclei is feasible with the time-of-flight spectrometer. And while many improvements can and will be made, it is now possible to undertake a serious study of the two-proton transfer reaction.

Fig. A5-e1

Fig. A5-e2 a & b

A6. Nuclidic Mass Relationships, Mass Equations and
the Residual Neutron-Proton Interaction

J. Janecke

Earlier work ^{1,2)} on the properties of the residual neutron-proton interaction and its connection with nuclidic mass relationships and mass equations has been continued. Extensive numerical calculations have been performed to establish the magnitude and the properties of the small systematic errors contained in the Garvey-Kelson nuclidic mass relationships. ³⁻⁵⁾ Several new generalized nuclidic mass relationships have been established. These relationships represent a step in between a mass relationship and an equation. They can be used as recursion relationships. A criterion has been established which makes it possible to test the consistency of the predictions of masses of very neutron-rich or proton-rich nuclei. Such a criterion may be useful in connection with astrophysical calculations related to the r-process.

The residual neutron-proton interaction represents the most important factor for making reliable mass predictions for unknown nuclei. Existing macroscopic and microscopic shell-model theories for this interaction show only moderate agreement with the experimental evidence.

Solutions for the above generalized nuclidic mass relationships have been derived. These solutions represent a kind of mass equation which should combine the accuracy of an ordinary mass equation with that of a nuclidic mass relationship. A paper describing the above results is essentially completed. ⁶⁾ Preliminary numerical calculations have been performed to apply these solutions to the prediction of unknown masses of light nuclei. The results are encouraging. As a by-product, it was found that, contrary to the

results of ref. 5, the Coulomb displacement energies between mirror nuclei are well reproduced including shell and pairing effects.

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A7. Applications in Nuclear Medicine

J. Bardwick

The trial production of ^{11}C labelled dopamine to be used for visualizing the adrenals has not gone forward. The necessary laboratory facilities for labelling short half-life materials have yet to be obtained by the Department of Nuclear Medicine. A more serious setback is that the dopamine has an uptake time of about two hours in the human adrenal glands, considerably longer than realized. This would require of the order of a 6500 source rather than the 100 originally planned. We are not in a position to handle such material, nor could the chemistry be done safely.

More recently Nuclear Medicine has requested experimental quantities of ^{67}Cu ($T_{1/2} = 61\text{h}$) not available commercially to be used to localize breast tumors. It is known ¹⁾ that ^{64}Cu labelled bleomycin localizes in the soft tissue tumors of rats, but its decay scheme precludes its use in humans due

to the radiation dose. The use of ^{67}Cu does appear feasible. When the chemistry is worked out, we may try several experimental runs.

It might be noted that with the new low resolution beam line, an excellent area for target irradiation is available. A simple vacuum lock at the focus of the first quadrupole magnet is being planned for this

~~purpose by Professor Griffin for nuclear chemistry irradiation.~~

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B. CYCLOTRON MODIFICATIONS, BEAM DIAGNOSTICS, AND ORBIT STUDIES

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B1. Introduction

When the cyclotron and its ancillary equipment became operational in 1964, the first interest of the users called for relatively low energy deuterons, α -particles and ^3He ions, and these beams were obtained, albeit with moderate quality, without extensive studies of internal orbits. Soon, however, interest developed in spectroscopic problems that required higher particle energies and intensities and better resolution. Various attempts to obtain the higher energies were made by "empirical twiddling" by the research staff for their particular experiments. Over the past several years this has resulted in inefficient operation and not infrequently damage to components of the cyclotron. While some beams were adequate, others were not.

This highly unsatisfactory situation motivated a study of the internal orbits and the extraction problem, and while the study continued spasmodically over some years, a systematic effort was begun in early 1972. Some of the results of this effort were reported last year. The problem, stated simply, was to present to the external ion optical system adequate currents of ions of well-defined energy, phase space density and position. In addition, it was essential that procedures for tuning up various beams be well proscribed, quickly done, and that the beams be reproducible.

The studies are now complete and the problem is considered solved.

The problem of obtaining high quality beams from an isochronous cyclotron is a complex one, there are many factors to be understood and controlled. In what follows we describe briefly some of these.

B2. Cyclotron Modifications

As a result of the earlier studies the cyclotron was shut down beginning in mid-April, 1972 to convert from a two-dee to a one-dee system. The primary purpose in converting from two 150° dees to one 180° dee was to remove from the deflector channel the rf dee voltage which, because of its phase at the time of extraction, opposes the DC deflector voltage and, equally important, introduces an energy spread in the extracted beam. The one-dee system offers further advantages. The equivalent first harmonic, due to a gap-crossing driving force which is a function of the dee geometry and dee voltage balance in the two-dee system, is essentially eliminated, and control of the central orbits, in particular the selection of phase width, is facilitated.

The modifications to the rf system in converting to a one-dee system were in themselves trivial. It was only necessary to remove one dee and dee stem. The conversion, however, did necessitate a variety of other changes, mechanical and electrical. For example, a dummy dee had to be installed on the ground sheets, a new ion source structure and phase-defining slits were required, and modifications were necessary in the beam probes and the extraction system. These changes were completed by mid-June, 1972. The ion source, however, continued to give difficulty over the next several months and underwent several minor modifications.

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83. Stability Requirements

Beams of particles precisely defined in energy and quality require high stability of the electric and magnetic fields in the cyclotron. The total magnetic field consists of contributions from the main field windings, the twelve pairs of gradient coils and the inner and outer sets of harmonic coils. The total field must be stable to about $1:10^5$ for a stability in energy of $1:10^4$. The necessary control and regulation of the individual components were developed over the years and reported on in earlier reports. For the main magnetic field, current regulation is not sufficient, and one of the key elements is an NMR feed-back loop. The system provides a regulation of better than $1:10^5$. For the gradient and harmonic coils, current regulation is adequate and stabilities of $1:10^5$ in the result field are relatively easily obtained. The stability of the rf frequency must be $1:10^5$. This was the main reason for converting to the MOPA system described in the 1969 annual report. The dee voltage must be stable to better than $1:10^4$ and this is not a trivial problem. The regulation scheme has been described in an earlier report (1969). Due to occasional fibrous discharges in the dee system, there are fluctuations of very short time duration. The long term stability, however, is about $1:10^4$ as measured by the fluctuations in position of a single turn of the beam at a large radius. The effect of thermal changes in the rf resonator is automatically corrected by the regulator system.

B4. Diagnostic Instrumentation

The diagnostic instrumentation developed for these studies is of prime importance. The principal instruments are the integral and differential current probes, the "burn pattern" probe, the phase probe, and the devices for measuring phase space density and source position of the extracted beam.

Integral and differential current measurements are made with a "center-line" probe which moves parallel to and offset by 3" from a radius vector at an azimuth corresponding very nearly to the center of a hill. The head of the probe used to measure the total circulating current is approximately 1-1/2 inches in radial length, 3/8 inches wide, and 2 inches high, filling the vertical aperture of the dee. The ΔR probe used to measure the current density as a function of radius is a tungsten wire, normally 0.032" in diameter and 2 inches long (in the Z-direction), carried by but insulated from the probe head. The wire can be extended from the probe head toward smaller radii by as much as one inch, or it can be retracted into it. The ΔR measurements are used to determine the amplitudes of both the coherent and incoherent betatron oscillations. At various times a second similar probe, located 180° in azimuth from the center-line probe, has been used for shadow measurements as well as for R- ΔR measurements. A 3-finger probe was used in the past for measurements of the current distribution in the Z-direction, but the burn pattern technique¹⁾ gives more information and is now used to determine the vertical motion of the beam at all radii.

The phase and phase width of the circulating beam are measured with a gamma-ray time-of-flight system (called the phase probe) which measures the time interval between a fixed reference point on every other rf cycle and the

arrival of γ -rays emitted when the beam strikes the center-line probe. The two γ -ray peaks displayed in the multichannel analyzer are therefore separated by 360° in phase, and this serves to calibrate the time scale of the analyzer. Zero phase is found by adjusting the magnetic field first to the upper and then to the lower edge of the resonance. If the probe is held at a fixed radius during this process, the observed phase will move from 90° lead to 90° lag as the field is lowered. A measured phase difference of 180° between the upper and lower cutoff points gives assurance that there are no large phase shifts at smaller radii, and thus permits zero phase to be established. The time resolution of the system is better than 0.8 ns so the isochronism of most fields can be adjusted to within 2° . The phase probe is useful not only for determining the phase and phase width of the circulating beam as a function of radius, but also for determining whether the beam blows up vertically at any radius, when it strikes the septum, and how it moves down the extractor channel as the deflector-voltage is changed.

The emittance ϵ and effective source position of the extracted beam are measured using the slotted-plate technique.²⁾ The quality of the extracted beam, by which we mean the quantity $(1/\epsilon) \cdot (E/\Delta E)$, is determined from the ratio of the currents per unit energy interval at the foci of the first and second beam preparation magnets.

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85. The Magnetic Field

The magnetic field had been accurately measured previously.³⁾ It was remeasured during the recent shut down when Rose shims were added in the

magnet gap to extend the maximum deuteron energy. A computer program is available to predict the magnetic fields resulting from any combination of main field coil and gradient coil currents. With the aid of this program, isochronous fields can be generated for any particle and energy of interest. Verification of several fields has been effected by measuring phase as a function of radius using the phase probe technique. Any required correction to the field, as indicated by the phase measurements, is readily made by referring to the computer output for differential contributions to the field by adjacent pairs of gradient coil currents.

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86. The Central Region

The central region is all important in obtaining well defined and centered orbits. Vertical focusing forces on the beam are obtained by proper shaping of the magnetic and electric fields: a central magnetic cone provides magnetic focusing while electric focusing is obtained by making the aperture of the dummy dee small where the ions leave the driven dee and large where the ions enter the driven dee. The central region also contains the arc tower-puller system, a slit for controlling phase width, a slit to control the divergence (incoherent betatron oscillation amplitude) of the beam, electrostatic suppressor plates for suppressing the vertical motion, and baffles for eliminating unwanted ion species.

As a guide in locating these elements, a computer study was made of the central orbits for a variety of beams. The calculations made use of a point-wise Runge-Kutta integration technique of the radial motion with a twelfth

order fourier decomposition of the magnetic field. The electric field for the central region was approximated by analytic expressions for the first half turn and an impulsive acceleration thereafter. The validity of these expressions was checked against the mid-plane electric fields measured with the conducting paper electric field mapping apparatus.

The central region computer program was used to study the effect of slits on the divergence of the beam resulting from the tower-puller geometry, on the efficiency of phase selection in the first few turns, and on the centering of the orbits. From these studies it was concluded that the most efficient phase selection could be achieved on the first turn after acceleration through approximately 180° . As a result the phase defining slit is located on the first turn 190° in azimuth from the puller face. The size of the slit jaws and the slit opening can be varied easily to accommodate beams of varying energy and ion species. Measurements of phase width versus slit position verified the effectiveness of the phase defining slit.

The use of the gated ion source (Section A5-b) offers an important advantage with respect to phase selection. With a conventional source the current through the puller is a function of dee voltage, and the maximum current per degree of rf phase occurs when the puller-tower voltage is at maximum. In this case the most desirable slice of phase to accept is that which has gained something near the maximum energy possible. However, the distribution of phase with radius at the slit location is sinusoidal with $dR/d\phi = 0$ at $\phi = 0$, making it difficult to achieve good phase selection. The gated ion source eliminates this problem since the beam through the puller is determined by the DC grid bias and is independent of dee voltage and hence of the rf phase. As a result the phase selecting slit aperture and position can

be chosen to achieve any desired phase and phase width without loss in beam intensity. A further advantage is that the grid-puller geometry stops ions with a leading phase greater than about 15° , while essentially all lagging phases are accepted; thus the phase versus radius function becomes single valued. Typically a phase width $\Delta\phi = 7^\circ$ centered on an rf phase ϕ of about thirty degrees lag is selected. Since the magnetic field at the center ($R = 0$) is already above the isochronous value (to achieve vertical focusing), its level is simply adjusted by the inner gradient coils to bring the phase of the accelerated beam to zero at the radius at which the field becomes isochronous ($R \approx 12''$).

It was originally planned to control the beam divergence by means of a slit on the first turn at approximately 270° in azimuth. (The divergence results inherently from the puller-tower geometry.) However, measurements showed that the divergence at that position was small, and as a result the divergence slit is located at a larger radius where the divergence caused by any asymmetries in the electric field in the central region can be controlled. The slit is adjustable in aperture and can be located at any radius larger than two inches. The most effective radius at which to locate it is easily determined by taking a turn pattern with the slit retracted below the dee aperture. The affect of the divergence slit is demonstrated by the turn pattern shown in Fig. B7-2.

In addition to the phase and divergence slits, a baffle has been installed in the puller structure just behind the puller face to eliminate unwanted ion species. For deuterons, for example, the turn patterns near the center of the machine were often obscured by the presence of other molecular species, particularly the molecule D_3^+ which is accelerated on the third

Fig. B6-1

harmonic. Because these molecules follow a drastically different path through the region behind the puller, it is a particularly easy place to eliminate them. In addition to washing out the turn pattern of the wanted D_1^+ beam, these molecules, if allowed to circulate, would increase the space charge being circulated through the minimum v_z region and could result in a reduction of the D_1^+ intensity. The puller baffle effects virtually 100% rejection of D_3^+ with no reduction in intensity of the D_1^+ beam. An additional baffle mounted on the ion source is useful in eliminating unwanted ion trajectories and spurious beam generated as a result of the relatively high gas pressure near the tower. The central geometry for the 11-MeV deuteron case is shown in Fig. B6-1.

B7. The Intermediate Region

To obtain well-centered orbits at all radii, it is essential that the tower-puller-phase-slit system be accurately positioned, and that any equivalent first harmonic in the magnetic field (due to any combination of magnetic and electric fields) be compensated. The optimum radius to compensate is in the first $v_r = 1$ region where the radial stability is minimum. For this purpose a set of three paired harmonic coils (see Section C-2), extending in radius from 5" to 12", were installed.

The orbit centering problem was investigated both theoretically and experimentally. The central region computer program was extended to track orbits to large radii, and the effective centering determined for a variety of tower-puller positions using measured electric and magnetic fields. The

Fig. B7-1. Effect of harmonic coils on centering.

program was also used to check the results of a simpler calculation ⁴⁾ which indicates that the puller should be displaced $0.75 R_1$ from the magnetic center, where R_1 is the radius of the first half turn. A useful way of presenting the information is illustrated in Fig. B7-1. The radial momentum of an ion of constant energy is plotted against radius for three successive positions of the ion separated by 120 degrees corresponding to the 3-fold azimuthal symmetry of the magnetic field. These three points form a triangle, the area of which is a measure of the centering at that energy. The particle is then accelerated through a half turn and another radial phase-space triangle is constructed, and the process continued. A perfectly centered beam would be represented by a succession of triangles of zero area. However, an ion centered on one half turn must necessarily be miscentered after acceleration through the next half turn, thus a well-centered trajectory would consist of a series of triangles of area monotonically decreasing with radius, shrinking to a point at the extraction radius. By computing such radial phase-space plots for a variety of tower-puller positions, the optimum position required to achieve centering at large radii is determined. Solutions to within $1/8''$ can be fairly quickly achieved. The optimum positions calculated in this way have been shown experimentally to produce the best centering. Equally important, the optimum position does correspond to $0.75 R_1$ off center, so that it is not necessary to do the calculation for each new beam.

The other principal sources of miscentering are first harmonics in the magnetic field or asymmetries in the electric field. Accurate measurements for a variety of excitations of the magnetic field indicate that the maximum values of the first harmonic components are of the order of a few gauss. The electric field asymmetries have been shown to produce an equivalent first harmonic even

Fig. B7-3. Turn patterns for 29-Mev deuterons.

smaller except on the first half turn. It was to compensate for the effects of these asymmetries that the inner harmonic coils were installed. The effect of the first harmonic generated by these coils is shown in Fig. B7-1, which shows the phase space plots for first harmonic bumps of 5 gauss and 15 gauss, both at 0° azimuth for the 29-MeV D_1^+ beam. This plot demonstrates the wide range of control over the radial oscillation. A further example of the effectiveness of the coils is given below.

Experimentally the most useful tool for investigating orbit centering is the "wire" or ΔR probe, which measures current density as a function of radius. Two such plots are shown in Figs. B7-2 and B7-3 for 11-MeV deuterons and 29-MeV deuterons, respectively. Considerable information is contained in such plots. For a perfectly centered beam with no coherent or incoherent oscillation the spacing between turns should decrease with radius as $1/R$, and the area under each turn should be constant with radius (neglecting range effects of the ions in the wire). If the beam is not properly centered, the turn spacing will be modulated at the precessional frequency ν_p of the betatron oscillation. It is easily shown that the amplitude of the oscillation is

$$A = \frac{N}{4\pi} [(\Delta R_{\max} - \Delta R_{\min}) - \Delta R_1 \left(\frac{R_1}{R_2} - 1\right)]$$

where N is the number of turns per full precessional period, R_1 is the radius of a minimum in the turn separation, R_2 the radius of the next maximum in the turn separation, and ΔR the separation of adjacent turns at the maximum and minimum. The number of turns per modulation period is a measure of ν_p .

If the orbits are badly centered, "bumps" occur, such as the one near $R = 36''$ in Fig. B7-3a, corresponding to overlapping of turns. Incoherent oscillations due to divergence of the beam lead to a modulation in amplitude

of the turn pattern at a frequency $2\nu_r$, again as shown in Fig. B7-3a. Coupled with and directly related to the amplitude modulation is a modulation in the width of the turns. This follows from the fact that the integrated area under a single turn must be constant. This effect is quite distinct from the modulation in ΔR . For a well-centered turn pattern the average current to the wire is constant, while for a modulation in ΔR the average value changes, an extreme example being the bump at $R = 36''$ in Fig. B7-3a. The turn pattern of Fig. B7-3b indicates a beam well-centered out to $R = 36''$ with essentially no incoherent oscillation. The effectiveness of the "divergence" slit in limiting the amplitude of the incoherent oscillation is evident in Fig. B7-2. The amplitude is limited of course only at the expense of total current. These and other significant points are discussed more fully in a paper being prepared for publication.

B8. The Z-Motion

The circulating ions will in general undergo an oscillation in the Z-direction. In the central region where the focusing forces are relatively small the amplitude may become large due to small and unknown asymmetries in the central geometry. Because there is no effective damping mechanism (adiabatic damping is a relatively small effect in cyclotrons of this size), the oscillations persist to extraction. Changes in the field index due to slight misadjustments in the isochronous field can reduce the vertical restoring force (and ν_z) and cause loss of beam.

An investigation of the Z-motion by the burn pattern technique led to the introduction of "suppressor" plates to suppress the motion. The plates,

VERTICAL MOTION

Fig. 88-1a.

Fig. 88-1b.

one inch wide (azimuthal direction) and extending two inches in radius and located near the center of the cyclotron, are designed to give to the ions an impulse equal and opposite to their Z-momentum at the instant when $Z = 0$. The effectiveness of the plates in reducing the vertical amplitude is illustrated by the two burn patterns shown in Fig. B8-1 for a 22-MeV $^3\text{He}^{++}$ beam. The pattern in Fig. B8-1a shows a larger vertical oscillation beginning at small radii. The amplitude is considerably reduced with plus and minus 600 volts applied to the top and bottom suppressor plates, respectively, as shown in Fig. B8-1b. The frequency of oscillation given by the burn patterns gives the value of v_z as a function of radius.

Use of burn patterns led to the discovery of a shift in the median surface that resulted in a rapid shift of the beam in the +Z direction at $R = 34''$ (Fig. B8-1b). The shift was traced to an asymmetry that developed in gradient coil number 8, as reported last year. Because the isochronous field for the higher particle energies requires relatively larger currents in coil number 8, it is believed this was one of the factors contributing to beam instability at the higher energies.

B9. The Extraction Problem

The problem of maintaining high voltages in the extractor channel was investigated previously and the results summarized last year. The removal of the west dee necessitated the design and construction of a new deflector channel. The contour was determined by calculating the trajectories of the ions through the channel for a range of initial conditions. In the process the channel was lengthened by 15° to reduce the voltage required for

extraction. It is now about 80 kv for 35-MeV deuterons, and for higher energy deuterons it will be proportionally larger.

To improve the extraction efficiencies particularly at the higher energies a predeflector has been constructed. It consists of a pair of short parallel plates 35° upstream from the entrance to the main extractor, and is designed to increase the turn spacing at the entrance to the main extractor. It has not yet been tested, mainly because the extraction efficiency for the beams used to date, although not 100%, has been adequate.

B10, Beam Tuning Procedure

The procedure for establishing high quality internal and extracted beams of any ion species at any energy is now well established and is relatively quickly completed.

As a first step, the magnetic field is set as described in Section B5.

Using the theoretical centering conditions as a guide, the tower position is adjusted to meet the centering criterion for the given dee voltage and phase width selected. The radii of the first few turns are then measured with the wire probe as a check on the effective dee voltage. Next a complete turn pattern is taken from 3" to extraction radius. The fact that the phase of the radial oscillation changes by 180° as the tower-puller offset is moved through the optimum position is a useful indicator in centering the orbits. From the turn pattern the optimum location for the divergence slit is determined. The use of the divergence slit is usually essential in the centering process since the modulation in turn width at twice the frequency ν_r often obscures the compression and expansion of the turns due to miscentering.

Fig. B10-1. Effect of harmonic coils on turn pattern near extraction.

Note, for example, in Fig. B6-1 the sharpening of the turns at 15 inches due to the passage through the divergence slit. (Note also the presence of a small amount of D_3^+ at small radii.) Once the beam is centered however, it is usually possible to open the divergence slit to gain intensity. With the divergence limited, the effect of various first harmonic amplitudes and phases can be easily seen. The dramatic effect the harmonic coils have upon the orbits is illustrated in Fig. B10-1, which shows the turn pattern from 30" to 37" for an amplitude of 5 gauss first harmonic at the azimuths indicated. By an iterative process it is possible to arrive at a setting of the amplitude and phase of the harmonic coil currents which results in a centered turn pattern such as is shown in Fig. B7-3.

The procedure described above is used only once for establishing the proper conditions for a particular beam. Once these conditions are determined however, the beam can be reproduced quickly at any time.

B11. Results

The improvement resulting from the conversion to a one-dee system, and the subsequent program of orbit studies, is demonstrated by the results obtained for 11.4-MeV deuterons. This low energy was chosen so that the number of turns to extraction could be varied easily from 175 to 370. Also, the relatively small radial field gradient and resulting lower radial stability limit provided a more sensitive indication of the presence of any residual first harmonic components in the magnetic field. Measurements for the 175-turn case gave a radial emittance of 3.1 mm mrad for at least 50% of the beam, with an effective source width of 0.20 mm, as determined from emittance

EMITTANCE MEASUREMENTS

Fig. B11-1

patterns such as shown in Fig. 811-1. The extraction efficiency is about 86%, and of the extracted beam essentially 100% appears at the image surface of the first of the two beam preparation magnets. This is to be compared with earlier measurements for 15-MeV deuterons which gave an emittance of 24 mm mrad for 30% of the beam with an effective source width of 0.51 mm, an extraction efficiency of 75% with only 30% of the extracted beam appearing at the focus of the first beam preparation magnet. Normalizing the emittance measured for 11.4-MeV deuterons to 15 MeV, the radial emittance of 2.7 mm mrad for 50% of the beam is to be compared with 24 mm mrad for 30% of the beam.

For the 370 turn case the measured emittance and source width are essentially identical to that for 170 turns although the tuning is more critical to obtain a single effective source. The extraction efficiency is lower, 45 - 50%, as was expected since the turn separation at extraction is 0.057" compared to 0.120" (the septum is a carbon sheet 0.020" thick). Also, less than 50% of the extracted beam appeared at the focus of the first beam preparation magnet.

Results for a 44-MeV ^3He beam give 4.4 mm mrad emittance for 60% of the beam, 0.2 mm source width, and an extraction efficiency of 50%.

The most carefully tuned beams are the gated beams used for neutron time-of-flight measurements for which single turn extraction is essential. All particles in an extracted pulse of beam must have made the same number of turns from the tower to the extraction channel. For all the particles to make the same number of turns to gain their final energy, the phase width which can be tolerated is limited. Further, if the beam is not accelerated at zero rf phase, the acceptable phase width is even more restricted. For example, the 21-MeV ^3He beam makes about 120 turns to extraction. Under

ideal conditions the phase width to obtain single turn extraction must be less than 14° . However, if the beam rides 10° off zero phase, the permissible width is only about 4° . The fact then that single turn extraction is achieved for these beams is indicative of effectiveness of the phase slit, of the isochronism of the magnetic field, and of the stability of the magnetic field and the dee voltage.

A variety of beams have been aligned using the procedures outlined above, including 11-, 15-, 21-, 29- and 35-MeV deuterons and 21- and 45-MeV ^3He . (The conditions for ^4He are essentially identical to those for deuterons at half the ^4He energy). At the present time typical currents in the scattering chamber are 40 - 50 na per $E/\Delta E = 10^4$ for deuterons and 20 - 30 na per $E/\Delta E = 10^4$ for the doubly ionized ions $^3\text{He}^{++}$ and $^4\text{He}^{++}$. Using dispersion cancellation, which permits the energy defining slits to be increased by a factor of 3 to 8 without loss of resolution, the total current at the target is increased by the same factor. This, however, is still a large factor below that expected for both deuterons and doubly ionized ions and in fact is a reduction from the 100 na per $E/\Delta E = 10^4$ occasionally obtained for both deuterons and ^4He with the two-dee system as reported last year. The reduction is directly attributable to the change in ion sources and results from the high population density of unwanted ion species in plasma discharge (see Section A5b). We are convinced these numbers will be improved when a new ion source, working at a high anode temperature, is constructed.

We believe that we now have a reasonably complete understanding of our cyclotron and that, aside from the ion source problem, it is producing the kind and quality of beams for which it was designed.

Section B - REFERENCES

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C. FACILITIES IMPROVEMENTS

A number of improvements, some minor and some of greater consequence, were incorporated in the facility this past year. The major modifications, several of which are related to the conversion from two-dee to one-dee operation discussed in the last report, are described below. Minor modifications, some of which are aimed at improving the general efficiency of conducting research, are listed under miscellaneous.

C1. Ion Source Development

The conversion to single dee operation necessitated a redesign of the ion source which now must be offset from the machine centerline. As indicated in Section A5-b and Section B, it has some deficiencies and in particular is less than satisfactory for doubly-ionized particles and has not been used for the production of heavy ions. Because the acceleration of a large variety of heavy ions is of compelling interest to some of the staff, a new source is being designed. While the design draws heavily on the experience of others known to be successful, a mock-up incorporating some of our own ideas is being constructed and will be evaluated in a test chamber before finalizing the design.

C2. Harmonic Coils

To obtain more effective control of the amplitude and phase of radial oscillations of the ions during acceleration, a set of harmonic coils have been installed to cover the first $v_r = 1$ region. The method of construction and of powering are sufficiently unique to warrant a brief description.

The three pairs of coils spaced at 120° intervals in azimuth, each extending in radius from 5 to 12 inches, have been installed under the ground sheets, one member of each pair being located under the bottom ground sheet and the other member above the top ground sheet. They are constructed of double-sided two-ounce copper printed circuit board of ten turns each, capable of carrying 20 amperes. The total thickness of the assembly, including the epoxy base and Mylar insulation, is only $1/8$ inch.

To produce the maximum first harmonic field component with the design base of 20 amperes, bipolar power supplies are used. As an economy measure commercial unipolar supplies were purchased and a SCR crossover switch was designed to switch the polarity of output. The required polarity for each pair of coils is determined from the position of the triple-ganged sine-pot used to control the current amplitude, hence amplitude and phase of the (first harmonic) magnetic field. Light emitting diode couplers switch the appropriate SCR on or off while simultaneously the corresponding supply is pulsed to zero to insure proper switching.

The resulting first harmonic contribution to the main magnetic field can be easily adjusted from zero to 20 gauss in amplitude and continuously in phase from 0° to 360° .

C3. Gated Ion-Source Pulser

To gate with a period corresponding to $f/3$ or longer, the control grid is pulsed rather than driven in the $f/2$ cw-rf mode. The pulser provides a negative 3 kilovolt peak pulse with a rise and fall time of 35 nsec and a plateau of approximately 20 nsec. The output stage consists of five RCA 8122 tubes in parallel driven in a grounded cathode configuration by a sixth RCA 8122 tube. The driver stage is operated grounded grid and is switched by three 2N3866 transistors. Schottky TTL logic provides the pulse shaping for the input. The pulser is connected to the control grid of the ion source by a 175-ohm coaxial transmission line constructed with Teflon dielectric spacers.

C4. Reaction Products Chamber No. 2

A vacuum chamber connecting analyzer magnets number 2 and 3 (AM2 and AM3) and carrying the reaction product detectors was constructed and installed. The chamber allows the nuclear emulsion holder, the position-sensitive detector array, and the spark chamber to be placed at the image surface of AM2. The position and angle of the detectors can be adjusted under vacuum to correct for the kinematic shift in the image surface with scattering angle. Alternatively, with the detectors removed, the reaction products pass into AM3. A similar chamber was installed between AM1 and AM2 some time ago. A third chamber for use at the exit of AM3 has yet to be constructed.

C5. Low Resolution Beam Line

The installation of the new low resolution beam line ($E/\Delta E = 2000$) is complete. Magnetic field regulators, slits, viewports, and monitoring equipment have been installed in the neutron time-of-flight area, and beams of 45-MeV ^3He , 20-MeV ^3He , 11-MeV deuterons, and 29-MeV deuterons have been transported through the entire system. Transmission through the system is essentially 100%, with all of the beam allowed to enter the area being transmitted to the target locations. The system is versatile and the optics can be adjusted to meet the needs of a variety of measurements, such as in-beam γ -ray spectroscopy (Section A4), neutron time-of-flight spectroscopy (Section A5), and in-beam β -spectroscopy, and for the irradiation of targets with unanalyzed beam.

C6. Miscellaneous

The "centerline" probe was offset to operate in the electric field free region behind the dummy dee. At the same time the probe support and drive mechanism were rebuilt to ensure precise alignment of the probe over its entire travel and to allow for simple and rapid changing of probes.

An ion-source vacuum lock was installed to allow the source to be removed without breaking vacuum in the main chamber. A system of ways and guide tracks were installed to allow the source to be removed easily by untrained personnel.

A new extractor channel and deflector, adjustable from the console,

was constructed and installed.

New slits for defining the central geometry were installed.

A wire scanner for routine emittance measurement was installed.

The helium-3 recovery system was modified to permit continuous recycling.

A weather shed was constructed at the end of the neutron tunnel to protect the neutron detectors, a concrete walk laid between the shed and the laboratory building, and cable conduit installed (from funds supplied by the University).

D. PERSONNEL

Faculty

J. Bardwick III	R. Polichar
W.S. Gray	R.S. Tickle
J.W. Janecke (on leave 1/1/72 - 8/1/72)	H.C. Griffin (Nuclear Chemistry) (on leave 7/1/71 - 9/1/72)
W.C. Parkinson	A.C.T. Wu (7/1/72 - 8/1/72)

Student Assistants

Advanced Graduate

A.S. Broad	G.P. Neff (Term. 12/31/72)
R.H. Day	J.F. Petersen
M.A. Firestone	J.A. Splett
D.A. Lewis	A.M. VanderMolen
P.F. Julien (Term. 2/28/73)	K.L. Hull (Nuclear Chemistry - no financial support)

Graduate

C.E. Chapin (Appt. 5/8/72 - Term. 1/30/73)	F.L. Milder (Appt. 2/2/73)
D.P. Duston	D.J. Overway (Appt. 2/1/73)

Undergraduate and Hourly Assistants

A.H. Bennish (Appt. 1/29/73)
P.T. Kolen (Appt. 4/23/73)
W.A. Manwaring (Appt. 2/26/73)
R.A. Preston (Appt. 7/10/73 - Term. 9/15/72)

Engineers

D. DuPlantis - Cyclotron

A.V. Smith - Design

Electronic Technicians

J.L. Ferguson (Appt. 9/4/72)

R.E. Pontius (Term. 3/30/73)

Cyclotron Operations

W.E. Downer - Supervisor

J.A. Koenig - Chief Cyclotron Operator

R.H. Ball - Operator (Appt. 12/7/72 - Term. 1/12/73)

S. Gillies - Operator (Term. 10/31/72)

Instrument Makers

M.W. Prince

D.M. Schleede

Scanners

S. Grabner (Appt. 1/8/73 - Term. 4/24/73)

A. Halstead (Term. 12/14/72)

N. Hidayet (Appt. 10/24/72)

F. Hilberer

W.C. Stout (Term. 8/25/72)

Secretary

M. Lammers

E. PUBLICATIONS

Abstracts

1. "Analysis of Neutron Orbitals in ^{237}U via Deformed Bound State Wave Functions", A.S. Broad, Bull. Am. Phys. Soc. 17, 924 (1972).
2. "Nuclidic Mass Relationships and Mass Equations", J. Janecke and H. Behrens, Bull. Am. Phys. Soc. 17, 924 (1972).
3. "The University of Michigan Fast Neutron Time-of-Flight Scintillation Detector Array", P.F. Julien, R.M. Polichar and W.C. Parkinson, Bull. Am. Phys. Soc. 18, 617 (1973).

Publications

- *4. "Energy Determinations from Nuclear Reactions in Medium and Heavy Nuclei", W.C. Parkinson, Atomic Masses and Fundamental Constants 4, ed. by J.H. Sanders and A.H. Wapstra, Plenum Publ. Co., Ltd, London-New York (1972), pp. 38-53.
- *5. "Coulomb Energies and Nuclear Shapes", Joachim Janecke, Atomic Masses and Fundamental Constants 4, ed. by J.H. Sanders and A.H. Wapstra, Plenum Publ. Co., Ltd, London-New York (1972), pp. 221-235.
- *6. "Neutron-Proton Interaction in Mirror Nuclei", J. Janecke, Physical Review C6, No. 2, 467 (1972).
- *7. "Multiplet Structure of ^{210}Bi from the $^{209}\text{Bi}(d,p)$ and $^{209}\text{Bi}(\alpha, ^3\text{He})$ Reactions", C.K. Cline, W.P. Alford, H.E. Gove, and R. Tickle, Nuclear Physics A186, 273 (1972).

8. "Nuclidic Mass Relationships", J. Janecke and H. Behrens, Z. Physik 256, 236 (1972).
9. "Modifications to The University of Michigan 83-Inch Cyclotron to Improve Beam Quality, W.C. Parkinson, W.S. Gray, J.F. Petersen, and R.H. Day, Proceedings of the Sixth International Cyclotron Conference, Vancouver, Canada, 18-21 July, 1972, AIP Conference Proceedings No. 9, ed. by J.J. Burgerjon and A. Strathee, American Institute of Physics New York (1972), pp. 366-373.
10. "The Reaction $^{26}\text{Mg}(d,h)^{25}\text{Na}$ and the Structure of ^{25}Na ", Joachim Janecke, Nuclear Physics A204, 497 (1973).

In Press

11. "Studies of ^{205}Bi and ^{207}Bi by Proton-Transfer Reactions", Karl A. Erb and Walter S. Gray, Phys. Rev. C, in press.
12. "A Gated Ion-Source for Time-of-Flight Spectroscopy", R.H. Day and W.C. Parkinson, Nucl. Inst. & Meth., in press.
13. "Structure of Alisauakes-Jucys Form of the $9j$ Coefficients", A.C.T. Wu, submitted to Journal of Mathematical Physics.

* Reported last year as being in press.