Gamma Rays from the Proton Bombardment of Sodium*

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The yield of the (p,γ) capture process in Na^{23} has been studied for proton energies ranging between 0.85 and 1.70 Mev. Resonances were observed corresponding to excited levels of Mg^{24} at 12.71, 12.72, 12.79, 12.86, 12.90, 12.94, 12.97, 13.01, 13.02, 13.08, 13.10, 13.14, and 13.32 Mev. The energies of the γ rays emitted from the most pronounced resonances were measured by photographing the pulse-height spectrum obtained with a single crystal scintillation spectrometer. These experiments indicate two competing modes of decay: the radiative cascade decay leading to the ground state of Mg^{24} and the emission of a low-energy γ ray of energy 1.6 Mev which is attributed to the $Na^{23}(p,\alpha\gamma)$ Ne^{20} reaction. No single-step transitions to the ground state were found in the capture process. Both two- and three-step transitions are observed, but all except one of the γ-ray cascades lead to the well-known 1.37-Mev state in Mg^{24}.

INTRODUCTION

THE present paper is concerned with the first phase of a program designed to study in detail the properties of the Mg^{24} nucleus. This nucleus may be formed in a highly excited state by the proton bombardment of Na^{23}. Two different modes of decay have been reported: the radiative transitions to the ground state of Mg^{24} [1,2] and the emission of two α-particle groups leading to the ground and first excited states of Ne^{20}.[1,3] These reactions are known to be in competition with the elastic and inelastic scattering of the protons by Na^{23}.[3] At least some of the processes show a pronounced resonance structure[4,5] for proton bombarding energies ranging between 0.25 and 2.0 Mev. As a portion of the present work, states in Mg^{24} between 12.55 and 13.35 Mev were re-examined. The measurements have given more detailed information than previously reported. From a combination of the thick-target data and thin-target data, the energies of these states have been calculated. We have also used a single crystal scintillation spectrometer to measure the energies of the γ rays resulting from the decay of the compound nucleus. While the results that can be obtained from such a spectrometer are only semi-quantitative, the measurements were made to see whether the γ rays observed could be fitted into a decay scheme consistent with well-established results of other experiments.[6]

APPARATUS AND PROCEDURE

Both thick and thin targets were bombarded with protons from the University of Kansas electrostatic generator.[7] Considerable difficulties were encountered in trying to prepare thin targets free of contamination. Fluorine contamination in both the target backing material and in the targets themselves was never completely eliminated but was reduced to a low level. Tungsten was found to be the most satisfactory backing material. Thin sodium targets were prepared by two methods: by vacuum evaporation of sodium onto tungsten disks and by electrical heating of tungsten strips in an oxygen atmosphere. Sodium was found in the oxide formed by the last method. Gamma-ray yield curves obtained with the two types of targets revealed that evaporated targets could be made much thinner than the oxidized targets could be made. Such curves also revealed that resonance peaks attributable to the $F^{19}(p,\alpha\gamma)$ reactions[8] were more prominent with the evaporated targets than with the oxidized targets. As a consequence, most of the data were taken with oxidized targets at energy intervals of 5 kev. Those energy regions at which resonances were observed were than re-examined in steps of 1 kev with the use of the evaporated type of targets with which much better resolution could be obtained. Slices of sodium metal were used as thick targets. Whereas sodium carbonate, sodium hydroxide, and oxides of sodium were undoubtedly present in all targets, neither hydrogen nor oxygen (p,γ) resonances have been observed for proton energies less than 2 Mev, and any resonances resulting from carbon (p,γ) reactions should be easily recognizable.[9]

The γ rays were detected with a scintillation counter consisting of an RCA 5819 photomultiplier tube and a NaI(Tl) crystal in an Argonne-type[10] crystal mount.

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[1] Stehlson, Preston, and Goodman, Phys. Rev. **86**, 629 (1952).

[2] H. Casson, Phys. Rev. **89**, 809 (1953).

[3] Donahue, Jones, McEllistrem, and Richards, Phys. Rev. **89**, 824 (1953).

[4] R. L. Burling, Phys. Rev. **60**, 340 (1941).

[5] R. Tangen, Kgl. Norske Videnskab. Selskabs Skrifter, 1946, No. 1 (1947).

[6] For a review of the work done up to 1950, see D. E. Alburger and E. M. Hafner, Revs. Modern Phys. **22**, 373 (1950).

[7] A description of the electrostatic generator, its control and stability, will be published elsewhere.

[8] Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).

[9] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[10] R. K. Swank and J. S. Moenich, Rev. Sci. Instr. **23**, 502 (1952).

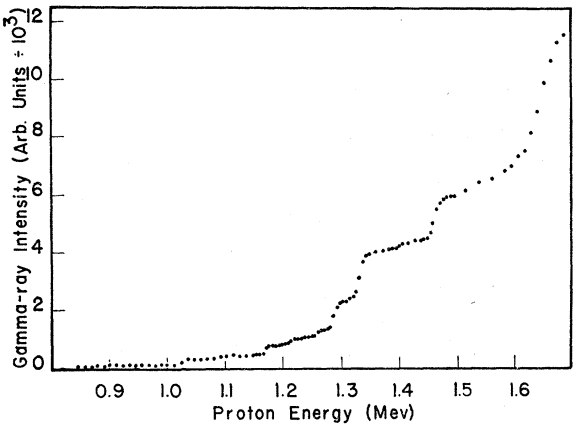

FIG. 1. The γ-ray yield observed when a thick sodium target was bombarded with protons.

The pulses from the photomultiplier were amplified with a linear amplifier, counted by a scale-of-32, and observed simulataneously on a driven-sweep oscilloscope.[11]

The γ-ray yield was measured as a function of proton energy for both thick and thin targets. Since the observed γ-ray yield was very highly dependent upon amplifier setting and the bias of the discriminator in the scaler, a procedure was adopted of counting pulses of height equal to or greater than those produced when a Cs^{137} source was placed near the detector. With this procedure, it was found necessary to shield the counter with several inches of lead in order to decrease the background caused by bremsstrahlung radiation from the electrostatic generator and by radiation induced by ions striking other than target atoms. Even with such shielding, the background radiation was sufficiently large to make it necessary to apply a background correction. The correction was obtained by intercepting the proton beam with a tantalum plate just ahead of the target. All γ-ray yields were normalized to equal numbers of bombarding protons. The relative numbers of protons per run were measured with a current integrator of the type developed by Gittings.[12]

The γ-ray spectrum resulting from the decay of the compound nucleus was obtained by photographing the pulse-height distribution observed on the oscilloscope. To prevent fogging of the film, all pulses smaller than those produced by the γ rays from Cs^{137} were rejected by adjusting the discriminator bias control on the X-axis sweep. This discrimination caused each pulse to appear to start slightly above the true base line. To facilitate the measurement of the pulse height, the edge-lighted grid furnished with this model oscilloscope was illuminated for about one second during each exposure. This procedure superimposed a rectangular coordinate system on all photographs. At the customarily used sweep speed of 1 cm/μsec, the pulses did not recover from overshoot during the 12-cm sweep. For the purpose of aligning the bottom of the coordinate grid with the base line of the pulses, pulses were observed visually at a reduced sweep speed of 0.01 cm/μsec, and the Y-position control of the oscilloscope was adjusted until the trace following the overshoot coincided with the bottom line of the grid.

Gamma-ray energies ranging between 700 kev and 18 Mev were observed. Care was taken that neither the linear amplifier nor the amplifier in the oscilloscope was ever used at such high gain that appreciable nonlinearity of pulse amplification resulted. Two different gain settings were used on the oscilloscope: one for observing γ rays of energy greater than 3 Mev, another for low-energy γ rays. During all runs the high voltage on the photomultiplier tube was maintained at 650 volts, and the linear amplifier gain was kept constant. A 1-cm thick NaI(Tl) crystal was used for the observation of the low-energy γ rays, whereas the high-energy γ rays were detected with a $1\frac{1}{2}$-in. thick crystal.

The system was calibrated by photographing pulse-height distributions corresponding to γ rays of known energy. Cs^{137} and Sb^{124} sources were used at low energies, whereas the γ rays resulting from the proton bombardment of thick targets of lithium and fluorine gave calibration points at high energy. In a typical run, Sb^{124} and Cs^{137} sources were placed, one at a time, near the γ-ray detector and calibration photographs taken for each source. These sources were then removed, and a fresh thin sodium target was bombarded at various energies with a proton beam of about 1 microampere for approximately 2 hours. The target chamber was then opened, and a tantalum calibration disk was inserted just ahead of the target. One side of the calibration disk had been treated with hydrofluoric acid, and a thick slice of lithium was pinned to the other side. Calibration photographs were taken while one side of the disk was bombarded with protons of about 1 Mev; then the disk was reversed, and a calibration was made with the other side in place. The calibration disk and the previously used sodium target were then removed from the target chamber and a fresh sodium target inserted. So that the effects of carbon deposits would be minimized, no targets were ever bombarded for more than two hours.

RESULTS

Gamma-ray yields were obtained as a function of proton bombarding energies varying between 0.85 and 1.70 Mev. Figure 1 shows the results obtained from a typical thick target. Figure 2 summarizes the work done with thin targets. The upper portion of the graph shows the γ-ray yield over the entire energy range as obtained with a target prepared by heating tungsten in an oxygen atmosphere. The individual resonance peaks shown in the lower portion are the results of experiments with very thin evaporated sodium targets. The thicknesses of these evaporated targets were calcu-

[11] Model 514D Tektronix.
[12] H. T. Gittings, Rev. Sci. Instr. **20**, 325 (1949).

lated by the method described by Fowler *et al.*[13] The area under each of several resonances was divided by the height of the corresponding step in the thick target curve. Such calculations were made for the resonances at 1164, 1284, 1330, and 1459 kev, and in each case the target thickness was found to be less than 500 ev.

The resonance peaks in Fig. 2 that are due to sodium are indications of excited levels in Mg^{24}. Since the target thickness was found to be negligibly small, the energies of the excited states in Mg^{24} can be calculated by the equation $E_e=11.74+(23/24)E_m$, where E_e is the excitation energy in Mev and E_m is the proton energy in Mev (in the laboratory system) at which a maximum occurs for the γ-ray yield.

The proton energies at which resonance maxima appear and the corresponding values of the excited states in Mg^{24} are listed in Table I. Also shown are the relative intensities of the resulting radiation and the width of the resonances at half-maxima. All values were read from the lower portion of Fig. 2. The two resonance peaks shown at 1.328 and 1.332 Mev on the lower curve may or may not be due to separate energy levels in the Mg^{24} nucleus. Resolution of the two peaks has been obtained only with this particular set of data and therefore must be considered very dubious. The small shoulder shown at 1.320 Mev is quite definite and has been reproduced many times. With the bias of the discriminator set to reject pulses due to photons of energy less than 2 Mev, a small peak is observed at 1.320-Mev proton energy and no peak is observed at 1.328 or 1.332 Mev.

The two peaks labeled *F* on each curve in Fig. 2 are very probably due to fluorine.‡ The proton energies at which these resonances occur, as well as the energy of the γ rays emitted, leave no doubt as to their identification. Pulse-height analysis of the γ-ray spectrum shows that part of the resonance structure above 1.6 Mev is also due to fluorine. In spite of the likelihood of carbon deposits on the targets, no evidence was found that any of the resonances observed could be attributed to carbon contamination.

TABLE I. The proton energies at which resonance maxima appear in the γ-ray yield curve obtained when Na^{23} was bombarded with protons, the corresponding values of excited states in Mg^{24}, the relative intensities of the radiation, and the width of the resonances at half-maxima.

Proton energy at resonance (Mev)	Energy of excited states of Mg^{24} (Mev)	Width at half-max (kev)	Relative peak height	Relative intensity (height × width)
1.009	12.71	4	1.5	6
1.020	12.72	6	1.5	9
1.094	12.79	10	0.8	8
1.164	12.86	4	4.1	16
1.212	12.90	4	3.1	12
1.256	12.94	4	3.6	14
1.284	12.97	8	7.1	57
1.320	13.01			
1.330	13.02	10	10.4	104
1.395	13.08	4	3.0	12
1.417	13.10	4	3.0	12
1.459	13.14	12	9.8	118
1.647	13.32	33	10.7	353

[13] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1938).

‡ *Note added in proof.*—Private communication with E. Goldberg, University of California, shows that recent $Ne^{20}(\alpha,\alpha)Ne^{20}$ data indicate we should obtain a sodium resonance near 874 kev. Further investigation here has shown that the first peak labeled *F* is primarily due to fluorine but is also partially due to a small sodium peak at 877 kev. Further details on this measurement will be included in a later paper.

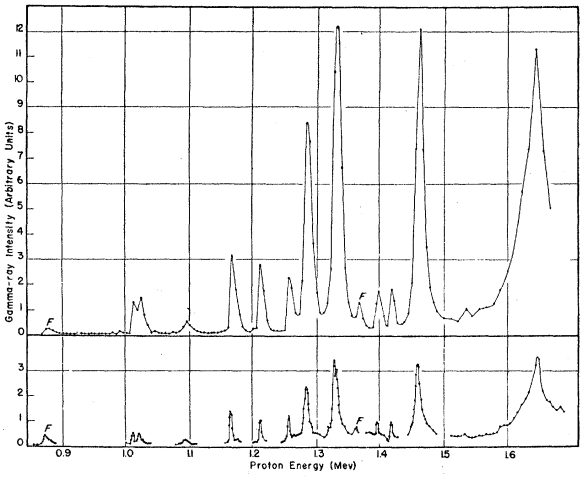

FIG. 2. The γ-ray yields observed when thin sodium targets were bombarded with protons. The upper yield curve was observed using targets prepared by heating tungsten sheet in an oxygen atmosphere. Sodium was found in the oxide layer thus formed. The lower yield curve was observed with use of targets prepared by vacuum evaporation of sodium onto tungsten backing material. The peaks labeled F are primarily the result of slight fluorine contamination of the targets.

Photographs of pulse-height distributions of the γ-ray spectrum observed at several of these resonances reveal that the compound nucleus decays by at least two different processes. Table II gives a summary of the results obtained from the present experiments. The occurrence of γ rays having energy of 1.6 Mev is undoubtedly the result of the well-known process $Na^{23}(p,\alpha)Ne^{20*}(\gamma)Ne^{20}$, whereas the high-energy γ rays observed at several of the resonances can only be understood by assuming transitions that lead ultimately to the ground state of Mg^{24}. With the experimental technique used, no precise determination of the γ-ray energies could be attempted. It was, however, possible to see whether a decay scheme could be established, assuming the existence of the energy levels in Mg^{24} that had been predicted from other experiments. Of those levels, the most accurately known occur at 1.37 and 4.14 Mev. Others have been shown to exist at 1.7, 5.5, 7.5, and 8.5 Mev, respectively.[6] Figure 3 shows an energy-level diagram of Mg^{24} in which the transitions consistent with the results of the present experiments are indicated. For completeness, the results obtained from other experiments are also included.

Many of the pulse-height distributions obtained showed the presence of a γ ray having energy of approximately 6 Mev. Such a γ ray can be attributed,

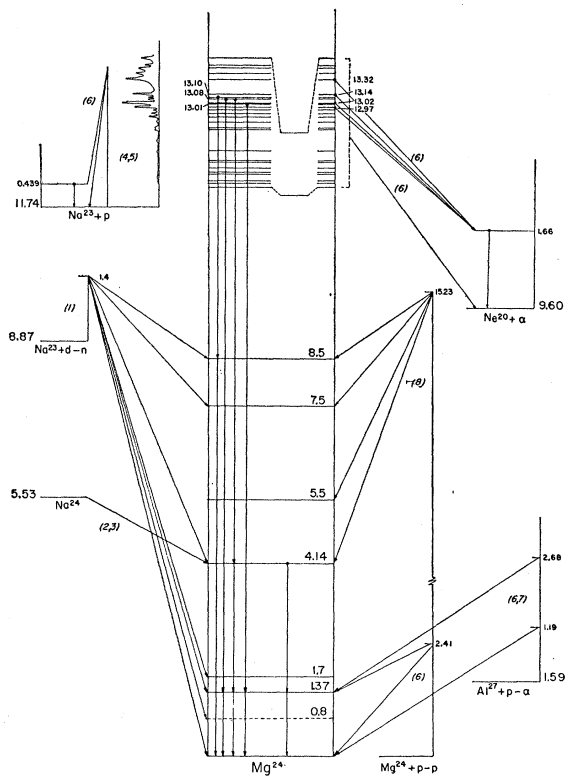

FIG. 3. Energy-level diagram of Mg^{24}. This energy-level diagram has been constructed using the results of the present work as well as published results of other investigations.§ The general form and notation are the same as that employed by F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952). The numbers in parentheses appearing in connection with several of the reactions refer to the following references: (1) C. E. Mandeville, Phys. Rev. **76**, 436 (1949); (2) M. L. Wiedenbeck, Phys. Rev. **72**, 429 (1947); (3) K. Siegbahn, Phys. Rev. **70**, 127 (1946); (4) R. L. Burling, Phys. Rev. **60**, 340 (1941); (5) R. Tangen, Kgl. Norske Videnskab. Selskabs Skrifter, 1946, No. 1 (1947); (6) Donahue, Jones, McEllistrem, and Richards, Phys. Rev. **89**, 824 (1953); (7) Shoemaker, Faulkner, Bouricius, Kaufmann, and Mooring, Phys. Rev. **83**, 1011 (1951); (8) H. W. Fulbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948).

within the limits of accuracy, to a transition from the 5.5-Mev state to the ground state of Mg^{24}. The failure to observe simultaneously a 7.5-Mev γ ray is not sufficient evidence to discount the possibility that the 6-Mev γ ray is emitted in a $Na^{23}(p,\gamma)$ process inasmuch as it is conceivable that it partakes in a many-step transition composed of several low-energy γ rays. The very large variation in intensity of this γ ray, obtained with different targets, left, however, little doubt that it was a result of fluorine contamination.

Examinations of many photographs of pulse-height distributions reveal that in no instance does there appear a one-step transition leading directly to the ground state of Mg^{24}. All the γ-ray cascades lead to the 1.37-Mev state with the exception of that from the 1.395-Mev resonance. For this resonance such a mode of decay is still apparent but much less intense than the two-step transition giving rise to the γ rays having energies of approximately 4.5 and 8.5 Mev, respectively. The results of investigations on the β decay of Na^{24} exclude the possibility of a single transition to the ground state from the 4.14-Mev state,[14] and therefore the alternative process indicated on the energy-level diagram is proposed.

It is of interest to note that in all those instances in which the (p,γ) process is operative there appears to be a conspicuous lack of short-range α particles leading to the first excited state of Ne^{20}. To be sure, there is some indication of the 1.6-Mev radiation at all the bombarding energies for which pulse-height distributions were taken, but the intensity is very low except at those particular energies at which this radiation is the only contributor to the resonances observed. This seems to suggest that the spins and parities of some of the compound states make this mode of decay from those states forbidden. With the information available no specific spin and parity assignments are possible. It is hoped that a more detailed study of the yield of the long- and short-range α particles and their angular distributions will lead to the additional information necessary for such assignments. Such a study is now in progress.

We wish to thank Mr. R. K. Smith, Mr. D. H. Byers, Mr. R. A. Moore, and Mr. R. B. Smith for their assistance in much of the experimental work.

TABLE II. Summary of the results of γ-ray energy determinations. Column 1 lists the excited states in Mg^{24} for which γ-ray energy determinations were made. Column 2 lists the energies of the γ rays observed. In calculating these energies from the electron energies of the pulse-height spectrum, it was assumed that all pulses corresponding to electron energies greater than 5 Mev were due to the pair process. The lower-energy γ rays were observed as two peaks, one resulting from the photoelectric process, the other from the Compton process. The γ rays listed in parentheses were extremely weak and should be considered questionable. Column 3 shows the reaction giving rise to the most intense γ rays observed.

Energy of excited states in Mg^{24} (Mev)	γ-ray energies (Mev)	Dominant process
12.97	1.6	(p,α)
13.01	11.6; 1.37[a] (1.6)	(p,γ)
13.02	1.6	(p,α)
13.08	4.5; 8.5 (11.9; 1.37) (1.6)	(p,γ)
13.10	9.0; 2.76; 1.37 (1.6)	(p,γ)
13.14	1.6	(p,α)
13.32	1.6	(p,α)

[a] The energies of 1.37- and 2.76-Mev γ rays could not be determined to the accuracy indicated. The values given for these two energies are in accordance with determinations from other experiments.

§ *Note added in proof.*—Errata in Fig. 3: The left-hand vertical decay line should start at 13.08 Mev. The third from the left verticle decay line should start at 13.10 Mev. See Table II.

[14] M. L. Wiedenbeck, Phys. Rev. **72**, 429 (1947).