Photoproteons from zinc-64

Gary Edwin Clark

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Photoprotons from zinc-64

by

Gary Edwin Clark

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Department: Physics
Major: Nuclear

Approved:

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1. ISOSPIN OF ZINC-64

1.1 Introduction

The giant dipole resonance, that ubiquitous feature of photonuclear cross sections, appears as a peak in the photodisintegration cross section at an energy which varies from 25 MeV to 13 MeV for light and heavy nuclei respectively. The main features of the giant resonance have been explained by either electric dipole excitations of single nucleons between major shells or oscillations of nuclear fluids in spin or isospin modes. In either model isospin may be of some consequence in photonuclear reactions.

Although the formalism of isospin was developed by Wigner (1) as long ago as 1937, the applicability to medium and heavy nuclei was not of interest until recent years. It was thought that the stronger Coulomb interactions in heavier nuclei would destroy the isospin symmetry. There is now some evidence that isospin is still a good quantum number, to some extent, even in heavy nuclei.

One of the consequences of isospin effects is the splitting of the giant dipole resonance into two components separated by a few MeV, but there is some controversy over the observation of this effect in zinc-64. This paper is concerned with the experimental observation of photoprotons from zinc-64 and the interpretation of the photoproton cross section in the light of isospin considerations.

The paper begins with an introduction and history of the isospin formalism followed by a summary of the previous investigations of zinc-64 in Section I. In Section II is described the experimental apparatus such
as the accelerator, scattering chamber, and electronics. The experimental procedure used to collect the data is described in Section III. The method of data analysis is outlined in Section IV. The conclusions which were drawn from this experiment are presented in Section V.

1.2 Theory of Isospin

The basic idea of isospin is simple. If the mass and charge differences of the proton and neutron are ignored, they can be thought of collectively as a nucleon with two alternative states of existence. The formalism of angular momentum can be used by assigning an isospin of \( T = \frac{1}{2} \) to the nucleon with a z-component of \( +\frac{1}{2} \) for neutrons and \( -\frac{1}{2} \) for protons. (The opposite sign convention is also used.) A nuclear state is then characterized by the addition of the isospin vectors of the individual nucleons. For a particular nucleus the numbers of protons and neutrons are fixed, so the z-component of isospin is constant at \( T_z = \frac{1}{2}(N-Z) \). The total isospin is allowed to range from \( \frac{1}{2}(N-Z) \) to \( \frac{1}{2}(N+Z) \) with the nuclear ground state always having the lowest possible value, which for zinc-64 is \( \frac{1}{2}(34-30)=2 \). A sequence of corresponding levels in neighboring isobars with the same \( T \) but different values of \( T_z \) is called an isobaric multiplet.

The operator for electric dipole interactions in the long wavelength approximation can be expressed in terms of the isospin operator \( T_z \), for which the eigenvalues are \( +\frac{1}{2} \) for a neutron and \( -\frac{1}{2} \) for a proton:
\[ D = e \sum_{i=1}^{Z} r_i \]
\[ = e \sum_{i=1}^{A} r_i (\frac{\hbar}{2e} - T_i Z) \]
\[ = \frac{2}{\sqrt{e}} \sum_{i=1}^{A} r_i - e \sum_{i=1}^{A} r_i T_i Z, \]

where \(e\) is the electronic charge, and \(r_i\) is the position of the center of mass of the \(i\)'th nucleon. The first term is responsible for Thomson scattering. The second term is responsible for the dipole transitions. The selection rules are \(\Delta T = 0, \pm 1, 0 \neq 0\), and these were first demonstrated for self-conjugate nuclei by Trainor (2) and later extended to the general case by Radicati (3) and Gell-Mann and Telegdi (4). Conservation of the \(z\)-component eliminates \(\Delta T = -1\), thus the giant dipole resonance is composed of two parts, states with \(T = T\) and \(T = T + 1\), where \(T\) is the isospin of the ground state. If the magnitudes of the reduced matrix elements were equal, the relative strengths would be proportional to the geometrical factors, \((T T 1 0 | T T)^2 = T/(T+1)\) and \((T T 1 0 | T+1 T)^2 = 1/(T+1)\), which give \(2/3\) and \(1/3\) for zinc-64.

A consequence of the isospin selection rules is that the \(T_>\) states cannot decay by neutron emission to the \(T_<\) states of the residual nucleus. As an example the decay of the \(T_> = 3\) states of zinc-64 to the \(T_< = 3/2\) states of zinc-63 is isospin forbidden since that would require a change in isospin of \(3/2\), and the neutron can carry away a change of only \(1/2\).

On the other hand, the proton channel is not blocked. The \(T_> = 3\) states of zinc-64 can decay by proton emission to either the \(T = 7/2\) or
T = 5/2 states of copper-63. Thus the two decay channels, neutron and proton emission, should exhibit different characteristics due to the isospin selection rules.

A special sum rule first derived by Goulard and Fallieros (5) has been extended to the general case by O'Connell (6,7). It relates the bremsstrahlung-weighted cross section of the (T+1) component of the cross section to the total bremsstrahlung-weighted cross section,

$$\frac{\sigma_{-1}(T+1)}{\sigma_{-1}} = \frac{1}{T+1} \left[ 1 - \frac{1.97 T <R_p^2>(1-\eta)}{A^{4/3}} \right],$$

where

$$\sigma_{-1} = \int (\sigma/E) \, dE,$$

$$\eta = \frac{(2T-1)A^{2/3}}{3NZ},$$

and $<R_p^2>$ is the mean square charge radius of the nucleus. Using the most recent rms charge radius for zinc-64 (8) this gives $\sigma_{-1}(T+1)/\sigma_{-1} = 0.256$. The geometrical factor, $1/(T+1) = 1/3$ for zinc-64, represents the upper limit for any theoretical calculation. The remaining factor, called the dynamic factor, is always less than unity.

It is possible to observe the two isospin components because there is an energy difference between the two parts of the giant dipole resonance. The center of strength is defined as

$$\bar{E} = \frac{\int \sigma dE}{\int (\sigma/E) dE},$$

and the energy splitting due to isospin effects is
\[ \Delta E = \bar{E} - \bar{E}' \]

A rough estimate has been derived by Akyüz and Fallieros (9),

\[ \Delta E = (60 \text{ MeV}) \frac{(T+1)}{A}, \]

which gives \( \Delta E = 2.8 \text{ MeV} \) for zinc-64. A more complicated formula has been given by Leonard! (10):

\[ \Delta E = \frac{T+1}{A} 2\bar{E} \left( \frac{1-\alpha}{\alpha} \right) \left[ 1 + \frac{2(1-T)}{\alpha A} \left( 1 + \frac{4T}{\alpha^2 A^2} \right) \right]^{-1}, \]

where

\[ \alpha = \frac{3\beta}{2ME} \left( \frac{<R_p^2>}{<R_p^2>^2} - \frac{Ne}{2T} \right)^{-1} \]

with

\[ \epsilon = <R_p^2> - <R_p^2>. \]

For zinc-64 Leonardi used \( \bar{E} = 18 \text{ MeV} \), \( <R_p^2> = (3.90 \text{ fm})^2 \), \( \beta = 1.5 \), and \( \epsilon = 0 \) to obtain \( \Delta E = 3.2 \text{ MeV} \), which is probably an upper limit.

By comparison with available experimental data in the same mass region as zinc-64, Paul, Amann, and Snover (11) found that a good fit was obtained with

\[ \Delta E = 67 \text{ MeV} \left( 1 - 3.9 \frac{T}{A} \right) \frac{(T+1)}{A}, \]

which gives \( \Delta E = 2.8 \text{ MeV} \) for zinc-64.

The first attempt to experimentally observe the isospin splitting of the giant dipole resonance in zinc-64 was undertaken by Schamber et al. (12,13). That experiment, a measurement of the \((\gamma,n)\), \((\gamma,np)\), and \((\gamma,2n)\)
cross sections described in Section 1.3, gave evidence for an isospin splitting of $\Delta E = 7$ MeV, more than twice the theoretical value. That result was somewhat surprising, but magnesium-26 also seemed to exhibit a spectacularly large isospin splitting, and it was thought that both results were due to a deformation effect (10).

In a measurement of the $^{63}\text{Cu}(p,\gamma)^{64}\text{Zn}$ cross section, Paul et al. (11) found evidence of an isospin splitting of $\Delta E = 3$ MeV for zinc-64. This clearly disagreed with Schamber's value, but neither experiment is entirely conclusive with regard to the isospin splitting because it is not possible to tag individual events in a particular reaction channel with the isospin quantum number of the nuclear state.

A clear resolution of the controversy can be provided in only one way, by observing all decay channels and comparing reaction strengths in the various energy regions with predictions which use the isospin selection rules. The missing element in the photodisintegration picture of zinc-64 is the photoproton cross section, which is the subject of this paper. Since evidence of the $T>_{g}$ giant resonance for medium and heavy nuclei in photonuclear physics is still paltry, it would be extremely helpful to clarify the situation for zinc-64.

1.3 Previous Investigations of Zinc-64

A diagram of the energies involved in the photodisintegration of zinc-64 taken from Schamber (12) is shown in Figure 1, in which the $T<_{g}$ and $T>_{g}$ giant resonances are centered at 18 MeV and 25 MeV. Two known $T = 5/2$ levels in zinc-63 are indicated as solid lines, although there are
Figure 1. An energy diagram showing decay modes of $^{64}_{30}\text{Zn}^-$ allowed by isospin selection rules.
undoubtedly others. Schamber (12,13) has investigated the cross sections for the reactions $^{64}_{\text{Zn}}(\gamma,n)^{63}_{\text{Zn}}$, $^{64}_{\text{Zn}}(\gamma,np)^{62}_{\text{Cu}}$, and $^{64}_{\text{Zn}}(\gamma,2n)^{62}_{\text{Zn}}$ by using activation techniques in which coincident annihilation gamma rays from the induced positron activities were detected and the different activities separated by half-life. This gives no information about the $^{64}_{\text{Zn}}(\gamma,p)^{63}_{\text{Cu}}$ cross section because copper-63 is stable.

Since the decay of the $T_\geq$ states in zinc-64 to the ground state in zinc-63 is isospin forbidden, Schamber expected to see substantial $T_\geq$ strength in the $(\gamma,np)$ cross section. He found a 25 MeV $(\gamma,np)$ peak which was similar in shape and only about 20% of the magnitude of the $(\gamma,n)$ peak at 17.5 MeV. He found that both the $(\gamma,np)$ and $(\gamma,2n)$ cross sections peak at 25 MeV, but with the latter having only 1/3 the amplitude of the former. He identified the 25 MeV peak with the $T_\geq$ giant resonance, which gave $\Delta E = 7$ MeV for the isospin splitting.

In a recent study of the reaction $^{63}_{\text{Cu}}(p,\gamma)^{64}_{\text{Zn}}$, Paul, Amann, and Snover (11) found increased reaction strength in two regions of proton energy which correspond to gamma excitations of zinc-64 at 16 MeV and 19 MeV, which also appear in the $(\gamma,n)$ cross section of Schamber (12). Paul et al. wish to assign the $T_\leq$ giant resonance to the 16 MeV region and the $T_\geq$ giant resonance to the 19 MeV region, thus obtaining $\Delta E = 3$ MeV for the isospin energy splitting, which is in better agreement with theory than the assignment of Schamber (12). Paul et al. have pointed out that there is at least one particle stable $T = 5/2$ level in zinc-63 to which decay could occur, thus explaining the appearance of the $T_\geq$ strength in the $(\gamma,n)$ cross section. In addition the high threshold of 18.6 MeV for the $(\gamma,np)$
reaction would prevent observation of the true shape of the $T_>$ resonance if it were at 19 MeV.

Before a definite assignment of the isospin strengths can be made, the $^{64}\text{Zn}(\gamma,p)^{63}\text{Cu}$ cross section must be analyzed. Relative to the $(\gamma,n)$ cross section, the $T_>$ giant resonance should be enhanced over the $T_<$ giant resonance. In addition information will be obtained for decays to residual excited states of copper-63 which do not appear in the $(p,\gamma)$ cross section because the initial copper-63 nucleus must be in the ground state.

No previous measurement of the $^{64}\text{Zn}(\gamma,p)^{63}\text{Cu}$ cross section has been made with the separated isotope. A cross section for the production of fast protons from natural zinc and some angular correlations have been given by Osokina and Ratner (14), but there is no other $(\gamma,p)$ cross section for natural zinc although the protons have been observed in two other cases (15,16). Three of the five stable zinc isotopes ($A = 67, 68,$ and $70$) give radioactive residual copper nuclei in the $(\gamma,p)$ reaction. Cross sections have been measured by activation techniques for $^{67}\text{Zn}(\gamma,p)^{66}\text{Cu}$ (17) and $^{68}\text{Zn}(\gamma,p)^{67}\text{Cu}$ (18,19), but no cross section has been determined for $^{70}\text{Zn}(\gamma,p)^{69}\text{Cu}$ although the process has been used to produce copper-69 (20). The remaining stable zinc isotope, zinc-66, leads to stable copper-65 in the $(\gamma,p)$ reaction, and no measurement of the cross section exists.

The most recent measurements of the $^{64}\text{Zn}(\gamma,n)^{63}\text{Zn}$ cross section have been made by Costa et al. (21), Owen et al. (22), and Schamber et al. (12,13).

From the above information it is seen that the photodisintegration
picture of zinc-64 in the giant resonance region is fairly complete except for the ($\gamma$,p) reaction. This paper attempts to complete the picture and give a clear resolution of the controversy over the magnitude of the isospin splitting.
II. EXPERIMENTAL APPARATUS

2.1 The Electron Prototype Accelerator

The Electron Prototype Accelerator (EPA) at Los Alamos was built to test the design for the LAMPF proton accelerator and was intended to be only a temporary machine. Even as this paper is being written, the EPA is being dismantled. It was a linear electron accelerator with side-coupled cavities operating in a standing wave mode (23). Some of the characteristics of the EPA are listed here:

- maximum electron energy: 27 MeV
- beam power: 22 kW avg. at 1 mA
- current: 18 mA peak, 1 mA avg.
- energy resolution: 0.5% full width at half max.
- pulse repetition rate: 120 pps
- pulse length: up to 520 $\mu$s

The long duty factor of the EPA made it uniquely suited for $(\gamma,p)$ experiments. A duty factor of 6% could routinely be used on the EPA compared to about a 0.1% duty factor typical of the previous generation of linacs. Since counting rates in photoproton measurements are limited by pulse pile-up, counting rates with a high intensity linac are directly proportional to the duty factor. It now appears to be feasible to design a machine with a 100% duty factor, which would be the ideal.

The energy analyzing system consisted of a pair of symmetric magnets with a 0.5% energy resolution slit between them. The output of an NMR probe in the analyzing magnet system was monitored at the control console by means of a digital voltmeter. After calibration with the oxygen spectra from the small chamber, to be described in Section 2.2, the NMR
output was used to set up the machine for specific energies.

The analyzed electron beam impinged on a 10 mil tungsten bremsstrahlung converter embedded in a wire mesh, after which the remaining electrons were deflected into a water-cooled beam dump. The bremsstrahlung beam passed from the accelerator room to the experimental room through a hole in a six foot lead wall. The hole contained collimating inserts and some beam hardening material in the form of 15 in of polyethylene.

2.2 The Oxygen Monitor

Upon entering the experimental area, the bremsstrahlung beam first passed through a small chamber filled with oxygen to a pressure of 20 in-Hg. At approximately 6 in from the center of the beam and at an angle of 90° was placed a 2 mm thick Si(Li) detector which looked at photoprotons from the oxygen. The electronics were completely separate from that of the large target chamber, which is described later. Spectra from the small chamber were used to determine the bremsstrahlung endpoint energy by comparing with the oxygen photoneutron spectrum (43).

2.3 The Target Chamber

The aluminum target chamber, shown in Figure 2, was constructed at Yale University for earlier experiments at the EPA. The center section through which the beam passed was 4 ft long with Mylar windows at each end. The downstream window could be removed for manipulating the zinc foil and the aluminum detector shields used for background runs. The target chamber was evacuated for all runs except no. 22, for which oxygen
Figure 2. A scale drawing of the scattering chamber showing the zinc foil at the center.
at 20 in-Hg was introduced for detector calibration.

Although the chamber had seven arms, detectors were placed at the ends of only four, those indicated in Figure 2 making angles with the incident beam of 45°, 90°, 135°, and 160°. A bias of 200 V was applied to each of the detectors, which were 2 mm thick Si(Li) detectors of surface areas 200 mm² manufactured by Kevex Corporation. Each detector was thermally coupled to one end of a copper finger, the other end of which dipped into a dewar of liquid nitrogen. The leakage currents in the detectors were about 1.0 μA at room temperature and very nearly zero when cooled. Strong permanent magnets were placed before the detectors to deflect low energy electrons produced in the zinc target.

The entire chamber, except for the two end windows, was shielded by at least six inches of lead. The shielded target chamber was supported on a sturdy aluminum stand with adjustable feet.

2.4 Electronics

A block diagram of the electronic setup is shown in Figure 3. The unusual feature which needs explanation at this time is the multiplexer. Four single channel analyzers (SCA) were used to determine which pulses were suitable for analysis. Upon receipt of a signal from an SCA, the multiplexer did three things. First, all inputs except the one of interest were gated off for 30 μs. Second, a pedestal was placed under the pulse from the proton detector as the unavoidable result of gate feedthrough. Third, a routing pulse was supplied to the appropriate input of the MCA, so that the proton pulse was stored in the proper quarter of the 1024 channel memory, thus enabling the four 256 channel
Figure 3. A block diagram of the electronics. The system enclosed by the dashed line is one of four similar data channels.
spectra to be accumulated simultaneously.

The MCA had two types of output, an oscilloscope display and a teletype unit. Polaroid prints were made of the oscilloscope displays, and the teletype produced punched paper tape and hard copy output.

Not shown in Figure 3 is the completely separate system which monitored the oxygen spectra from the small chamber described in Section 2.2.

2.5 The Dose Monitor System

The ionization chamber used as a dose monitor was a replica of the type P2 chamber designed and calibrated at the National Bureau of Standards by J. S. Pruitt and S. R. Domen (24). The P2 chamber was open to the atmosphere. In the lower left corner of Figure 3 is shown how the charge from the P2 chamber was recorded. The Ortec current digitizer sent one pulse to the TSI scaler for each $10^{-10}$ Coul of charge. The treatment of the data from the TSI scaler is described in Section 4.3.
III. EXPERIMENTAL PROCEDURE

3.1 Preparation of the Zinc-64 Target Foil

A sample of 2.987 gm of zinc-64 in the form of ZnO powder isotopically enriched to 99.6% in the desired zinc isotope was obtained from Oak Ridge. The technique for making the metal foil, outlined below, was developed by the Metallurgy and Chemistry Division of the Ames Laboratory with the assistance of B. Beaudry, T. Scott, and H. Jensen.

The ZnO powder was dissolved in 10% sulphuric acid, and metallic zinc was obtained from the solution by electrodeposition onto an aluminum cathode which was lacquered except for an exposed area of 0.25 in\(^2\). During deposition oxygen was liberated at a platinum anode. A potential of 3.6 V was high enough to deposit the zinc but low enough to alleviate the problem of hydrogen formation at the cathode from the electrolysis of water. An average current of 150 mA enabled slightly over 96% of the zinc to be deposited in about 8 hours. The deposited zinc was shiny and bright, and the remaining solution was perfectly clear. During deposition the electrolytic solution was constantly but gently stirred, and it was surrounded by a water bath for temperature control.

After the zinc was stripped from the aluminum cathode, bits of adhered lacquer were cleaned off with acetone. The zinc was placed in a crucible of spectrographic graphite, which was then heated to above the melting point of zinc, 419.5 °C, and quickly cooled with liquid nitrogen.

The resulting zinc button was rolled out to a thickness of about 1/3 mil. During rolling, the mill was heated by infra-red lamps, and the
foil was placed in a hot stainless steel sandwich, which was kept well oiled. Although very thin, the zinc foil was self-supporting and required no backing material.

The mass and area of the foil were carefully measured to give $6.465 \text{ mg/cm}^2$, which corresponds to an average thickness of 0.364 mil, just slightly larger than the desired 1/3 mil but nevertheless sufficiently thin so that 10 MeV protons produced at the center would be degraded in energy by no more than 90 keV.

For use in the target chamber, the zinc-64 foil was taped to a light aluminum frame on a plastic base. As shown in Figure 2, the plane of the foil made an angle of 45° with the incident beam.

3.2 Irradiation of the Zinc-64

At the Los Alamos EPA during the period from June 2 to June 8, 1971, 27 different runs were started. Some were used for setting up and testing out the equipment, and some were aborted for one reason or another. Out of these, data from 15 runs were selected for analysis. The machine parameters for these runs are shown in Table I, and some other parameters are shown in Table II. The time allotted to each run was chosen to complete the experiment within the time available on the machine. During each run, spectra were obtained at the four angles: 45°, 90°, 135°, and 160°. Run 15, which was not used, was aborted early because of an operator error. After the background runs were completed, some additional time was available on the EPA, so a second run, number 27, was done at the bremsstrahlung endpoint energy of 15.2 MeV. For later analysis run 27 was combined with run 18, also at 15.2 MeV.
Table I. Machine parameters for the various runs.

<table>
<thead>
<tr>
<th>Run number</th>
<th>rf power (kW)</th>
<th>rf pulse length (µs)</th>
<th>Electron beam current (mA)</th>
<th>Beam pulse length (µs)</th>
<th>P2 current (µA)</th>
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</thead>
<tbody>
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<td><strong>Zinc runs</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>800</td>
<td>550</td>
<td>2.2</td>
<td>480</td>
<td>0.26</td>
</tr>
<tr>
<td>13</td>
<td>687</td>
<td>500</td>
<td>2.1</td>
<td>470</td>
<td>0.23</td>
</tr>
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<td>14</td>
<td>540</td>
<td>600</td>
<td>2.4</td>
<td>400</td>
<td>0.20</td>
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<tr>
<td>16</td>
<td>420</td>
<td>550</td>
<td>7.5</td>
<td>450</td>
<td>0.28</td>
</tr>
<tr>
<td>17</td>
<td>360</td>
<td>550</td>
<td>10.0</td>
<td>470</td>
<td>0.28</td>
</tr>
<tr>
<td>18</td>
<td>285</td>
<td>550</td>
<td>7.0</td>
<td>480</td>
<td>0.10</td>
</tr>
<tr>
<td>19</td>
<td>560</td>
<td>580</td>
<td>6.0</td>
<td>480</td>
<td>0.20</td>
</tr>
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<td>500</td>
<td>0.20</td>
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<td>500</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>800</td>
<td>580</td>
<td>5.0</td>
<td>500</td>
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<td>480</td>
<td>0.20</td>
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<td>300</td>
<td>580</td>
<td>5.5</td>
<td>500</td>
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Table II. Monitored parameters for the various runs.

<table>
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<tr>
<th>Run number</th>
<th>Time (min)</th>
<th>P2 scaler</th>
<th>Bar. press. before (in-Hg)</th>
<th>Bar. press. after (in-Hg)</th>
<th>$E_O$ (MeV)</th>
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<tr>
<td><strong>Zinc runs</strong></td>
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<td>132.50</td>
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<td>22.98</td>
<td>25.0</td>
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<td></td>
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<td>22.93</td>
<td>25.0</td>
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<td>09924</td>
<td>22.87</td>
<td>22.93</td>
<td>15.2</td>
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</table>
The photoproton spectra from the Si(Li) detectors for the zinc runs are presented in Figures 4 through 7. For these runs the zinc-64 target foil was placed at the center of the evacuated target chamber. The proton energy calibration which will be discussed in Section 4.4 was used on the abscissas. The square root of the reduced counts, which means the number of counts per 0.01 Coul of corrected charge collected in the P2 chamber, was used on the ordinates. The corrected charge is listed in Table III and will be further explained in Section 4.3. The square root plots in Figures 4 through 7 were used to make the statistical error bars equal over all parts of the graphs.

The effects of the lower level cutoffs of the SCA's can be seen at the low energy ends. The large low energy tails were due to the electron background, and the results of subtracting the backgrounds will be shown in Section 4.1. The background was due to pile-up of high energy electrons in the Si(Li) detectors. This will be discussed further in Section 3.4. As there was no significant background above 7 MeV, the true proton spectra are exhibited in this region.

3.3 Oxygen Calibration Run

The spectra from the Si(Li) detectors for run 22 are presented in Figures 8 and 9. For this run the chamber was filled with oxygen to a pressure of 20 in-Hg; of course, the zinc foil was not in position. Figures 8 and 9 exhibit the well known oxygen photoproton spectrum (25). The square root display on the ordinate was used to give a constant size error, the magnitude of which is 1/2.
Table III. Bremsstrahlung beam characteristics.

<table>
<thead>
<tr>
<th>Run number</th>
<th>P2 counts</th>
<th>Corrected charge (Coul)</th>
<th>Total integrated beam energy (MeV)</th>
<th>Total number of photons</th>
</tr>
</thead>
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<tr>
<td>Zinc runs</td>
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<td></td>
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<tr>
<td>12</td>
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<td>0.0068270</td>
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<td>56132</td>
<td>0.0070277</td>
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<td>0.233468 E 16</td>
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<tr>
<td>14</td>
<td>39126</td>
<td>0.0049103</td>
<td>0.125634 E 17</td>
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<tr>
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<td>0.136211 E 17</td>
<td>0.215968 E 16</td>
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<tr>
<td>17</td>
<td>40569</td>
<td>0.0051047</td>
<td>0.130660 E 17</td>
<td>0.221420 E 16</td>
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<tr>
<td>18</td>
<td>13408</td>
<td>0.0017031</td>
<td>0.043604 E 17</td>
<td>0.082882 E 16</td>
</tr>
<tr>
<td>19</td>
<td>29616</td>
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<td>0.143327 E 16</td>
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<tr>
<td>20</td>
<td>46339</td>
<td>0.0057921</td>
<td>0.148178 E 17</td>
<td>0.201138 E 16</td>
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<td>27</td>
<td>05525</td>
<td>0.0006899</td>
<td>0.017663 E 17</td>
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</tr>
<tr>
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<td>0.0041689</td>
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<tr>
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<tr>
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<td>0.167909 E 16</td>
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<td>0.085584 E 17</td>
<td>0.128389 E 16</td>
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<tr>
<td>26</td>
<td>09924</td>
<td>0.0012678</td>
<td>0.032459 E 17</td>
<td>0.061697 E 16</td>
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</table>
Figure 4. Dose corrected data from all zinc runs at 45°. Starting at the bottom the bremsstrahlung endpoint energies are: 15.2, 17.5, 18.9, 20.2, 21.4, 22.7, 23.9, 25.1, and 26.2 MeV.
Figure 5. Dose corrected data from all zinc runs at 90°. Starting at the bottom the bremsstrahlung endpoint energies are: 15.2, 17.5, 18.9, 20.2, 21.4, 22.7, 23.9, 25.1, and 26.2 MeV.
Figure 6. Dose corrected data from all zinc runs at 135°. Starting at the bottom the bremsstrahlung endpoint energies are: 15.2, 17.5, 18.9, 20.2, 21.4, 22.7, 23.9, 25.1, and 26.2 MeV.
Figure 7. Dose corrected data from all zinc runs at 160°. Starting at the bottom the bremsstrahlung endpoint energies are: 15.2, 17.5, 18.9, 20.2, 21.4, 22.7, 23.9, 25.1, and 26.2 MeV.
Figure 8. Oxygen photoproton spectra of run 22. Data from:
(a) the detector at 45°,
(b) the detector at 90°.
Figure 9. Oxygen photoproton spectra of run 22. Data from:
(a) the detector at $135^\circ$,
(b) the detector at $160^\circ$. 
The spectrum of Figure 8(a) from the 45° detector goes off-scale at the left end because of the large electron background. The 160° detector also had a large background, shown in Figure 9(b), because it saw a rather long cylinder of oxygen in the beam.

The prominent peaks were fitted, and the centroids used for the proton energy calibration. This procedure will be described in Section 4.4.

3.4 Background Runs

The four background runs were done with each detector shielded from the zinc foil by a 50 mil aluminum plate, which was thick enough to stop protons of all energies detected in the foreground runs. Clearly, the background is due to electrons. A relativistic electron traveling normal to the surface of the detector would have lost about 0.7 MeV, and a high peak at that energy was observed in early singles spectra, but the lower levels of the SCA's were above that for all runs used for analysis.

The background spectra are presented in Figures 10 through 13 as semi-logarithmic plots. The logarithmic scale represents the number of counts per 0.01 Coul of corrected charge collected in the P2 chamber. The method of calculating the corrected charge will be described in Section 4.2. Each curve is displaced above the one lower by one logarithmic cycle with the base line at the right at the level of one. Each curve in Figure 10 runs from one up to about 10^5.

When dose corrected, all background spectra for all angles and all runs seem to be nearly exponential and of nearly the same slope. The logarithmic scale was chosen to exhibit these properties. The error bars
Figure 10. A logarithmic plot of the dose corrected background data from the detector at 45°. The bremsstrahlung endpoint energies are: (a) 25.0 MeV, (b) 23.2 MeV, (c) 20.2 MeV, and (d) 15.2 MeV.
Figure 11. A logarithmic plot of the dose corrected background data from the detector at 90°. The bremsstrahlung endpoint energies are: (a) 25.0 MeV, (b) 23.2 MeV, (c) 20.2 MeV, and (d) 15.2 MeV.
Figure 12. A logarithmic plot of the dose corrected background data from the detector at 135°. The bremsstrahlung endpoint energies are: (a) 25.0 MeV, (b) 23.2 MeV, (c) 20.2 MeV, and (d) 15.2 MeV.
Figure 15. A logarithmic plot of the dose corrected background data from the detector at $160^\circ$. The bremsstrahlung endpoint energies are: (a) 25.0 MeV, (b) 23.2 MeV, (c) 20.2 MeV, and (d) 15.2 MeV.
are quite large near the base lines, and the points plotted on the base lines were really null counts, but no plotting below the graphs was permitted. The bremsstrahlung endpoint energies of the background runs were 25.0, 23.2, 20.2, and 15.2 MeV. Even with this large change in the bremsstrahlung endpoint, the spectrum from any one detector remained the same to within statistical errors.
IV. DATA ANALYSIS

4.1 Background Subtractions

Since the background for each individual detector was found to be independent of the electron beam energy, the four background runs for each detector were averaged, thereby reducing the statistical error by 50%.

Prior to the channel by channel subtraction of the background from the zinc runs all data had been normalized to counts per 0.01 Coul of corrected charge from the P2 chamber.

The only exception was that the background at 45° was reduced by 49% before subtraction. This was necessary because at this small angle with the incident beam, additional electrons were knocked out of the aluminum shield in front of the detector. The factor used for the reduction resulted from the criterion that the background subtraction should produce no negative values in any spectrum. When the same criterion was applied at 90°, 135° and 160°, no significant change from the results of direct subtraction was found.

The resulting photoproton spectra with background subtracted are presented in Figures 14 through 17. The solid curves were drawn by a computer subroutine which used four point smoothing with no account taken of statistical errors. These solid curves were used for display only and not for any numerical calculations.

One of the features which remained after background subtraction was the peak at 2.7 MeV in Figure 15. Using the method outlined in Section 4.4, the expected energy spread of monoenergetic protons due to the thickness of the zinc foil was calculated, and found to be in good
Figure 14. Dose corrected data with background subtracted for the detector at 45°. The ordinate represents the number of counts per 0.01 Coul of corrected charge from the P2 chamber. Starting at the bottom the bremsstrahlung endpoint energies are: 15.2, 17.5, 18.9, 20.2, 21.4, 22.7, 23.9, 25.1, and 26.2 MeV.
$^{64}$Zn $(\gamma, p)^{63}$Cu

45° spectra
Figure 15. Dose corrected data with background subtracted for the detector at 90°. The ordinate represents the number of counts per 0.01 Coul of corrected charge from the P2 chamber. Starting at the bottom the bremsstrahlung endpoint energies are: 15.2, 17.5, 18.9, 20.2, 21.4, 22.7, 23.9, 25.1, and 26.2 MeV.
$^{64}\text{Zn} \ (\gamma, p)^{63}\text{Cu}$

$90^\circ$ spectra
Figure 16. Dose corrected data with background subtracted for the detector at 135°. The ordinate represents the number of counts per 0.01 Coul of corrected charge from the P2 chamber. Starting at the bottom the bremsstrahlung endpoint energies are: 15.2, 17.5, 18.9, 20.2, 21.4, 22.7, 23.9, 25.1, and 26.2 MeV.
$^{64}_{\text{Zn}} (\gamma, p)^{63}_{\text{Cu}}$

$135^\circ$ spectra
Figure 17. Dose corrected data with background subtracted for the detector at 160°. The ordinate represents the number of counts per 0.01 Coul of corrected charge from the P2 chamber. Starting at the bottom the bremsstrahlung endpoint energies are: 15.2, 17.5, 18.9, 20.2, 21.4, 22.7, 23.9, 25.1, and 26.2 MeV.
$^{64}_{\text{Zn}} \, (\gamma, p)^{63}_{\text{Cu}}$

160° spectra
agreement with the width of the peak. The fact that a thin absorber removed the peak was convincing evidence that the peak was due to protons. Several other features are evident, but before the proton spectra are further analyzed, some subsidiary calculations will be described.

4.2 Photon Beam Calibrations

A rough calibration curve for the EPA, which gave electron energy versus rf power when operating at a 6% duty factor, was available; however for the zinc-64 experiment the duty factor was usually nearer 6.5%, so it was necessary to read the calibration at an rf power reduced by about 10%. Although not very accurate this was used in early runs for setting up the machine for a particular energy, and this resulted in non-integral energy values. Later runs, for which a better calibration was available, were done at energies which interlaced with the energies of the earlier runs, so all bremsstrahlung endpoint energies are non-integral.

The most accurate means of obtaining the bremsstrahlung endpoint was provided by a small oxygen filled chamber with a single Si(Li) detector placed just ahead of the target chamber. The oxygen photoproton spectrum was continuously recorded during each run on a separate pulse-height analyzer, and the endpoint of the spectrum was noted. The bremsstrahlung endpoint energy was then determined by comparison with the known oxygen photoproton spectrum (25).

The output of the NMR probe, described in Section 2.1, proved to be very linear with machine energy, but this was not known until a calibration was established with the oxygen photoproton spectra of the early runs. For later runs the NMR output was useful in setting the machine
energies prior to taking data.

A computer program was written to calculate the average energy per photon in the beam passing through the hardening material, which consisted of 15 in. of polyethylene. The initial photon distribution was obtained from the Schiff function. The composition of the polyethylene was assumed to be:

0.131 gm/cm$^3$ of hydrogen,
0.789 gm/cm$^3$ of carbon.

The atomic cross section for photoelectric processes was approximated as

$$\tau = \frac{5.656 \varepsilon Z^5 E^{-7/2}}{137^4}$$

where $E$ is the photon energy, $Z$ is the atomic number, and

$$\varepsilon = 6.651 E^{-25} \text{ cm}^2.$$

The atomic cross-section for pair production was approximated above 2.5 MeV as

$$\kappa = \frac{3}{8} \frac{\varepsilon Z^2}{\pi 137} (2.713 \log(E) - 4.367),$$

and was neglected at lower energies.

The atomic cross section for Compton scattering was approximated as

$$\sigma = 0.75 \varepsilon Z \left(\frac{\log(1+2E)(E^2-2E-2)}{2E(1+2E)} + \frac{2(1+E)^2}{(1+2E)E^2} - \frac{(1+3E)}{(1+2E)^2}\right).$$

The effect of the beam hardening material can be seen in Figure 18, in which is shown the relative intensity distribution (a) before and (b)
Figure 18. The relative bremsstrahlung intensity spectra with $E_0 = 22.7$ MeV:
(a) without beam hardening material,
(b) with 15 in of polyethylene in the beam.
after the beam hardener. The upper curve (a) was obtained from the equation $\text{BS}(e)$ of Koch and Motz (44), and the lower curve (b) was calculated with the attenuation of the atomic cross sections just described. At the endpoint energy of 22.7 MeV, only about 10% of the photons in the original beam were passed through the beam hardening material, but there was no problem in producing plenty of beam from the EPA.

The computer program described above was used to calculate the average energy per photon for each bremsstrahlung endpoint energy. This was then divided into the total integrated beam energy, listed in Table III, to obtain the total number of photons passing through the zinc-64 foil for each run, also listed in Table III.

4.3 Dose Monitor Response Corrections

The bremsstrahlung beam monitoring system employed a replica of the type P2 ionization chamber designed and calibrated at the National Bureau of Standards (24). In the zinc-64 experiment, photon beams were used with endpoint energies between 15 MeV and 27 MeV, intensities of about 100 $\mu\text{W/cm}^2$, and beam diameter of about 10 cm at the P2 chamber. The P2 chamber was well calibrated for these conditions, and a calibration curve was available from which the total integrated beam energy could be obtained (26).

The charge from the P2 chamber was collected and measured with an Ortec current digitizer, which gave a pulse for each $10^{-10}$ Coul of charge. These pulses were counted by a TSI scaler of eight decimal digits with only the five most significant digits being recorded.
Before using the calibration curve for the P2 chamber, it was necessary to apply several corrections to include the effects of: barometric pressure, temperature, dead time, radius of the beam, and filtering by the beam hardening material. These corrections, carried out according to NBS Monograph 48, will be discussed now.

The largest correction was for barometric pressure. The P2 chamber was open to the atmosphere, and because of the high altitude at Los Alamos (7200 ft), atmospheric pressure was only about 580 mm-Hg, which was far below the 760 mm-Hg of the P2 calibration curve. Barometric readings were taken to the nearest 0.01 in. at the start of each run, as recorded in Table II, and a simple average of the pressures before and after each run was used. The temperature at the P2 chamber remained at a constant 18.5°C for all runs, while the calibration curve was given at 22°C. The ideal gas law was used to make temperature and pressure corrections, which together averaged +30%.

The charge from the P2 chamber was compensated for the hardened beam by multiplying by \((0.985 + 0.00038 E_0)\), where \(E_0\) is the bremsstrahlung endpoint energy, and this resulted in an average correction to the collected charge of -.7%. The correction factors in this paragraph and the next are linear approximations to graphical data presented by Pruitt and Domen (24).

The calibration depended on beam size because the fraction of the radiation which was scattered in the thick front wall of the P2 chamber increased with larger beam diameters. A photon beam of radius 5.1 cm at the P2 chamber was used. This was larger than the 2.1 cm beam used for
the calibration curve. The size of the beam was determined by placing Polaroid films on the two ends of the target chamber and extrapolating the spread in the beam out to the P2 chamber. The correction factor was approximated as \((1.0053 - 0.00013 E_0)\) and resulted in an average correction to the collected charge of +0.36%.

It was necessary to calculate the fractional dead time of the photoproton data channels and correct the P2 charge accordingly. Although the counting rate averaged only 40 cps, the 6% duty factor and dead time per pulse of about 30 \(\mu\)s resulted in an average correction to the collected charge of -2%.

The dead time per analyzed pulse in the MCA was given by

\[
t_d = (15 + 0.08 C) \mu s,
\]

where \(C\) was the channel number which ran from 0 to 255. Each analyzed proton pulse created a dead time on all four inputs of 30 \(\mu\)s due to the action of the multiplexer, but if the analyzed pulse went above channel 187, where \(t_d = 30 \mu s\), the extended dead time calculated from \(t_d\) was used. Clock pulses were stored in channel zero with a dead time of 15 \(\mu\)s each, but only 6% could have occurred during beam pulses.

The total beam time for each run was calculated from the clock time and the duty factor, which was a function of the beam pulse length in Table I. The ratio of the total dead time to the total beam time was the fraction by which the charge from the P2 chamber was corrected.

In the region of interest the P2 dose calibration curve (26) could be expressed as
\[ C = (3.885 + 0.0176 \log_{10}(E_0)) \times 10^{-18} \text{Coul/MeV} \]

for \(^{22}\text{C}\) and 760 mm-Hg. This was used after all the above corrections had been applied, and the total integrated energy of the beam which passed through the zinc-64 sample was obtained. This is shown in Table III.

### 4.4 Proton Energy Calibration

Before beam time was available, an \(^{241}\text{Am}\) alpha source was placed in the evacuated target chamber so that alpha particles could be detected in the \(90^\circ, 135^\circ,\) and \(160^\circ\) detectors. The output of a precision pulser was matched to the 5.476 MeV alpha pulses, which gave a rough estimate of the energy scales. Because the alphas could be degraded in energy by the source thickness or by a thin dead layer on the detectors, this method was not expected to give an accurate energy calibration; however the calibration with oxygen was not available until the end of the experiment.

The linearity of each of the four systems was measured with the pulser by finding peak positions for twenty points corresponding to energies from 2 MeV to 20 MeV. A fifth order polynomial was fitted to the points and gave an average error of 30 keV, which was less than half a channel width.

The energy scales were given a linear correction using energy values obtained from the oxygen photoproton spectra of run 22. The oxygen cross section has peaks at 20.85, 22.15, 22.95, and 24.15 MeV which produced peaks in the photoproton spectra of Figures 8 and 9. The solid curves in these figures were for display only and were not good fits, especially in the case of the photoproton peak due to the 22.95 MeV peak in the
cross section. To find the proton energies the above four energies were reduced by the mass difference, 12.13 MeV, and kinematically shared with the residual nitrogen nucleus. Furthermore, the energies were reduced to account for energy loss in passing through the oxygen using the equation

\[ \frac{-dE}{dx} = \frac{0.61144 + 0.09672 \log E}{E} \]

At this point the energy scales represented the true energies of the protons detected, but an additional adjustment was necessary to account for loss within the zinc-64 foil.

For the detectors at 45° and 135°, which viewed the foil normally, the foil half-thickness of 0.4623 \( E \) cm was used, and the energy loss was calculated from

\[ \frac{-dE}{dx} = \frac{A (\log(BE))^2}{2 E \log(BE) - E} \]

with

\[ A = 873.03 \text{ MeV}^2/\text{cm}, \]

\[ B = 4.1 \text{ MeV}^{-1}. \]

The parameters \( A \) and \( B \) were determined from a fit to published proton range graphs (27). Typical energy losses were:

<table>
<thead>
<tr>
<th>initial energy</th>
<th>energy loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 MeV</td>
<td>172 keV</td>
</tr>
<tr>
<td>6</td>
<td>128</td>
</tr>
<tr>
<td>8</td>
<td>103</td>
</tr>
<tr>
<td>10</td>
<td>87</td>
</tr>
</tbody>
</table>

For the 90° detector the above half-thickness was divided by \( \cos(45°) \), and for the 160° detector it was divided by \( \cos(25°) \).
4.5 Yields

In preparation for using the computer program Cook's Least Structure Routine (CLSR) (28,29) to calculate cross sections, the yields, which were needed for input data, were determined. All necessary data for finding absolute cross sections were available. The yields were calculated with the formula:

\[
\text{Yield} = \left(\frac{\text{beam area}}{\text{no. Zn nuclei}}\right) \left(\frac{1}{\text{solid angle \times eff.}}\right) \left(\frac{\text{no. protons}}{\text{no. photons}}\right)
\]

where the various factors are described below.

The first set of parentheses enclose a factor which is constant for all runs. The area of the beam, which was found by exposing Polaroid films on either end of the target chamber, was 21.56 cm\(^2\) at the position of the foil and normal to the beam. Because the zinc-64 foil was placed at 45°, the beam illuminated an ellipse of area 30.49 cm\(^2\). Since the mass per unit area of the foil was 6.465 mg/cm\(^2\), the mass of zinc-64 in the beam was 197.1 mg. Taking the atomic weight of zinc-64 to be 63.929 gm/mole, the number of zinc-64 nuclei in the beam was calculated to be 19.568 E 20 nuclei.

The second set of parentheses enclose a factor which depends only on the detectors. The procedure for calculating the solid angles subtended by the detectors was straightforward. The 160° detector was 46.3 cm from the center of the zinc-64 foil, while the other three detectors were only 38.1 cm from the foil. Each detector had a circular mask which prevented protons from entering near the outer edges of the detectors. The mask radii were 0.700, 0.744, 0.800, and 0.742 cm. From these parameters the following solid angles were calculated:
45° 1.0605 E -3 steradian
90° 1.1980 E -3 steradian
135° 1.3851 E -3 steradian
160° 0.8069 E -3 steradian.

Because of the large beam size, all but one of the detectors were shadowed somewhat from the extreme ends of the illuminated ellipse on the foil due to the geometry of the scattering chamber. The geometrical efficiencies as a result of this shadowing were calculated to be 78.52%, 96.63%, 78.54%, and 100% for the 45°, 90°, 135°, and 160° detectors respectively.

The third set of parentheses enclose a factor which varies from run to run. The numbers of protons above selected energies were determined for each zinc run. The numbers of photons were obtained from Table III.

Some of the yields are shown in Figures 19 and 20. Only protons with energies greater than 8 MeV were included in the yields of Figure 19. The angular distribution is seen to be definitely not isotropic for these high energy protons. The protons in the 4 MeV wide bin from 4 MeV to 8 MeV, which straddles the hump in the proton spectra, were included in the yields of Figure 20. At the lower bremsstrahlung endpoint energies the angular distribution is essentially isotropic, but the higher endpoint energies give rise to some interesting distributions. An extended discussion of the angular correlation will be given in Section 4.7.

4.6 Cross Sections

The cross sections were calculated by means of the computer program CLSR (28,29), which has been extensively used for this purpose. For the present application two modifications were required. First, it was
Figure 19. Yields of protons with $E_p > 8$ MeV for several bremsstrahlung endpoint energies.
Figure 20. Yields of protons with $4 \text{ MeV} < E < 8 \text{ MeV}$ for several bremsstrahlung endpoint energies.
necessary to have the revised program accept yields at irregularly spaced energies, but the cross sections were still calculated with even spacing. Second, the number of points at which the cross section was calculated was greater than the number of yield points. It must be emphasized that regardless of the number of output points, no greater detail was revealed than could be resolved by the separation of the bremsstrahlung endpoint energies of the yield points. An advantage of better smoothness was achieved with the greater number of points in the cross section because the weighted sum of the second differences was chosen as the smoothing function.

In the theory of CLSR a variational problem is solved to give, in matrix form,

\[ Y = (N + \lambda(N)^{-1} W^{-1} S) \sigma \]

where

- \( Y \) is a vector of the yields,
- \( N \) is the bremsstrahlung matrix,
- \( \lambda \) is the variational parameter,
- \( W \) is diagonal with elements \( W_{ii} = (1/\Delta Y_i)^2 \),
- \( S \) is the smoothing matrix which picks out squares of second differences in \( \sigma \),
- \( \sigma \) is a vector of the calculated values of the cross section.

In the usual case we can write for simplicity

\[ Y = M\sigma, \]

and the solution is
\[ \sigma = M^{-1} Y, \]
because \(M\) is a square matrix. In CLSR, solutions are obtained for different values of \(\lambda\) until the chi-squared test
\[
\chi^2 = \sum_{i=1}^{n} \frac{(y_i - \bar{y}_i)^2}{(\Delta y_i)^2} = n
\]
is satisfied.

For the analysis of this paper the computer code of CLSR was modified so that a rectangular \(M\) matrix could be used. The solution was
\[
\sigma = (\hat{M} M)^{-1} \hat{M} Y,
\]
and iterations with different \(\lambda\)'s were performed until the same chi-squared test was satisfied.

A discussion of the performance of CLSR as compared to other methods of unfolding yields curves has been given by Bramanis et al. (30).

The cross sections at the four angles, shown in Figures 21 through 24, are for the production of protons with energies greater than 4 MeV. This lower energy limit was chosen for two reasons. First, the discriminator after the \(45^\circ\) detector had to be set at nearly 4 MeV because of the very high background at this angle, so it was necessary for purposes of comparison to use this same low energy limit at all angles. Data at lower energies was available from the other angles, and the added information obtained from that data will be presented later. Second, by not including the lower energy protons, it was assured that only protons from the \((\gamma,p)\)
Figure 21. Photoproton cross section at $45^\circ$ for production of protons with $E_p > 4 \text{ MeV}$. 
Figure 22. Photoproton cross section at 90° for production of protons with $E_p > 4$ MeV.
Figure 25. Photoproton cross section at $135^\circ$ for production of protons with $E_p > 4$ MeV.
Figure 24. Photoproton cross section at $160^\circ$ for production of protons with $E_p > 4$ MeV.
Figure 25. Total cross section for production of protons with $E_p > 4$ MeV.
process would be counted, and few protons from the \((\gamma,\text{pn})\) or \((\gamma,\text{2p})\) processes would be included. By extrapolation of the photoproton energy spectra, it was estimated that 85% of the protons had energies above 4 MeV.

It is obvious that there is increased reaction strength in three regions of excitation energy, 16 MeV, 19 MeV, and 22 MeV, and that the angular distributions for these three regions are different. In later sections of this paper arguments will show that the 16 MeV region can be assigned to the \(T_\text{<}\) giant dipole resonance, the 19 MeV region can be assigned to the \(T_\text{>}\) giant dipole resonance, and the 22 MeV region can be assigned to the giant quadrupole resonance.

The cross section for the production of protons with kinetic energies greater than 8 MeV is shown in Figure 26. The magnitude of the 19 MeV peak indicates that about 30% of the reactions in this region may leave the residual copper-63 nucleus in the ground state. The 22 MeV peak also appears in Figure 26.

The separation energies for single particles from zinc-64 are:

\[
\begin{align*}
(\gamma,\alpha) & \quad 4.0 \text{ MeV} \\
(\gamma,p) & \quad 7.7 \text{ MeV} \\
(\gamma,\pi) & \quad 11.9 \text{ MeV} \\
(\gamma,^3\text{He}) & \quad 16.7 \text{ MeV} \\
(\gamma,t) & \quad 19.0 \text{ MeV}.
\end{align*}
\]

The first reaction may amount to four or five percent of the total gamma absorption cross section and has been investigated by Hoffmann et al. (31), who found the photoalpha spectrum to be a maximum near 8 MeV. For the present work the thickness of the foil, the low energy limit of 1 MeV, and the small \((\gamma,\alpha)\) cross section were deemed sufficient to reduce the number
Figure 26. Total cross section for production of protons with $E_p > 8$ MeV.
of alphas detected to a negligible amount. The second reaction is the one under investigation. The third reaction produces neutrons which would not be detected. The cross sections for the last two reactions are less than 0.1% of the total cross section (42).

The separation energies for two particles emitted from zinc-64 are:

\[(\gamma, 2p) \quad 13.8 \text{ MeV} \]
\[(\gamma, np) \quad 18.6 \text{ MeV} \]
\[(\gamma, 2n) \quad 21.0 \text{ MeV}. \]

The first reaction may have contributed counts to the proton spectra, but no attempt was made to remove them. Assuming the energy is evenly divided in the second reaction, it is not energetically possible to have observed the protons since that would require an excitation energy of 26.6 MeV to give a 4 MeV proton. The third reaction would not be detected.

A comparison of the \((\gamma,p)\) cross section from the present experiment with the sum of the \((\gamma,n)\), \((\gamma,np)\) and \((\gamma,2n)\) cross sections of Schamber (12) is shown in Figure 27. Both curves have approximately the same energy resolution, about 1 MeV. The behavior at 16 MeV and 19 MeV is easily explained if the \(T_\lambda^\right\) and \(T_\lambda^\left\) giant dipole resonances are at these energies. The great enhancement of the 19 MeV peak in the \((\gamma,p)\) cross section is then due to the isospin selection rules, which forbid neutron decay from the \(T_\lambda^\right\) = 3 states in zinc-64 to the \(T_\lambda^\left\) = 3/2 states in zinc-63 but permit proton decay to either the \(T_\lambda^\left\) = 5/2 or \(T_\lambda^\right\) = 7/2 states in copper-63.

A calculation has been done by Arenhövel and Weber (32) using the dynamic collective model, in which low energy quadrupole vibrations of the nuclear surface are coupled to the giant dipole oscillations. The resulting
Figure 27. A comparison of the $^{64}$Zn $(\gamma,p)^{63}$Cu cross section of this work with the $(\gamma,n + np + 2n)$ cross section of Schamber (12).
Figure 28. Total photodisintegration cross section of zinc-64.
TOTAL CROSS SECTION (mb)
theoretical cross section for zinc-64 shown in Figure 29 has four peaks between 15 MeV and 20 MeV, and similar structure appears in the experimental (γ,n) cross sections of Costa et al. (21) and Owen et al. (22). The theoretical cross section of Huber shown by Owen et al. is incorrect because it misses entirely the reaction strength in the 16 MeV region. This was due to the use of a rather high energy of 20 MeV for the giant dipole resonance.

With some effort one can see some structure in the (p,γ) cross section of Paul et al. The resolutions of the (γ,n) cross sections of Schamber and the (γ,p) cross section of this work are not good enough to clearly reveal detailed structure, but it does show up somewhat even though highly smoothed over.

A curious feature is that the (γ,n) and (γ,p) cross sections as shown in Figure 27 do not peak at exactly the same energies. If the four peak structure for the total cross section calculated by Arenhövel and Weber (32) is assumed to be valid, and if the experimental cross sections are accurate, then it appears that the (γ,n) reaction strength is mainly in the two inner peaks while the (γ,p) reaction strength is mainly in the two outer peaks.

The inclusion of protons with kinetic energies less than 4 MeV results in a new feature of the cross section. It has been pointed out that the sharp peak near 3 MeV in the photoproton spectra at 90° and 160° is most likely due to nearly monoenergetic protons. The reason is that a thin absorber removes the peak, and the width is close to what one would expect due to the foil thickness and electronics. Assuming ground state
Figure 29. A comparison of the total photodisintegration cross section as calculated by Arenhövel and Weber (32) (solid curve) with the experimental cross section (points).
transitions, the peak in the photoproton spectra corresponds to an excitation energy of 11 MeV. A 1^- level in this region would be expected to make a strong appearance in the photoproton cross section because there is no competition from neutron emission, for which the threshold is at 11.86 MeV. Near 11 MeV proton emission is not excessively hindered by the Coulomb barrier or by competition from neutron emission, so the peak in the photoproton spectra is understandable.

4.7 Angular Distribution

The photoprons from zinc-64 were observed at four different angles, 45°, 90°, 135°, and 160°, so that some information could be obtained from the angular distribution, and this proved to be extremely important in analyzing the data.

In the region of 16 MeV the photoproton angular distribution was essentially isotropic. Since the reaction is undoubtedly electric dipole to a 1^- state, it must be assumed that in the region of excitation energy of 16 MeV mostly s-wave protons are produced. Because the f_{7/2} protons are expected to play a major role, it must be assumed that a great deal of mixing of states occurs before proton emission.

For the peak in the region of 19 MeV the normalized angular distribution is adequately described by 1 - 0.3 P_2(cos θ), where P_2(cos θ) is the second Legendre polynomial. For direct reactions the highest order Legendre polynomial with a non-vanishing coefficient is two as determined by the angular momentum of the excited 1^- state. Direct dipole reactions have the (A + B sin^2θ) distribution, so the angular distribution
is composed of up to but no more than about 76% compound nucleus formation, in which mostly s-wave protons are emitted. This agrees well with the estimate of 30% direct reactions given in Section 4.6.

The peak at 22 MeV has an angular distribution similar to what is shown in the high energy yield curves of Figure 20, but here the effect is more pronounced. This general shape can be described by a series of Legendre polynomials to fourth order, but in this case with only four angles, the coefficients cannot be determined. It is certain that the second order series is not enough; therefore we must conclude that the 22 MeV peak is probably due to electric quadrupole interactions.
V. CONCLUSIONS

5.1 Isospin Splitting of Zinc-64

The present measurement of the $^{64}\text{Zn}(\gamma,p)^{63}\text{Cu}$ cross section now enables one to construct a complete picture of the photodisintegration of zinc-64 in the region of the giant dipole resonance, and it is now possible to determine the magnitude of the energy separation of the isospin components with confidence.

The $T_\pi = 2$ giant dipole resonance has $E_\pi = 16$ MeV and the $T_\pi = 3$ giant dipole resonance has $E_\pi = 19$ MeV in zinc-64. These assignments are made on the basis of the shape of the photoproton cross section with the enhanced 19 MeV region and on the basis of the appearance of 16 MeV and 19 MeV peaks in the $(\gamma,n)$ and $(p,\gamma)$ cross sections.

The above assignments give an isospin energy splitting of

$$\Delta E = (3.0 \pm .5) \text{ MeV}$$

which is in agreement with the calculated values of Fallieros (9), Leonardi (10), and Paul (11). The value of $\Delta E = 7$ MeV by Schamber (12) was based on only the $(\gamma,n)$ and $(\gamma,np)$ cross sections, but the additional information obtained from the $(\gamma,p)$ and $(p,\gamma)$ experiments has not corroborated that value. In particular the absence of a peak at 25 MeV in the $(\gamma,p)$ cross section rules out that energy as the $T_\pi$ giant resonance.

An attempt has been made to explain the energy splitting in the $(\gamma,n)$ cross section of zinc-64 by deformation of the nucleus (33), but there is no experimental data which gives evidence of a permanent deformation of the
ground state. The low energy levels of this nucleus show the familiar equal spacing between the ground state, the $2^+$ first excited state, and the center of the $0^+, 2^+, 4^+$ triplet of levels, which is characteristic of vibrational nuclei, with no hint of a rotational level scheme. Furthermore, the theory for deformed nuclei predicts that the ratio of the two integrated components of the cross section should be two, which is not the case in zinc-64.

The sum rule of O'Connell quoted in Section 1.2 gives for zinc-64

$$\sigma_{-1}(T+1)/\sigma_{-1} = .26.$$ 

An attempt was made to fit two curves to the total cross section of Figure 28 to separate the isospin components. The bremsstrahlung weighted cross section was obtained by summing at 0.5 MeV intervals. The result was

$$\sigma_{-1}(T+1)/\sigma_{-1} = .2,$$

which is in remarkable agreement with the predicted value considering the crudeness of the calculation.

The ($\gamma$,n) cross sections of nickel-58 and nickel-60 also have a double hump shape in the region of 18 MeV, the former at 16 and 19 MeV and the latter at 17 and 21.5 MeV. An interpretation of these cross sections in terms of isospin splitting has been given by Min (34) but without the benefit of the complete photodisintegration picture as has been obtained for zinc-64.
5.2 Electric Quadrupole Giant Resonance

On the basis of the information from the angular correlation of this experiment, it is possible to assign the reaction strength at 22 MeV to the electric quadrupole giant resonance. The possibility of observing the E2 giant resonance in the (γ,p) reaction has been pointed out by Moringa (35). The simple hydrodynamic model predicts that the main E2 giant resonance should be near an energy 1.6 times the E1 giant resonance, which in this case would give 26 MeV; however this model is not expected to apply to zinc-64 with accuracy. The theoretical treatment of Ligensa et al. using the dynamic collective model predicts five major E2 giant resonances which are degenerate in spherical nuclei. The parameters of the problem are fixed by the energy of the giant dipole resonance and the lower energy levels of the nucleus with no free parameters. Calculations for $^{159}$Tb, $^{165}$Ho, and $^{166}$Er (36) give the five E2 giant resonances between 20 MeV and 25 MeV and agree well with experimental data.

The magnitude of the E2 giant resonance is expected to be about 7% of the giant dipole resonance (37).

No calculations have been done for zinc-64, but presumably the energy and magnitude of the E2 giant resonance will be similar to those given, although zinc-64 is not in the deformed region. In this regard the 22 MeV of the present work is a reasonable energy. From the data of Figure 28, the 22 MeV peak has about 1.5% of the area of the total cross section, which is somewhat smaller than the predicted 7% for heavy, deformed nuclei.

A question arises as to why there is no peak at 22 MeV in the (γ,n)
cross section of Schamber in Figure 27 since the E2 giant resonance should appear in both the $(\gamma,p)$ and $(\gamma,n)$ cross sections. The higher resolution $(\gamma,n)$ experiment of Owen et al. (22) does show a peak at 22 MeV, which combines with the present work to give a magnitude of about 3% of the giant dipole resonance, again lower than the predicted 7%; however no better agreement with theory can be expected because the calculations were done for heavy, deformed nuclei, and zinc-64 is a medium weight, spherical nucleus.

The fact that no 22 MeV peak occurs in the calculation of the dipole cross section by Arenhövel and Weber (32) provides further encouragement to assign this peak to the E2 giant resonance.

The above argument shows that the assignment of the E2 giant resonance to the 22 MeV peak with a magnitude of a few percent of the total photodisintegration cross section is in agreement with available theory. In addition, the angular correlation demands this assignment.

5.3 Total Photodisintegration Cross Section

The integrated photoproton cross section to 26 MeV is $160 \pm 2$ MeV-mb. The cross section of Schamber (12) was normalized to that of Owen et al. (22) who quoted 360 MeV-mb when integrated to 23 MeV. When the integral is extended to 26 MeV, Schamber's cross section gives 411 MeV-mb; therefore the total cross section integrated to 26 MeV is 571 MeV-mb with the $(\gamma,p)$ cross section accounting for 28% of the total. The classical dipole sum rule gives 60 NZ/A which is 956 MeV-mb for zinc-64, so the experimental total cross section integrated to 26 MeV is 60% of the dipole sum.
An attenuation experiment which gives the total photonuclear cross section has been done on several elements by Wyckoff et al. (38). Zinc was not done, but the neighboring element copper was shown to have a cross section integrated to 26 MeV of about 78% of the dipole sum. A photoneutron experiment by Costa et al. (39) gave the result that the integrated cross section to 30 MeV for natural zinc is 11% less than that of natural copper. Reducing the copper cross section integrated to 26 MeV of Wyckoff et al. by this amount gives 69% of the dipole sum. This is reasonably close to the value of 68% from the present work.

A calculation of the total dipole photo-absorption cross section of zinc-64 using the dynamic collective model has been done by Arenhövel and Weber (32). In this model the low energy quadrupole vibrations of the nuclear surface are strongly coupled to the giant dipole oscillations. The result shown in Figure 29 was obtained from the following parameters:

\[ E_1 = 17.8 \text{ MeV} \]
\[ E_2 = 0.99 \text{ MeV} \]
\[ \beta_o = 0.25 \]
\[ \Gamma = 1.5 \text{ MeV} \]

\( E_1 \) and \( E_2 \) are the energy of the giant dipole resonance and the spacing of the low-lying levels. The value of \( \beta_o \) is given by the reduced transition probability

\[ B(E2, 0^+ \rightarrow 2^+) = \left( \frac{3}{4} \frac{Z}{A} r_o^2 \right)^2 \beta_o^2 \]

and \( \Gamma \) is the common width used for the various giant resonance states.

Although the fit to the experimental points is only fair, it does
appear that with some adjustment of the parameters this model could adequately explain the spreading of the giant dipole resonance into several main states within a 5 MeV interval.

It is of interest to compare the results of this work with experiments on the neighboring element copper for which there is only one proton in the 2 $p_{3/2}$ level instead of two. Ratner (40) has given a cross section for $\text{Cu}(\gamma,p)\text{Ni}$ which shows three peaks at 12.5, 16.5, and 20.5 MeV. The lowest energy peak could correspond to the spike in the zinc-64 cross section at 11 MeV, and the other two peaks could correspond to the 16 and 19 MeV peaks in zinc-64. The magnitudes of the two cross sections are also comparable. Ratner's copper photoproton cross section is 22 mb at the 20.5 MeV peak, while the peak at 19 MeV in the zinc-64 cross section is $22.8 \pm .5$ MeV. These striking similarities lead to the conclusion that the major contributions to the photoproton cross section are due to protons in the 1 $f_{7/2}$ level, and adding a proton in the higher 2 $p_{3/2}$ shell has only a small effect.

A cross section for the sum of the reaction $(\gamma,n + 2(\gamma,2n) + \gamma,np)$ on copper has been measured by Fultz et al. (41). Here again the shape and magnitude of the copper photoneutron cross section is very similar to that of zinc-64.

In conclusion, the present experimental work has completed the photodisintegration picture of zinc-64 in the region of the giant resonance, and reasonable explanations of the contributing processes have been given.
VI. LITERATURE CITED


VII. ACKNOWLEDGMENTS

I wish to express my gratitude to the many people without whose encouragement, suggestions, and assistance this work would not have been possible. In particular I am deeply indebted to the following people:
Dr. D. J. Zaffarano for his guidance and support throughout my graduate career at I.S.U. Dr. R. C. Morrison, my major professor, for suggesting the project and greatly helping in all phases. Dr. B. Beaudry for working out the method of chemical separation. H. Jensen for melting the zinc metal. Dr. T. Scott and C. Owens for rolling the metal into a foil.
Dr. B. C. Cook, H. Vander Molen, G. Keith and especially Dr. J. E. E. Baglin for assistance in taking the data at Los Alamos. J. Busick and the staff at Los Alamos for their help and hospitality. In addition helpful suggestions were made by Dr. E. V. Fuller, Dr. E. Hayward and Dr. J. S. O'Connell of the National Bureau of Standards.

I especially wish to thank Carol Kline who carefully typed the thesis.