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*Abstract.* The Iowa State University 1.5 Mev undergraduate cyclotron experimental program is divided between cyclotron technology and nuclear physics experiments. Accelerator technology work has been done in the determination of the shape of the resonance curve as a function of the magnetic field strength and radius, the determination of magnetic tune-down as a function of radius, and the measurement of the vertical excursions of the beam. Nuclear physics experiments have been performed with the light elements.

The experimental program on the Iowa State University undergraduate 1.5 Mev cyclotron is divided between cyclotron technology experiments and nuclear experiments. Beam technology work has been done in the determination of the shape of the resonance curve as a function of the magnetic field strength and radius, the determination of the tune-down at various radii, and the measurement of the vertical excursion of the protons (beam height). The experimental measurements have been compared to the theoretical calculations made for the ISU cyclotron by A. H. Mueller (1). The nuclear physics experiments are limited to the lightest elements due to the low energy of the machine. Comprehensive experiments have been performed using lithium and carbon as the target material. A description of the cyclotron used in this work has been given by D. J. McGuire (2) in this journal and in the work of R. T. Crosland (3).

## BEAM TECHNOLOGY EXPERIMENTS

### *Experimental Method*

**Instrumentation.** Two methods were employed for determining the intensity of the beam. A sensitive electronic microammeter was connected directly between the target and ground, and its reading was taken as an indication of the *relative* number of protons hitting the target per unit time. The maximum beam current of this machine is about two microamperes. The second and probably more reliable method was to use a Geiger counter to measure the reaction counting rate from the $Li^7$ $(p,\gamma)Be^8$ reaction occurring in the lithium target. The reaction rate is proportional to the beam intensity. The measured beam current has been found to be proportional to the counting rate but only on approximate indication of absolute beam current. The maximum counting rate was about 1500/min against a background of about 20/min.

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The magnet current was determined with a Type K potentiomter operating across a 0.0005 ohm manganin shunt. The center magnetic field ($B_0$) was accurately correlated with the magnet current by means of a nuclear resonance gaussmeter. All field measurements were accurate and reproducible to better than four gauss out of 17,000.

The frequency ($f_1$) of the cyclotron r.f. supply was measured to five significant figures with a BC-221 frequency standard. The BC-221 was periodically calibrated against the frequencies of the radio station WWV.

**Procedure.** The variable frequency oscillator was tuned to the resonant frequency ($f_1$) of the dee-box, and the r.f. supply adjusted to produce a peak voltage of 10 Kv from dee-to-dee. Since the theoretical calculations were made for this voltage, it was used throughout the experiment.

The target radius ($r_2$) was fixed, and the beam tuned in by varying the center magnetic field strength ($B_0$). Beam intensities were determined for different values of $B_c$ within the tuning range of the beam. This procedure was repeated for various values of $r_2$ between six and eleven centimeters.

The vertical range of the beam was measured at different radii by the direct observation of the glow produced when a target coated with RCA 33-Z20A phosphorous was bombarded by the protons.

**Analysis of the data.** Curves of the intensity function were constructed from the data by plotting beam intensity as a function of $B_0$. A curve exists for each $r_2$ at which data were taken. The reaction counting rate was used to determine the beam intensity, while the data from the beam current indicator served mainly as a check.

The magnetic field ($B_1$) at which the ions are in exact cyclotron resonance at the r.f. supply frequency ($f_1$) is given by the cyclotron resonance equation,

$$B_1 = \frac{2\pi m f_1}{e}, \text{ (MKS units)} \tag{1}$$

where e and m are the charge and mass of the proton. The difference between the actual center field value ($B_0$) and the field $B_1$ at some larger radius $r_1$ is defined as the tune-down ($\delta B$):

$$\delta B = B_0 - B_1 \ . \tag{2}$$

The peak of the resonance curve was chosen to describe the tune-down at various radii. The $B_0$ corresponding to the maximum beam intensity is denoted by $B_m$. Thus to describe the tune-down for maximum intensity, equation 2 becomes:

$$\delta B_m = B_m - B_1 \ . \qquad (3)$$

The beam intensity (I) is a function of both $B_o$ and $r_2$. The data originally were taken by holding $r_2$ fixed and varying $B_o$. The family of curves giving I as a function of $r_2$ at constant $B_o$ was then extracted from the data.

*Experimental Results*

**Resonance curve shape.** Fig. 1 shows the theoretical and experimental shapes of the resonance curve at a target radius ($r_2$) of 9 cm. The experimental curve (a) is constructed from the data taken from the beam current microammeter, while curve (b) is from the $Li^7(p,\gamma)B_e^8$ reaction data. The two experimental

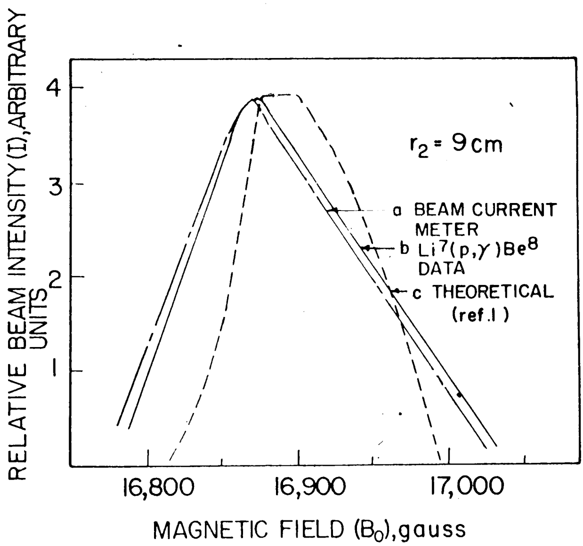


Figure 1. Relative beam intensity as a function of the center magnetic field.

curves are practically identical. They are about 150 gauss wide at half-maximum intensity. The theoretical curve (1), shown in broken lines, is quite a bit narrower—115 gauss at half-maximum intensity. In Fig. 2 the resonance curve shapes at other radii are shown. The maximum beam intensities shown are not comparable because the scale used was different for each target radius.

**Tune-down of the magnetic Field.** Fig. 2 shows that with $r_2$ less than 8 cm, $\delta B_m$ is observed to be zero. As $r_2$ is increased, the peak of the resonance curve ($B_m$) is seen to shift to the right

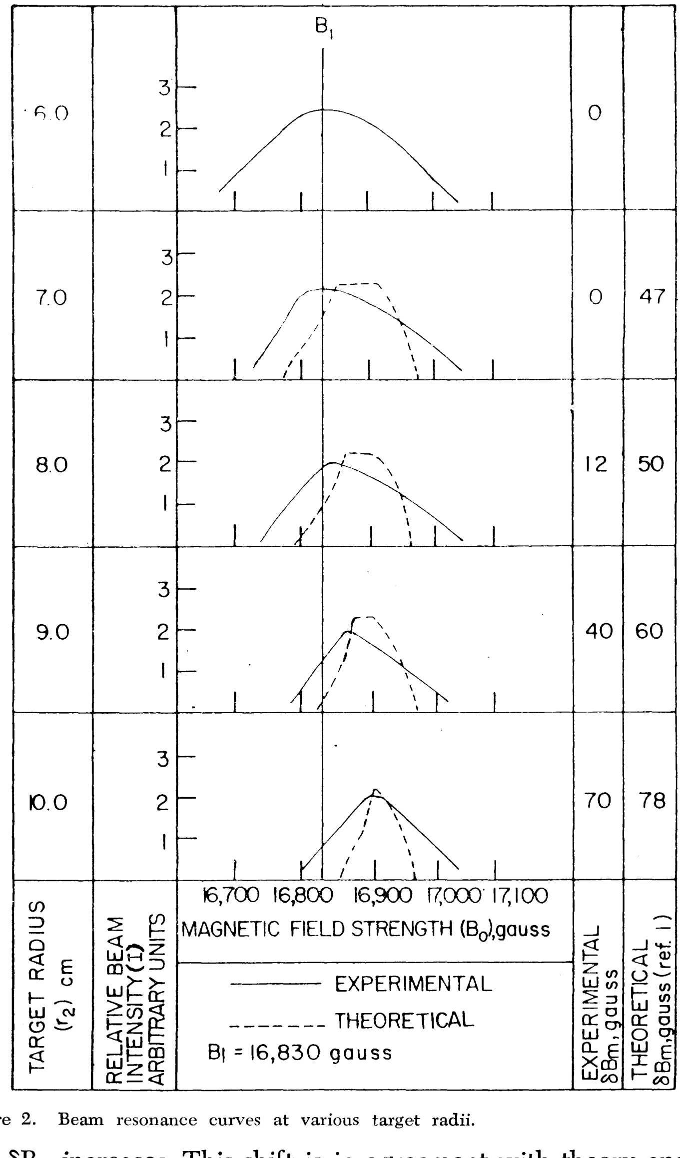


Figure 2. Beam resonance curves at various target radii.

and $\delta B_m$ increases. This shift is in agreement with theory and is due to the drop-off of the magnetic field strength with increasing radius. Fig. 3 shows how this shift to the right depends on $r_2$. The tune-down ($\delta B_m$) is plotted as a function of increasing target radius. A large difference is observed between the theoretical and experimental function, but the two curves do converge at the larger radii. The difference between the observed and calculated function is discussed by Mueller (1).

**Beam intensity as a function of radius.** The beam intensity (I) drops off very rapidly at large values of $r_2$. Table 1 gives both the measured and calculated (1) maximum I ($B_o = B_m$) at various values of $r_2$. The value of I at the $r_2$ of 6 cm is arbitrarily assigned the value of one. The beam falls off much more rapidly than predicted, and a discussion of this is given by Mueller (1).

Table 1. Mamium Beam Intensity as a Function of Target Radius.

| Target radius ($r_2$) centimeters | Maximum Beam Intensity ($I_m$) arbitrary units Experimental | Theoretical |
|---|---|---|
| 6.0 | 1.0 | 1.0 |
| 7.0 | 0.92 | 1.0 |
| 8.0 | 0.86 | 1.0 |
| 9.0 | 0.63 | 1.0 |
| 10.0 | 0.14 | 1.0 |
| 10.5 | .. | 0.68 |
| 11.0 | 0.034 | 0.11 |

**Vertical range of the protons.** The study of the beam height was carried out before the magnetic field was adequately regulated, and the results are only qualitative. At present a program is in progress to determine the vertical excursions of the protons by employing nuclear emulsions to "photograph" the beam and to determine its energy and energy spread.

**Discussion.** The experimental measurement of the width of the resonance curve shown in Fig. 2 was the most accurate part of the program. The curves were reproducible, and the maximum error in their widths amounted to only a few per cent. The value of $\delta B_m$ is not so well established as is the resonance curve width.

The small magnitude of $\delta B_m$ coupled with an error of several gauss in determining $B_m$ from the graph could produce uncertainties of greater than ten per cent.

The curves in Fig 2 describe the beam resonance in the cyclotron, and the shift to the right of $B_m$ has been described. The resonance curves have ions of greatest positive phase contributing to the extreme right of the curve, while ions of least positive phase contribute to the left of the curve. Theorectically, ions of greatest positive phase should not be lost as $r_2$ is increased. This was observed to be the case experimentally, although this fact cannot be inferred directly from Fig. 2. Ions of least positive phase should be lost as $r_2$ is increased. This is shown experimentally by the gradual shift to the right of the left-hand side of the curves with increasing $r_2$.

The cyclotron technology experiments would suggest that a revison of the theoretical calculations could be made. The ex-

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perimental results may serve as a guide to determine more realistic assumptions regarding the behavior of ions in the cyclotron.

## Nuclear Physics Experiments

### *Instrumentation*

The counting equipment consisted of both Geiger-Mueller counters and a sodium iodide (NaI) crystal scintillation spectrometer. The scintillation spectrometer used photomultiplier tubes in conjunction with both two- and three-inch NaI crystals in the conventional fashion. The pulses produced by the photomultiplier were amplified and then either analyzed with a single-channel integral-differential pulse height analyzer or studied by direct observation with an oscilloscope. The pulses were finally counted either with conventional scalers or with a count rate meter.

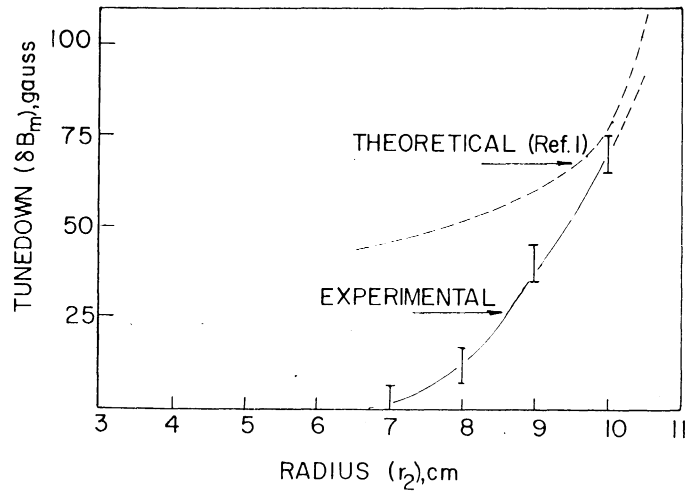


Figure 3. Tune-down of $B_m$ as a function of radius.

The scintillation spectrometer was calibrated using the unresolved (1.25 Mev) $\gamma$-rays from $Co^{60}$. The maximum voltage of this pulse from the amplifier was measured either with the pulse height analyzer or with the oscilloscope.

### *Experiments with $Li^7$ Targets*

The $Li^7(p,\gamma)Be^8$ resonance reaction has a threshold energy of 0.441 Mev and has a large cross section. A detailed study of this reaction has been made by R. T. Crosland (3) and by P. Moore and the author (unpublished data).

A thick (0.5 mm) $Li^7$ target was attached to the target and $r_2$ was set so that the energy of the protons would be about 1 Mev.

The NaI crystal was located about fifty centimeters from the target. The voltage of the pulse of the $\Upsilon$-ray from the lithium reaction was measured and the observed energy ($E_p$) corresponding to this pulse was estimated by simple proportion by using the calibrated pulse height. The result was about 15 Mev for $E_p$.

In the present geometry $E_p$ is approximately related to $E_\Upsilon$ by

$$E_p = E_\Upsilon - 0.5 \quad (\text{Mev}). \tag{4}$$

The difference comes from a secondary pair production process. When the positron resulting from the pair production is annihilated, about half of this annihilation energy is lost on the average. Then approximately,

$$E_\Upsilon = 15 + 0.5 = 15.5 \text{ Mev}.$$

The actual value is 17.5 Mev. This difference is within the experimental uncertainties.

The reaction actually yields two high energy $\Upsilon$-rays, the 17.5 Mev one and also one of energy of 14.5 Mev. The spectrum of the $\Upsilon$-rays has been determined with the differential pulse height analyzer. The spectrum shows the second energy peak

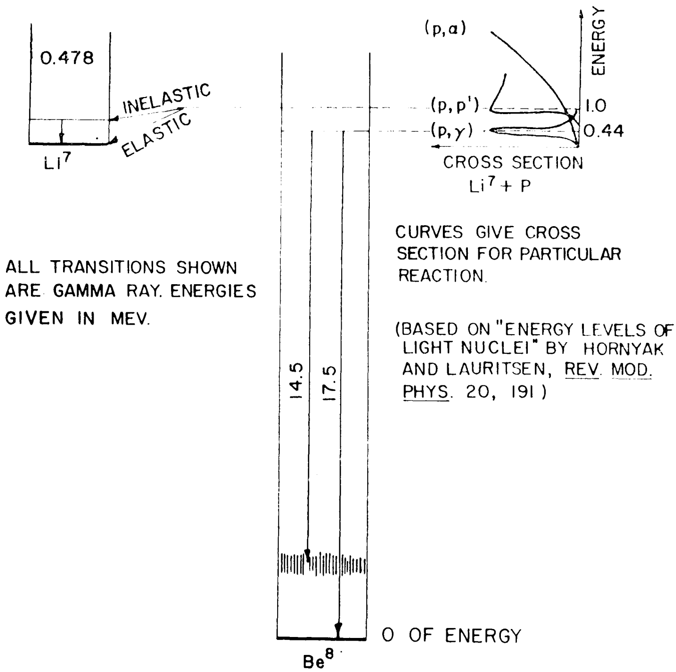


Figure 4. Energy levels observed in the $Li^7$ experiments.

in the neighborhood of the expected value of 14.5 Mev, and it had an undance of 30%, as determined by the relative counting rates.

The inelastic scattering of the protons by lithium also has been observed. The threshold energy for the $Li^7(p,p')Li^{7\star}$ reaction is about 1.0 Mev. The lithium is excited by the inelastic scattering process to the first excited state, which subsequently decays by emitting a 0.478 Mev Υ-ray.

Fig. 4 shows the energy level diagram involved in these experiments.

*Experiments with $C^{12}$ Targets*

The $N^{13}$ produced in the $C^{12}(p,\Upsilon)N^{13}$ reaction is a radioactive element with a half-life ($\tau_{1/2}$ of approximately ten minutes. The $N^{13}$ decays to $C^{12}$ by the emission of a positive electron. Satisfactory counting rates of the $\beta^+$— particle were obtained by taking advantage of the high sensitivity of the NaI scintillation counter for annihilation quanta.

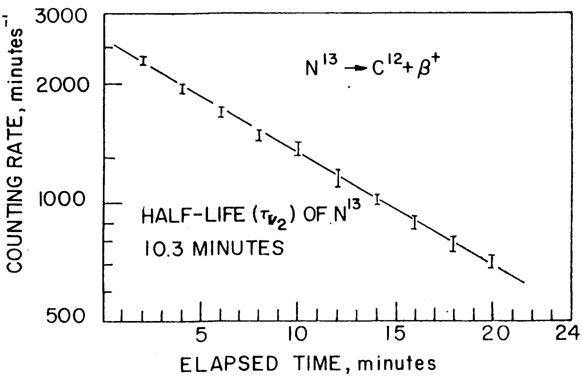


Figure 5. Radioactive decay curves for $N^{13}$.

The samples to be bombarded were machined (dry) in the form of thin wafers (1 mm thick) from spectroscopic carbon. The target radius was set so the energy of the protons would be only slightly greater than the threshold energy for the reaction. This was done to minimize the absorption of the $\beta^+$—particles leaving the sample, thus providing the maximum flux at the counter. The sample was then bombarded for about one half-hour.

After bombardment, the activated sample was removed from the machine and taped to a two-inch NaI crystal scintillation counter located in a lead house for minimum background. The counting was done for fifteen-second periods every minute for one half-hour. The initial counting rate was about 4,000 counts per minute. A plot of the natural logarithm of the counting rate versus elapsed time has a slope equal to $0.693/\tau_{1/2}$, where $\tau_{1/2}$ is the half life for the decay. The corresponding semi-log graph of the experimental data is shown in Fig. 5 for one of our runs which gave $\tau_{1/2} = 10.3 \pm 0.3$ min. The average value of three such determinations also yielded a half life close to 10.3 min. for the $N^{13}$. This is in reasonable agreement with the published value of 10.1 min.

The maximum energy of the positron was measured to be 1.1 Mev. This was measured by comparing the pulses produced by the positrons to the calibration pulses produced by the $Co^{60}$ Y-rays. The published maximum energy of the positron in 1.2 Mev. The difference can be accounted for by the absorption of the aluminum foil covering the NaI crystal, and also by the fact that most of the $N^{13}$ atoms are located below the surface of the carbon.

## Acknowledgments

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