THE SCATTERING OF 10-MEV PROTONS ON CARBON AND MAGNESIUM

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ABSTRACT

In order to study the mechanism of excitation of nuclear levels by inelastic scattering, a scattering chamber of 36-inch diameter was constructed. The deflected beam of the Berkeley 60-inch cyclotron was brought out of the shielding by means of strong focusing magnets. Particles from the nuclear reactions were detected by either of two systems, a quadruple proportional-counter telescope, or a coincidence crystal spectrometer. Energy resolution was of the order of 2.5%.

The angular distribution of protons from the reactions

$$C^{12}(p,p')C^{12*} \quad Q = -4.43 \text{ Mev} , \text{ and}$$

$$Mg^{24}(p,p')Mg^{24*} \quad Q = -1.38 \text{ Mev}$$

was found to be peaked in the forward direction. Since the compound nucleus is excited to about 13 Mev, where the level density is expected to be high and the statistical theory of the nucleus should hold, it is proposed that two processes of excitation occur. One, the formation of the compound nucleus and its subsequent decay--symmetrically about 90°; two, direct collision of the incident proton with a nucleon on the surface shell of the nucleus.

The elastic scattering of protons on the above nuclei was also studied and interference maxima were found.

Three new levels are believed to have been confirmed in magnesium-24.

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INTRODUCTION

The inelastic scattering of particles on nuclei has been used by a large number of investigators¹ recently, for it provides an excellent way of exciting nuclear levels. The energy of a level is simply the difference between the energies of the bombarding and the emerging particle in the center-of-mass system (see Fig. 1). The actual mechanism of this transfer of energy and angular momentum, however, has not been quite clear. Rhoderick² was the first to be concerned with this problem, for he found that the angular distribution of the inelastically scattered protons from the 1.38-Mev level in magnesium-24 was peaked in the forward direction. He was unable to reconcile this result with the idea that the excitation proceeded through compound nuclear formation, for the basic assumption underlying this theory is the Bohr assumption, which states that decay occurs in all energetically possible modes, independent of formation. Consequently, the emerging particle may carry away no knowledge of the input angular momentum axis and hence can have no angular distribution. Wolfenstein³ criticized this statement by pointing out that any compound nuclear state must have not only the same total angular momentum J and the same parity as the initial state, but also the same z -component of the total angular momentum m . This usually forgotten conservation of m may be said to have as its consequence that the compound nucleus "remembers" the axis of incidence of the initial particles--provided, of course, that J is different from zero. He showed further that if the density of compound nuclear states is large and the states overlap so that one may take a true statistical average⁴ over them, the angular distribution of the

Fig. 1. Schematic Description of Elastic and Inelastic Scattering Processes.

outgoing particle must be symmetric about 90° and is usually peaked in the forward and backward directions. The former follows from the fact that interference terms between outgoing waves of different parity are assumed to cancel out. The case in which the level density is low is very difficult to treat, for a detailed knowledge is required of the compound states and their spin orbit coupling.

Rhoderick's anisotropic distribution then requires either that the density of states in the compound nucleus be low or that we postulate in addition a new process of excitation, one that does not proceed through the compound nucleus at all. Two processes suggest themselves: electric charge excitation⁵, or a direct collision of the incident proton with a nucleon on the surface shell of the nucleus. Of these three choices we prefer the last, for (a) the present data were obtained at an excitation energy at which the level density is thought to be large (Appendix I) ;(b) the cross sections found are too large to be explained by electric excitation; and (c) the proposed mechanism bears a resemblance to the very successful Butler theory of (d, p) (d, n) (d, d') reactions.

Since the author undertook this problem three years ago, Gove and Stoddart⁶ measured the angular distribution of inelastic protons on magnesium and carbon with a bombarding energy of 7.3 Mev and found strong anisotropies. Roy Britten⁷ and Igo and Eisberg⁸ found anisotropies at 32 Mev.

Recently Gugelot⁹ has suggested similar concepts in connection with his work on level densities by inelastic scattering of protons. He refers to McManus and Sharpe¹⁰ for the direct collision theory.

We will follow an analysis given by Austern, Butler, and McManus¹¹. Let us examine their proposition:

1. The theory was developed for X(n,p)Y type reactions on medium to heavy nuclei, but is equally applicable to (n, n'), (p, n), and (p, p') reactions.
2. They expect that their direct collision process can compete with compound nuclear formation because the struck particle receives nearly all the energy and consequently may get over the Coulomb barrier. Compound nuclear formation, on the other hand, favors low-energy particle emission (many states are sharing the energy),

which may be suppressed by the barrier.

3. The energy region in which this type of reaction may be found is between 10 and 30 Mev. The lower limit is set by the barrier, the upper by nuclear transparency.

4. The anticipated cross section for emission of a high-energy proton group may be several millibarns. They arrive at this figure by correcting the total free n-p scattering cross section of 0.6 barns for the fraction of the time that the initial and final particles spend outside the nucleus. Certain angular effects are also considered.

5. They ask then: What is the angular distribution of particles, with large impact parameters, interacting with nucleons that find themselves outside the main core of the initial nucleus and whose wave functions in this region are the familiar exponential tails? The theory supplies the answer: Similar to the distributions of Butler stripping reactions, with sharp maxima depending on the allowed values of orbital-angular-momentum transfer. If the struck particle can be assumed to be in a single-particle state (i.e., nearly outside), then the angular distribution becomes especially simple.

6. How is the transition matrix element calculated? They calculated it for n-p scattering using the impulse approximation (which looks like a Born approximation), with the additional requirement that the neutron and proton are essentially free at the time of the collision. Since n-p scattering is essentially isotropic at this energy, the radial part of the wave function of these nucleons can be factored out. By limiting themselves to states of low angular momentum they could make further simplifications. Finally they expand what is left, namely $e^{i[(\vec{k}_0 - \vec{k}_f) \cdot \vec{r}_p]}$, in spherical harmonics and perform the necessary integrations, averages and sums. The cross section, which is proportional to the square of the outgoing amplitude, is:

$$\sigma(r, \theta) \propto | \langle r_{np} | \rangle |^2 \alpha f(r) \times (2l_p + 1) \sum_l C_{l,0}^2(l, 0; 0, 0) \{ j_l(Qr) \}^2$$

where l is constrained by the relation $l_n + l_p \geq l \geq |l_n - l_p|$

$$Q = | \vec{k}_0 - \vec{k}_f |$$

C is a Clebsh-Gordon coefficient,

j_l is a spherical Bessel function of order l ,

l_p and l_n are the orbital angular momenta of the proton of least binding (outer shell), and of the captured neutron (which in this case goes into the neutron state of least binding). The angular distribution is contained in the Bessel functions. The position of the first maximum determines the lowest allowed value of l , namely $|l_n - l_p|$. Unfortunately there is no form factor to suppress contributions from the higher allowed values of l as in the stripping reactions.

7. It can be seen that in this way, spins and parities of nuclear states can be determined. However, one must realize that this theory cannot be accurate in all detail. The assumption that both participating particles are free is quite drastic. When it is not possible to ascribe special orbitals to the interacting particles, the theory becomes more difficult. Still, it leads to angular distributions that exhibit a series of peaks in the forward direction. They arise from the same factor $j_l^2(Qr)$, except that now the selection rules governing the value of l are less stringent.

8. Butler, Austern, and McManus make a further calculation in which they consider the nucleus as a black sink for all incident-particle waves for which $l < kr$. This suppression of compound nuclear events from the outgoing wave somewhat modifies the character of the angular distribution.

We will apply the above theory only in its most simple aspects.

A by-product of this investigation was the measurement of the elastic scattering of 10-Mev protons on magnesium and carbon. Renewed interest in this type of scattering has been expressed recently by Cohen¹², who finds a remarkable number of diffraction maxima and minima. As is well known, they arise from the interference of the coulomb and nuclear scattering. From the usual formula for diffraction effects one might expect the angle at which any particular feature occurs to be proportional to $\frac{\lambda}{R}$ where λ is the wave length of the incident proton in the center-of-mass system and R is the nuclear radius. He finds that the $\frac{1}{R}$ law is borne out with an accuracy that would seem beyond expectation for elements ranging from magnesium to thorium. We will try to see if the angles of the maxima at 10 Mev are proportional to those found by Cohen at 22 Mev.

The theory of elastic scattering has been rather successfully treated by LeLevier and Saxon¹³, using a one-particle model for nucleon-nuclei scattering. They assumed a square well with a complex constant potential. Another possible model is one proposed by Feshbach and Weisskopf¹⁴, in which the complicated phenomena occurring inside the nucleus are described in terms of the surface values of the nuclear wave function. Which of the theories is more correct depends somewhat on the absolute differential scattering cross sections. These cross sections are presented in this work for magnesium and carbon.

Fig. 2.

EXPERIMENTAL METHOD

General

Although the Berkeley 60-inch cyclotron has existed and has accelerated particles since 1939, and a great deal of work on nuclear reactions has been done with this machine, no extensive equipment specifically for the electronic detection and counting of reaction products was installed until late 1952. With its supply of 10-Mev protons, 20-Mev deuterons, and 40-Mev alpha particles, this Berkeley machine is admirably suited for investigations in the medium-energy region. The current interest in the angular distributions of scattered protons and deuterons has prompted the construction of a scattering chamber large enough to permit the detection of particles with a variety of counters and with sufficient angular resolution.

Scattering experiments require beams that are well collimated, monoenergetic, and uniform in intensity, and that produce a minimum of background radiation. The complete realization of these conditions seems to depend on the whims of the machine, on the operating crew, and on the amount of money and time one is willing to spend. For these reasons expedient compromises must be drawn. A schematic of the experimental arrangement is shown in Fig. 2.

The deflected molecular hydrogen beam is brought to the target port after passing through a 1/4-inch collimating slit in the normal probe position. The position of the slit defines the beam's subsequent path and energy. Energy selection occurs because the slit is in the fringing field region of the cyclotron (about 75% of the central field). Immediately before reaching the target port the beam passes through an iron snout designed to reduce the magnetic field inside. Without this presnout, the beam would curve inwards toward the machine and travel on a path hitting the main magnet yoke. An additional iron snout is attached, and the beam is seen to travel in a straight line from the target port onward. It passes through the so-called "lighthouse" (used for alignment purposes) and through another collimating slit and into a long 1-3/4-inch-diameter brass pipe. Wrapped around this pipe are two magnetic quadrupole lenses, which bring the

Fig. 3.

beam to a focus on the target located further on. When not in use, the magnets roll on their dolly into a hole in the water shielding tanks. When they are stored here, paraffin is packed around them for maximum shielding.

The 36-inch scattering chamber can be seen connected to the brass pipe and is followed by the Faraday cup, where the beam comes to rest and is integrated. A set of three collimating holes defines the beam axis in the chamber. Since the cyclotron is far removed and the holes small, the chamber has its own vacuum system. The beam's energy can be measured by a double foil wheel. Reaction particles are detected by either of two systems, a quadruple proportional-counter telescope with range analysis, or a crystal spectrometer. The counter cabling is led to a patch panel which connects with the "counting area", more than 40 feet away. Over-all energy resolution is of the order of 2.5% for 10-Mev protons and 1.7% for 20-Mev deuterons.

Quadrupole Lenses

At the position of these lenses the beam cross section is an oval 1-1/2 inches in width and 7/8 inch in height. The divergence angle of the beam is hard to estimate, as it has no real source point; however, without focusing, this oval would have a size 2-1/2 x 4 inches at the target located 16 ft. further on, where the maximum proton beam intensity available was 2×10^{-9} amp through an 1/8-inch collimating hole. With the magnets this can be increased to 0.8×10^{-6} amp, a factor of about 400. The dimensions and parameters of the lenses are given in Fig. 3. The magnets are made of soft iron; each weighs about 150 pounds and is easily lifted by two men. Both are mounted and accurately positioned on the dolly already mentioned. (This is not shown, however, in the early photograph in Fig. 4.) Screw adjustments are provided to move the magnets with respect to the pipe. It has been found that a movement of the rear lens perpendicular to the beam moves the beam by a corresponding amount in the target plane. Although some motions provide an opposite effect, it is quite possible to direct the beam with great accuracy. The focusing properties of the lens system are also shown in Fig. 3. With a current of 12.5 amp per coil, the focal length for molecular hydrogen is calculated to be 10.8 feet. This is in good agreement with the experimental arrangement. It can also be seen that a simple pair of lenses is as -

Fig. 4. Quadrupole Lenses.

tigmatic because the principal plane for convergence in the Y direction is different from that in the X direction. This astigmatism can be made to compensate that of the original beam distribution so that the resulting spot may be round. The size and intensity distribution of this spot was determined by bombarding a thin copper foil with deuterons, cutting up the foil into 1-mm-square pieces, and observing the activity from the $\text{Cu}(d,p)$ reaction. The maximum beam intensity observed was $12 \mu\text{amp}/\text{cm}^2$.

Molecular hydrogen, deuteron, and alpha-particle beams are all focused with the same magnet parameters. Stripped atomic hydrogen, on the other hand, will not get through the final collimator when the magnets are set for molecular hydrogen. This fact assures that the molecular hydrogen beam has not scattered, either from slits or gas in the tube, and is expected to arrive at the chamber with no low-energy component.

When small deuteron beams are used, great care must be taken to prevent stray hydrogen, which is normally in the cyclotron tank, from being accelerated and traveling down the tube. This happens when the magnet field resonance is allowed to drift by 0.1% (the difference in the e/m ratios of molecular hydrogen and deuterium). Fortunately this effect can be immediately seen in the oscilloscope presentation of pulses from the crystal counter.

Beam Alignment

In order to assure that the beam passes through the center of the chamber an elaborate procedure is followed. The beam is brought out from the target port in steps, test photographs being taken at the end of each succeeding section of pipe. To take a photograph we place outdated nuclear emulsions in the path of the beam and note the burn pattern. With a sufficiently intense beam, scotch tape works as well. When the beam has been traced out through the water shielding, a small light bulb is lowered into its path at the "lighthouse". The chamber is aligned on the beam axis with a 6-power telescope. The telescope is accurately doweled on the rear of the chamber and looks through the collimators at the light. Further photographic measurements are taken to check the alignment when the chamber is under vacuum. This careful procedure is justified, for it minimizes slit scattering. It is thought that the beam passes within $1/64$ inch of the center of the chamber.

Fig. 5. 36-inch Chamber and Pumps.

Fig. 6. Inside View of Chamber Showing
Range Counter and Early Model Crystal Counter

36-Inch Chamber

Figures 5 and 6 show the outside and inside of the chamber, respectively. It is made of steel, and has a hinged lid made of aluminum. Glass viewing ports are provided in the lid and walls. Around the walls, level with the beam axis, are large window ports covered with 0.001-inch stainless steel. These were designed for gamma-ray experiments outside the chamber. The tank rests on a ring frame mounted on a four-foot steel base plate. Large rubber wheels permit the whole assembly to be rolled about the building, and screw jacks, centered on holes in the floor, lift it to the proper height. Final alignment is made by screw adjustments on the frame. The target mechanism can be seen mounted on the lid. Three targets can be lowered into the beam and rotated to any angle by remote control. A selsyn transmits the angle of rotation. A vacuum lock is provided to permit a change of targets without "letting the chamber down to air". Inside the chamber can be seen the collimating tube with its removable slits and the rotating counter table. The table can be set to within half a degree by remote control. Its six-inch shaft, driven from the outside, is sealed to the base of the chamber by a gasket with two O rings, and provides passage for the electrical connections.

Vacuum System

An operating pressure of 3×10^{-5} mm Hg is maintained in the scattering chamber by a pumping system containing a 6-inch oil diffusion pump. This pump is backed by a large mechanical pump which can double as a roughing pump. A refrigerator cools the top baffle on the diffusion pump, and an auxiliary liquid-air trap is provided. The system can be isolated from the chamber by a 6-inch head gate valve which opens by turning a lever through 90° . This valve has saved the pumps a number of times when thin windows have broken. Reset switches protect the diffusion pump in case of water or power failure. The whole unit, complete with thermocouple and ion-gauge power supplies, rolls on wheels and is easily moved about the building. It takes an average time of 15 minutes to evacuate the chamber to its operating pressure.

Beam Monitor

The beam was collected in a Faraday cup mounted on the rear of the chamber. The cup is separated from the chamber by an aluminum foil and is maintained at a pressure less than 1×10^{-5} mm Hg by a pumping system of its own. (Not shown in the early photograph.) A set of two permanent horseshoe magnets provides a flux of about 200 gauss to prevent secondary electrons from emerging. The charge was placed on a low-leakage condenser connected to the grid of a 5803 electrometer tube. Figure 7 is a simplified schematic diagram of the integrating electrometer. The feedback circuit (a) provides stability of operation, (b) assures minimum loss of collected charge because the grid circuit is effectively at ground potential, and (c) minimizes the effect of cable capacitance. The feedback voltage, or a fraction thereof, is applied to a Speedomax recording voltmeter which is self-calibrating against a standard cell. When the recorder reaches a preset voltage value, a microswitch is tripped. This actuates a fast relay and discharges the condenser. It also advances a stepping relay one notch and, if required, keeps the circuit discharged and gates off all the counting scalars.

The condensers used were compared on a bridge with a General Radio standard condenser whose capacitance was known to within 0.1%. Independent checks were made on this calibration by two people.

The system is believed to be accurate to 1% provided the recorder does not receive too fast a charging voltage. It was found that the ion gauge, used to measure pressure in the cup, produced a current of 1×10^{-10} amp in the electrometer circuit. It was, of course, turned off when measurements were made.

Beam-Energy Determination

The energy of the beam is measured by range with two foil wheels each containing a set of 12 absorbers. The coarse wheel provides enough range to almost stop the beam, and the fine wheel, which has aluminum foils in steps of 1.53 mg/cm^2 , measures the end of the Bragg curve. For making a measurement, the fine wheel was driven continuously by a 1-rpm motor, and the beam current, as caught by the cup, was displayed on the recorder chart. The average current

NOTE: "C" IS USED FOR INTEGRATING ELECTROMETER
"R" IS USED FOR CURRENT ELECTROMETER

Fig. 7. Electrometer (100% Feedback Type)
Simplified Schematic.

Fig. 8.

reading of a number of cycles is plotted as shown in Fig. 8. From the theoretical calculation of the range straggling for a 10-Mev proton and the measured curve, it can be inferred that the spread in the beam energy reaching the target for a given set of cyclotron parameters is about 1.0% (full width at half maximum). This 1% is not unreasonable, considering that energy selection was made with a 1/4-inch slit placed in a field of 11,500 gauss at a machine radius of 30 inches.

Beam-energy variations of a larger kind occur with changes of the cyclotron parameters. Principal variations are those occurring with changes in oscillator power, magnet resonance, deflector voltage, and ion-source position. Since the ion source is normally run about 1 inch north of the center of the tank, it is expected that there may be eccentric orbits which are affected by the dee voltage and the position of the feelers. Certainly the mechanism of rf deflection, which is believed to occur together with the purely dc deflection, is not well understood. On the day that the curve shown in Fig. 8 was taken, the parameters were as shown. Sometimes the relation of these parameters to the beam was reversed; no systematic theory can be postulated. I might add that because the cyclotron is used by so many different research groups, all requiring different types of beams, it is only by pure chance that any parameters are repeated at all over periods of weeks. Indeed, some experimental data cannot be published because the particular energy at which they were taken is not reproducible.

Targets

Targets must be sufficiently thin so that none of the beam misses the Faraday cup owing to multiple Coulomb scattering. The cup subtends a full angle of about 0.1 radian. Thin gold targets were made by evaporating gold onto a glass plate covered with a thin film of parlodion. The gold and parlodion were peeled off under water and mounted in the target frame. The parlodion was then dissolved off by immersing the frame in a 50% solution of ethyl alcohol and ethyl ether. To remove the last traces of film, the frame was suspended over a refluxing bath of the same solvent. Magnesium targets were made by rolling thin foils. Polystyrene ($C_6H_5CH:CH_2$) films 0.001-inch thin were used for carbon-hydrogen targets. To obtain thin carbon targets without hydrogen contamination is difficult. They can be made by spraying a thin colloidal suspension of graphite (aquadag) onto a clean sheet of teflon and peeling off the dry deposit. Some hydrogen is left in targets

produced this way, but the amount is vastly smaller than in a CH target. Silicon targets were made by evaporating silicon monoxide at a temperature of 1700°C onto an acetate film (Duco cement dissolved in amyl acetate), backed by a thin copper sheet that has holes in it. After evaporation the whole thing is gently lowered into a bath of amyl acetate. The silicon monoxide film floats away because the solvent dissolves the backing from the rear through the holes in the copper screen. These films can be made quite uniform. For silicon targets, the technique used on the gold targets did not work because the high filament temperature baked the parlodion to the glass. Target thickness was determined by weighing that portion of the target through which the beam passed on a semimicrobalance. The weight per cm^2 is believed to be known to 0.3%.

Proportional-Counter Telescope

Scattered particles are detected in a telescope of four proportional counters. The range, hence the energy of the particle, is determined by how much aluminum absorber must be interposed in the particle's path to require it to traverse the first two counters and stop in the third. A typical range curve is shown in Fig. 18. The fourth counter, which is separated from the third by a fine wire screen, provides an anticoincidence pulse if the particle travels too far. Aluminum absorbers can be selected from a set of twelve solenoid-driven foils of from 2 to 1665 mg/cm^2 in steps of 1 mg/cm^2 . So that no particles are lost owing to multiple scattering in the foils, the counters have an aperture that subtends plus or minus two root-mean-square scattering angles for the worst case of scattering that might be encountered.

Design

In design and operation the counter is similar to one built at MIT, and the reader is referred to reference 12. A few constructional details are as follows: Sensitive volume per counter: $4\text{ cm} \times 4\text{ cm} \times 1\text{ cm}$; number of wires per counter: 5; diameter of wires: 0.005 inch (nickel); gas: 1 atmcs. argon 96%, CO_2 4%; voltage on the separating plates: -1800 v. The rise time of this counter was measured and found to be $0.2\text{ }\mu\text{sec}$. Pulses were RC clipped to $3\text{ }\mu\text{sec}$. After some effort the pulse-height distribution of pulses produced by a collimated

PROPORTIONAL COUNTER TELESCOPE ELECTRONICS

Fig. 9.

alpha source was reduced to 12% (full width at half maximum).

Electronics

A block diagram of the electronics for this counter is shown in Fig. 9. The panels and controls are seen in Fig. 10. It can be seen that differential pulse-height discrimination is used on only the first two sections. The discriminator of the third counter was high enough to require the particle to travel at least two-thirds across the sensitive volume. In a way, the setting of this discriminator adjusts the "range bite" (discussed below).

Stability

Long-term stability of the electronics is very important, as pulses are counted on the very edge of discriminator plateaus. This stability is ensured by an excellent high-voltage supply (0.1% regulation) and by stabilizing the filaments of all critical equipment by sola transformers. All the electronic racks are cooled by a refrigerated air blower. Even so, counting rates drift over periods of half days, and frequent calibration checks on the range bite had to be made. Part of the difficulty may have been in the cathode follower outputs of the pre-amplifiers.

Calibration

In the course of a run, one measures the number of particles that stop in a given amount of range ΔR . This we call the "range bite" of the counter. Except for small corrections it is assumed that this is constant over the energy of all the particles that enter the counter. The ordinate of the curve shown in Fig. 18 therefore represents $\frac{dN}{dR} \Delta R$. To determine the number of particles scattered into the detector as a result of a given reaction, one measures the area under the spectral line and divides this by ΔR .

$$\therefore N = \frac{1}{\Delta R} \int_{R_{\min}}^{R_{\max}} \frac{dN}{dR} \Delta R dR.$$

If the cross section for a particular reaction is well known (it is assumed the scattering of 10-Mev protons on gold at small angles is pure Rutherford scattering) then the number N can be evaluated and ΔR calculated from a measured curve. For normal settings of discriminators ΔR was 0.57 mg/cm^2 of aluminum equivalent. This corresponds to about one-third of the thickness of gas in the last chamber. By lowering the discriminator of the last counter chamber, ΔR

Fig. 10. "Counting Area"

could be increased, with a resulting decrease of over-all counter resolution. The effect can be seen by comparing the resolution and counting rates of Figs. 18 and 18a.

Resolution

Nearly the total width of an elastic line (6 mg/cm^2) can be accounted for by the range straggling of the protons in the absorber foils and in the spread of the beam energy itself. The inelastic peaks suffer a little from target thickness effects as well, especially for scattering angles larger than 90° . Contribution to the line width from counter acceptance angle and range bite are small in comparison. Over-all energy resolution is of the order of 2.4%.

Background

The triple-coincidence requirement was so rigid that the target in-target out ratio was always greater than 10,000 to 1. At 10° , slit scattering produced some low-energy protons; measurements could not be taken for smaller angles. The accidental coincidence rate with target in, measured by delaying one channel, was found to be negligible.

Crystal - Proportional-Counter Telescope

Although there is no better quick way to measure the energy of a particle than with range, the analysis of the data obtained by the above-mentioned counter is very tedious. For this reason a crystal spectrometer, one that could identify the particle (by its $\frac{dE}{dx}$) as well as measure its energy, was built. Attempts to build such an instrument with the phototube standing vertically were failures. The energy resolution of such a vertical counter with an alpha source was never better than 6%.

Design

A successful counter is shown in Fig. 11. A sodium iodide crystal cleaved on all six sides is cemented to a 1/4-inch-thick glass plate with liberal amounts of myva-wax. This operation is carried out inside a dry box whose humidity is kept less than 10%. The glass plate is one wall of a container housing the aluminized reflector and a bag of silica gel. Once pumped out and sealed, this container is kept under hard vacuum. Crystals have been kept in this way over 4 months without deteriorating. Protons enter the container through a 0.00025-inch aluminum window. A long story could be told of the experiments carried out to determine if the resolution is dependent

CRYSTAL-PROPORTIONAL COUNTER
TELESCOPE

Fig. 11.

Fig. 12. Crystal Counter Telescope Electronics.

on the surface contamination of the crystals. Without boring the reader, the answer is emphatically yes, especially with alpha particles whose range in the crystal is very small.

The proportional counter in front of the crystal measures the ionization loss of the particle entering the telescope. Circular in cross section, it has a pulse-height distribution of 6% (full width at half maximum) with a collimated alpha source. Great care was taken with the gas, which was purified by circulation for a week through a hot calcium purifier¹⁶. A double kovar seal provides a guard ring for the high-voltage lead-through. From Fig. 11 it can be seen that either the proportional or the crystal counter can be disassembled without disturbing the other one.

Electronics

A block diagram of the electronics for this system is shown in Fig. 12. Broad differential pulse-height analysis for the $\frac{dE}{dx}$ counter is supplied by the standard UCRL variable-gate units. The E counter pulse, delay line clipped in the cathode follower, is analysed by a fast ($1/2$ μ sec resolution time) pulse-height analyser built after the design of Fairstein and Porter¹⁷. The circuit is shown in Fig. 13; 404A type tubes are used in the input gate circuits. These are 6AK5's with higher g_m , which makes them faster. These gate pulses are inverted in the buffer stage, and, should both gates fire, are mixed in the storage tube to disable the one-shot multivibrator 12AT7. The output tube has a split load to put out either positive or negative pulses of $1/2$ - μ sec duration. A short delay line was substituted at D to make possible better cancellation in anticoincidence circuit. Window widths from 1.1v to 8v may be used. Since the bias voltage for the discriminator is taken from B plus, this voltage must be carefully stabilized. Overall delay from input to output is about $1/2$ μ sec.

Stability

The gain of phototubes is notoriously sensitive to changes in supply voltage.^a For peace of mind, this voltage was continuously monitored by the unit labeled "high-voltage recorder". As shown in Fig. 14 the unit consists of a voltage divider network feeding a 100%-feedback dc amplifier whose current is monitored by a 1 ma Esterline

a. In fact, a 0.5% change in voltage produces a 3% change in gain.

Fig. 13. Schematic of Pulse-height Analyser

Fig. 15.

Angus recorder. The reference voltage is the drop across the OG 3 tube. The output current is relatively independent of the amplifier gain or supply voltage because of the feedback feature. This unit can also be used to monitor the B plus supply of the pulse-height analyser. The output meter has a full-scale sensitivity of 0.8% of the input voltage. Under normal operating conditions fluctuations of the high voltage were measured to be less than 0.1%.

Plateaus

A curve of the counting rate vs. the relative delay between the two counters is shown in Fig. 15. This curve is a measure of the total delay between coincident pulses due to rise-time differences and to any electronic jitter that there may be in the circuitry. It is seen the effects are small enough to justify the use of $1\frac{1}{2}$ - μ sec coincidence gate pulses. One wants to use as small a coincident gate as possible to minimize accidental counts. The beam-intensity plateau indicates that the maximum singles rate one may use in the proportional counter is 750 counts/sec. Why this rate is so low (1 count every 1300 μ sec) is not understood. Very likely it is because the cyclotron, when run at low beam currents, has a duty cycle. This modulation, brought about by ripple in the arc current and dee voltage, has sometimes caused as much as 70% off time. Another possibility is "pileup" in the crystal, which lowers the resolution and forces some pulses out of the differential pulse-height window. Needless to say, counting rates were always kept well below the maximum.

Energy Resolution

The energy resolution of the crystal counter depends largely on the surface condition of the crystal and on the amount of light collected. Figure 16 shows the results for 10-Mev protons elastically scattered from the gold. The curve was taken with a pulse-height analyser window of 1.1 volts. The pulse-height distribution from the proportional counter does not fare as well. This is largely owing to the Landau effect¹⁸, which can be summarized briefly by noting that in an ionizing collision, a very large range of possible momentum exchanges can take place.^a If very many collisions occur, almost all particles passing through the gas volume lose on the average the same amount of energy. This is called the most probable energy loss. If few collisions

a. Collisions are possible in which the energy lost is 1,000 times the average.

Fig. 16.

occur, however, the statistics of the events, not only with respect to the number of collisions but also with respect to the momentum loss per collision, broaden the distribution. There is a higher probability of collisions in which the energy loss is greater than the average than of those in which it is less than the average, and the distribution curve therefore has a high-energy tail. The effect becomes worse, of course, the smaller the total energy lost, i. e., the thinner the counter. The experimentally obtained curve is seen to fit quite well with the points calculated on the basis of the Simon-Landau theory.

Energy Calibration

Figure 17 shows an oscilloscope presentation of the pulse-height distribution in the crystal counter. Energy levels are clearly seen. The pulse height, however, is not linearly proportional to the energy because the particle loses energy by ionization in both the target and the proportional counter. The pulse height also depends on the overall gain of the system, which may not be linear. By using the Q values of known reactions, one can calibrate the energy scale. Eleven inelastic proton groups were identified with 16 known levels in aluminum¹. Three strong inelastic groups (1.8, 4.47, 4.91 Mev) were observed from silicon-28,¹⁹ and one from oxygen (6.13). Calibration achieved in this way was consistent within itself. Energies can be estimated to ± 0.1 Mev.

Particle Loss on the Proportional Counter Due to Multiple Scatterings

On the basis of the theory presented by Dickinson and Dodder²⁰ on the evaluation of particle loss due to multiple scattering, this loss in the crystal counter is calculated to be less than 1%. The loss must be considered in any collimated system which contains foils that the particles must traverse. Use is made of the fact that if the detector and foil radii are sufficiently different in size, the loss can be minimized.

Angular Resolution

The acceptance angle of the counter was $\sim 1^\circ$.

After this discussion the various relative advantages of the two detection systems are apparent. The range counter measures energy accurately and is able to count small particle groups in the presence of large ones. The absolute measurement of the number of particles is subject to the instabilities of the electronics. On the other hand,

Fig. 17. Oscilloscope presentation of pulse heights of protons inelastically scattered on a Si^{28}O target.

there is no uncertainty as to the number of particles that enter the crystal counter, but the energy measurement is subject to nonlinearities in the electronics. One advantage is being able to see at a glance the whole spectrum in the oscilloscope. Total counting rates in the crystal counter must be kept low.

Fig. 18. (Range bite ~ 1 mg/cm²)

Fig. 18a. (Range bite = 0.57 mg/cm^2)

RESULTS AND CONCLUSIONS

Particle Groups from Magnesium and Carbon Targets

Figure 18 shows the spectrum of protons resulting from a bombardment of naturally occurring magnesium with 10-Mev protons. Easily identified are the elastic peak and the 1.38 ± 0.01 -Mev and 4.16 ± 0.01 -Mev levels in Mg^{24} . Recently it has been shown²¹ that the second level is really a doublet whose energies are 4.13 and 4.24 Mev. Levels this close together are clearly not resolved by our equipment. Small peaks occur at 1.89 and 2.84 Mev and are assigned to Mg^{26} , whose abundance is 11.3%. Corroborative evidence from the crystal counter permits the assignment of two peaks to Mg^{25} . They correspond to Q values of 0.6 and 3.4 Mev. There is a strong line at 5.15 Mev seen also by the Pittsburgh group²¹ and reported by Gove and Stoddart²². Baker, Dodd, and Simmons²³ report three lines "corresponding to excitations higher than 4.14 Mev." An examination of Fig. 19, taken with the crystal spectrometer, shows these quite clearly. Energies correspond to Q values of 6.3 ± 0.1 , 5.9 ± 0.1 , and 5.1 ± 0.1 Mev if calculated for Mg^{24} . These figures are not as reliable as the energies taken from the range curve (see above). The 6.3-Mev level has been previously assigned to magnesium-24.²⁴

Figure 20 shows the spectrum from a carbon target at 35° . Figure 21 shows the pulse-height analysis from a polystyrene target at 24° lab. The elastic peak in the photograph contains about 5000 counts.

Differential p-p Scattering Cross Section

The differential p-p scattering cross section measured at 24° lab. and 9.94 Mev was found to be 141.6 millibarns/steradian. This corresponds to a cross section of 54.6 mb/steradian at 48° in the center-of-mass system. This figure is believed to be accurate within the statistical error of 3%, and compares well with those published by Allred et al.²⁵ and recently by Cork at 9.6 Mev.²⁶ Agreement with two independent observers using different detection equipment indicates that there are no large errors in our technique.

Fig. 19. Mgesium Spectrum.

Fig. 20. Carbon Spectrum.

Fig. 23.

Fig. 22. The angular distribution of elastically scattered protons from Mg. at 10 Mev.

Fig. 13. The angular distribution of elastically scattered protons from carbon at 10 Mev.

Angular Distributions of Elastic Events

The angular distributions of elastic scattering of 9.94-Mev protons on magnesium and carbon (reduced to center-of-mass system) are shown in Figs. 22 and 23. The general character of these curves and the absolute cross sections agree well with those published by Baker, Dodd, and Simmons²³ and Burcham, Gibson, and Rothblat²⁷. The energies used by these investigators was 9.6 and 9.5 Mev respectively. The magnesium curve shown in the present data is extended to further backward angles and shows a rise in the cross section leading to a second maximum. Since these data were taken at the same time as the hydrogen cross section was measured, it is felt that the absolute cross sections are accurate to within a 3%. The angular measurement is good to $1/2^\circ$. Relative cross sections are known to 2.5%. Unfortunately there are not enough data to fix the interference angles with greater accuracy. It can be seen that some of the effects are quite prominent in the measured curves but are washed out on the ratio-to-Rutherford curve.

Angular Distributions of Inelastic Events

Figures 24 and 25 show the angular distributions of protons inelastically scattered from the 1.38-Mev and 4.41-Mev levels in magnesium and carbon (corrected to C-M). The magnesium curve shows little or no resemblance to Baker's, possibly because of the different bombarding energy. The value of the cross section at 30° is quite below those at 45° and 60° . Figure 26 shows that this point is difficult to obtain, since the elastic cross section is very high compared to the inelastic, and the resolution is not perfect. The dotted lines show how the subtraction was made. Possibly the discrepancy between these results and those of Baker lies in the fact that Baker does not resolve the 1.59-Mev Mg^{26} level which appears as a satellite. This satellite must be subtracted at all angles. The magnesium curve was taken with both counters and the findings for angular dependence checked with each other to 1%. There was, however, a 5% difference in the absolute cross section between the two methods. This can be blamed on a faulty ΔR calibration in the range counter. It is clearly seen that the curve is not symmetric about 90° .

Fig. 14. The angular distribution of protons from the reaction $Mg^{24}(p, p')Mg^{24}$. $Q = -1.38$.

Fig. 25. The angular distribution of protons from the reaction $C^{12}(p,p')C^{12}$ $Q = -4.4$.

Fig. 26.

There is no essential disagreement with Burcham's curve on carbon. The absolute cross sections obtained here are lower, but the shape of the curve is the same. I disagree with their conclusion that the curve is symmetric about 90° because the points on these data, although not as many in number, have better statistics (1.5%). They fall within their quoted statistical error. An examination was made to see whether the counter efficiency varied with energy, hence with angle, of the incoming particle. Possible asymmetries in target alignment were checked. The conclusion was that errors from these sources were 3% at most. No data exist for 45° , for at this angle the hydrogen peak overlaps the inelastic peak and a subtraction of the hydrogen cross section cannot be made accurately.

Analysis of the Magnesium Inelastic Data

Analysis was performed in the following way: We assume that the angular distribution is the sum of contributions from compound nuclear formation and the direct collision process. We assume that the first is symmetric about 90° and that the latter is given from the Austern and Butler theory to be an l -th order Bessel function, i.e.

$$f(\theta)_{\text{experimental}} = C g(\theta) + a \left\{ j_l^2(\theta) \right\}.$$

Therefore

$$\begin{aligned} f(45^\circ) &= C g(45^\circ) + a \left\{ j_l^2(45^\circ) \right\}, \\ f(135^\circ) &= C g(135^\circ) + a \left\{ j_l^2(135^\circ) \right\}. \end{aligned}$$

Subtracting,

$$f(45^\circ) - f(135^\circ) = a \left(j_l^2(45^\circ) - j_l^2(135^\circ) \right).$$

This gives us the coefficient for direct scattering,

$$a = \frac{f(45^\circ) - f(135^\circ)}{j_l^2(45^\circ) - j_l^2(135^\circ)}.$$

Since we have excited the magnesium nucleus to its first level, which is believed to have a spin of 2, we assume that for a first approximation $l = |l_p - l_n| = 2$. The Bessel functions are therefore of the second order. The parameters QR in $j_l^2(QR)$ are of course $Q = |\vec{k}_o - \vec{k}_f|$ and the nuclear radius R where $Q^2 = (k_o - k_f)^2 + 4 k_o k_f \sin^2 \frac{\theta}{2}$ and $R = r_o A^{1/3}$.

The angular distribution for direct collision obtained in this way was then subtracted from the experimental curve. The resulting curve $Cg(\theta)$ (dotted in Fig. 17) should be symmetric about 90° . Various values of r_0 were tried. The best fit (i. e. symmetry about 90°) is quite sensitive to r_0 and was obtained with $r_0 = 1.6 \times 10^{-13}$ cm. The result of increasing the radius is to shift the peak to more forward angles and to decrease the amount of the process.

DISCUSSION

From the results we have seen that the data for inelastic events in magnesium can be fitted quite well with the theory. The applicability of the theory, however, is dubious and the reader must realize that we are far into the realm of speculation.

How many of the model's conditions can we satisfy? Magnesium-24 can hardly be considered heavy. On the other hand we are in the right energy range, and the anticipated cross section of several millibarns is actually found. It is certainly not unreasonable to choose the radius of the nucleus larger than the normally accepted $1.45 \times A^{1/3} \times 10^{-13}$ cm because the interacting particles are supposed to be outside the nucleus at the time of collision. (Neutron scattering leads to 1.57×10^{-13} ; Feshbach.¹⁴) Condition 7, that the struck particle is in a closed-shell-plus-one state, is not satisfied by Mg^{24} , and proposition 8 has not yet been considered in the analysis.

Let us now examine the elastic data. Column 2 of Table I lists the angles at which Cohen finds diffraction effects with a bombarding energy of 22 Mev. If $\theta \propto \frac{\pi}{R}$, and R is independent of energy, then at 10 Mev these angles should be larger by the factor

$$\frac{\theta_{10}}{\theta_{22}} = \frac{\pi_{10}}{\pi_{22}} = \sqrt{\frac{22}{10}} = 1.48 \quad .$$

Table I

		Angles at which effects are found (in degrees)		$\frac{\theta_{10}}{\theta_{22}}$
		Cohen 22 Mev	This experiment 10 Mev	
Carbon	max	36	50	1.39
	min	55	-	-
	max	88	120	1.37
Mg	max	28	-	-
	min	45	-	-
	max	70	97	1.38
	min	85	120	1.41
	max	102	-	-

Cohen's angles are taken from the ratio-to-Rutherford curve and are subject to shift with his normalization. Still, the results show a factor somewhat lower than the predicted one, and might indicate

that the nuclear radius measured by particles of different energy is not quite constant.

Certainly it is evident from the above discussion that a great deal of work needs to be done to confirm or reject the tentative conclusions reached here. Unfortunately, the author's experiments were sharply curtailed by the untimely shutdown of the cyclotron.

APPENDIX

Level Density in the Compound Nucleus

It is difficult to estimate what the level density of a highly excited, medium-heavy compound nucleus is. There are conflicting opinions on what type of model to use. One⁹ approach is to simply put numbers into Weisskopf's²⁸ evaporation model formula:

$$\omega(E) = C \exp(2\sqrt{aE}) .$$

This formula, Weisskopf stresses, is only approximately correct for odd A nuclei at an excitation of about 1 Mev.

The compound nucleus we wish to discuss is $Mg^{24} + p \rightarrow Al^{25*}$. Since Mg^{24} is a closed-shell nucleus, the binding energy of the extra proton in Al^{25} is unfortunately only 2.3 Mev.* Total excitation is therefore $10 + 2.3 = 12.3$ Mev. Substituting in the above:

$$\omega(E) \sim 0.5 \exp(2\sqrt{0.45 \times 12.3}) \sim 60 \text{ levels/Mev}$$

or an average spacing of 17 kev. Let us compare the formula with some known densities in Al^{27} and Al^{26} at 8.5 Mev. The average experimental spacings, measured by (p, γ) resonances, are about 32 kev. The formula predicts 35 kev.

What might be the width of an excited state? It is $\Gamma = \Gamma_{\text{rad}} + \sum_a \Gamma_a$ where Γ_a is the width for the emission of a particle "a" and Γ_{rad} is the width for emission of a quantum. Γ_{rad} can be neglected. A very rough estimate for Γ_a yields $\Gamma_a \approx \frac{4k}{K} \frac{D}{2\pi}$, where $\frac{4k}{K}$ is the usual impedance mismatch of the particle at the nuclear surface and D the level spacing. Substituting yields $\Gamma_a \sim \frac{1}{3} D = 5.7$ kev.

The spread in the beam energy was about 1% (i. e. 100 kev.). Another spread, due to the target thickness, may amount to another 100 kev. A total beam-energy spread of 140 kev would permit, therefore, the excitation of about 10 levels in the compound nucleus. Whether or not a statistical theory can be applied to this many levels is left up to the reader.

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