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Precision Determination of Gamma Rays Following $(p,p'\gamma)$ and $(p,n\gamma)$ Reactions*

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The gamma rays following $(p,p'\gamma)$ or $(p,n\gamma)$ reactions in seven isotopes have been studied with a bent quartz-crystal spectrograph. The intense gamma-ray sources necessary for such experiments were provided by bombarding various target materials with large proton-beam currents from the A-48 accelerator. The following reactions and associated gamma rays have been observed: $F^{19}(p,p'\gamma)$, 109.87±0.04 kev; $Ti^{49}(p,n\gamma)V^{49}$, 90.65±0.02 kev, 62.29±0.01 kev; $Mn^{55}(p,p'\gamma)$, 125.87±0.05 kev; $Ni^{61}(p,p'\gamma)$, 67.40±0.01 kev; $Cu^{65}(p,n\gamma)Zn^{65}$, 53.93±0.01 kev, 61.20±0.01 kev, 115.09±0.04 kev; $Ge^{73}(p,p'\gamma)$ 67.03±0.01 kev, and $Se^{80}(p,n\gamma)Br^{80}$ 37.05±0.01 kev.

I. INTRODUCTION

A SERIES of experiments in which the high proton-beam current produced by the A-48 linear accelerator was used in conjunction with a bent quartz-crystal spectrograph to make precise measurements of the wavelengths of nuclear gamma rays has been discussed in a previous paper.[1] The primary aim of these experiments was to study gamma rays following the electric (or Coulomb) excitation of heavy nuclei with 3.7-Mev protons. During the course of this work, it was discovered that gamma rays caused by other nuclear processes [such as $(p,n\gamma)$ reactions, $(p,p'\gamma)$ processes in which the proton enters the nucleus, and short-lived isotopes produced at the target by the proton beam] could also be observed with the bent quartz-crystal spectrograph.

Since the calculations which could be made indicated that neutron darkening of the plate (from recoil tracks and capture gamma rays) would make detection of lines difficult, the ability to observe nuclear gamma rays in the presence of other, neutron-producing reactions had to be demonstrated experimentally. It was found that in cases where the ratio of the number of gamma rays being measured to the number of neutrons produced was of the order of 0.2 or more, successful exposures could be made. The details of each exposure are discussed in Sec. III.

TABLE I. Wavelengths of calibration lines.

Element	Line	Wavelength in Siegbahn x units	Reference
Tantalum	$K_{\alpha 2}$	219.846±0.010	a
	$K_{\alpha 1}$	215.050±0.010	a
Wolfram	$K_{\alpha 2}$	213.382±0.010	a
	$K_{\alpha 1}$	208.571±0.010	a
	$K_{\beta 3}$	184.795±0.010	a
	$K_{\beta 1}$	183.991±0.010	a
Wolfram	Gamma rays	188.259±0.018	b
	from nuclear	182.638±0.018	b
	levels in W^{182}	123.599±0.014	b

[a] E. Inglestam, Nova Acta Regiae Soc. Sci. Upsaliensis **4**, No. 5 (1936).
[b] Murray, Boehm, Marmier, and DuMond, Phys. Rev. **97**, 1007 (1955).

A serious limitation of the present experiments is that the bent quartz-crystal spectrograph operated as in reference 1 is useful principally for the measurement of gamma-ray energies in the 100-kev region. In lighter nuclei ($Z<40$), levels in this energy region are relatively rare compared to the heavier elements so that a systematic study of the low-lying levels in a series of isotopes is not possible. A compensating feature is that the cross sections for producing nuclear gamma rays in light isotopes may be as much as an order of magnitude larger than typical electric excitation cross sections. This has the consequences that much shorter exposure times are possible in some cases and that gamma rays resulting from isotopes with low abundances (~1%) can be observed in other cases.

II. EXPERIMENTAL METHODS

The experimental methods used in the present work were similar to those described in reference 1. The neutron count during each run was monitored by a lithium iodide neutron scintillation counter in order to adjust the exposure time to prevent severe darkening of the nuclear emulsions. In two cases, it was found expedient to operate the machine at 1.8 Mev by turning off the final accelerating stage.

The spectral plates were calibrated by exposing a Ta^{182} source in the spectrograph before or after each exposure. The wavelengths of all the calibration lines used in these experiments are shown in Table I. The methods used to calculate the wavelengths, λ, and the

TABLE II. Spectrograph radius computed from the calibration lines on the various plates.

Plate	Spectrograph radius in millimeters
Fluorine	1992.6±0.8
Titanium (No. 1)	1992.2±0.8
Titanium (No. 2)	1993.9±0.8
Manganese	1992.7±0.9
Nickel	1990.1±0.8
Copper	1992.1±0.8
Germanium	1992.3±0.8
Selenium	1992.6±0.8

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[1] Chupp, DuMond, Gordon, Jopson, and Mark, Phys. Rev. **112**, 518 (1958).

TABLE III. Wavelengths and energies of all nuclear gamma rays observed in these experiments.

Bombarded element	Reaction	Wavelength in Siegbahn x units	Energy in kev	Best previous value of energy	Reference
Fluorine	$F^{19}(p,p'\gamma)$	112.61 ± 0.04	109.87 ± 0.04	109	b (scint.)
Titanium (Plate No. 1)	$Ti^{49}(p,n\gamma)V^{49}$	136.48 ± 0.03	90.65 ± 0.02	89 ± 1	c (scint.)
		198.63 ± 0.02	62.29 ± 0.01[a]	63 ± 1	c (scint.)
	Unknown	131.50 ± 0.03	94.09 ± 0.02	···	···
Titanium (Plate No. 2)	$Ti^{49}(p,n\gamma)V^{49}$	136.50 ± 0.08	90.64 ± 0.05	89 ± 1	c (scint.)
		198.64 ± 0.02	62.28 ± 0.01[a]	63 ± 1	c (scint.)
	Unknown	131.53 ± 0.08	94.07 ± 0.05	···	···
	Unknown	349.72 ± 0.18	35.38 ± 0.02	···	···
Manganese	$Mn^{55}(p,p'\gamma)$	98.30 ± 0.04	125.87 ± 0.05	125	d (conv.)
Nickel	$Ni^{61}(p,p'\gamma)$	183.57 ± 0.02	67.40 ± 0.01	70	e (scint.)
Copper	$Cu^{65}(p,n\gamma)Zn^{65}$	229.44 ± 0.02	53.93 ± 0.01	54	f (conv.)
		202.17 ± 0.02	61.20 ± 0.01[a]	65	f (conv.)
		107.50 ± 0.04	115.09 ± 0.04	119	f (conv.)
Germanium	$Ge^{73}(p,p'\gamma)$	184.59 ± 0.02	67.03 ± 0.01	67.8	g (scint.)
Selenium	$Se^{80}(p,n\gamma)Br^{80}$	333.95 ± 0.06	37.05 ± 0.01	37	h (scint.)

[a] Cascade gamma ray.
[b] See reference 2.
[c] See reference 4.
[d] See reference 5.
[e] See reference 6.
[f] See reference 9.
[g] See reference 12.
[h] See reference 13.

standard deviations, $\sigma(\lambda)$, of the unknown lines are identical to those described in reference 1. The radius parameter of the spectrograph, R, computed for each of the plates from the calibration lines, is shown in Table II, which is to be compared with the mechanical measurement of 1990.5±0.5 mm.

III. RESULTS

Ten materials, calcium fluoride, aluminum, titanium, manganese, cobalt, nickel, copper, zinc, germanium, and selenium were bombarded in the course of this work. The CaF, Mn, Ge, and Se targets were made by evaporating a thin layer of the material onto a copper plate. The Zn target was made by tinning copper with high-purity zinc. Solid metal targets of aluminum, cobalt, titanium, nickel, and copper were used.

No nuclear gamma rays were observed on the spectral plates obtained from the bombardment of aluminum, cobalt, and zinc. At least one nuclear gamma ray was present on each of the remaining nuclear emulsion plates. The wavelengths and energies of the observed nuclear gamma rays[2–13] are shown in Table III. The origin of the lines and the best previous energy measurements are also shown.

Calcium Fluoride (Ca, $Z=20$; F, $Z=9$)

A calcium fluoride target was exposed to the 1.8-Mev proton beam for 6.6-milliampere hours. One nuclear gamma-ray line at 109.87 kev was observed on the plate. This gamma ray results from the reaction $F^{19}(p,p'\gamma)$. Previous measurements[2,3] have shown that there is a level in F^{19} at this energy and the line is therefore assigned to this isotope. No nuclear lines were observed which could be attributed to reactions in the isotopes of calcium. No neutrons were produced during this exposure, since 1.8 Mev is below the threshold for neutron production in the copper target backing.

Titanium ($Z=22$)

Two spectral plates were made by bombarding titanium with 3.7-Mev protons. The first was exposed for 20 milliampere hours and the second for 11 milliampere hours. Three nuclear-gamma ray lines at 62.29 kev, 90.65 and 94.09 kev were observed on the first plate. On the second plate, four nuclear gamma-ray lines were present, three of which had energies very close to those observed on the first plate, while the energy of the fourth was 35.38 kev. The second plate was made because the presence of the low-energy line was indicated on a test strip placed in the low-energy end of the spectrograph during the first exposure. To demonstrate the excellent reproducibility of the measurements, the results for both plates are listed in Table III.

The lines on the first plate at 62.29 and 90.65 kev are produced by the reaction $Ti^{49}(p,n\gamma)V^{49}$ in 5.5% abundant Ti^{49}. The threshold for this reaction is

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[2] Sherr, Li, and Christy, Phys. Rev. **94**, 1076 (1954), and **96**, 1258 (1955).

[3] R. B. Day, Phys. Rev. **89**, 908(A) (1953).

[4] Nussbaum, Wapstra, Nijgh, Ornstein, and Verster, Physica **20**, 165 (1954).

[5] Huus, Bjerregard, and Elbek, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 17 (1956).

[6] Housman, Allen, Arthur, Bender, and McDole, Phys. Rev. **88**, 1296 (1952).

[7] Fagg, Geer, and Wolicki, Phys. Rev. **104**, 1074 (1956).

[8] Nussbaum, Wapstra, Bruil, Sterk, Nijgh, and Grobben, Phys. Rev. **101**, 905 (1956).

[9] E. M. Bernstein and H. W. Lewis, Phys. Rev. **107**, 737 (1957).

[10] Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955), and J. B. Marion and R. A. Chapman, Phys. Rev. **101**, 283 (1956).

[11] Welker, Schardt, Friedlander, and Howland, Phys. Rev. **92**, 401 (1953).

[12] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **96**, 430 (1954), and **104**, 967 (1956).

[13] E. Breitenberger, Proc. Phys. Soc. (London) **A69**, 453 (1956).

1.42 Mev. Gamma rays at similar energies (63±1 and 89±1 kev) have been observed[4] in the β decay of Cr^{49}. The first excited level in this isotope, according tf reference 4, is at 89±1 kev, and the second level is at 150±1 kev. A cascade gamma ray at 63±1 kev is also observed. The assignment of the 90.65-kev gamma ray to the first excited level and the 62.29-kev line to the cascade transition between the second and first level in V^{49} is made on the basis of these data. No line was found at 150 kev. Since the efficiency of the spectrograph at 150 kev is a factor of 20 smaller than at 60 kev this circumstance is not surprising. No reasonable isotopic assignment can be made for the gamma rays at 94.09 kev and 35.38 kev (second plate). The possibility that they may come from impurities in the target material cannot be ruled out.

The most abundant isotope of titanium, Ti^{48}, did not contribute to the neutron background since the $Ti^{48}(p,n)$ threshold is above 3.7 Mev. It is this circumstance which made it possible to observe gamma rays produced in an isotope of relatively low abundance. No gamma rays arising from the electric excitation of titanium isotopes were observed.[5]

Manganese ($Z=25$)

A manganese target was bombarded with 1.8-Mev protons for 189 milliampere hours. One nuclear gamma-ray line at 125.87 kev was observed on the resulting nuclear emulsion. This gamma ray corresponds to the first excited level in Mn^{55} and is produced[5,6] by the reactions $Mn^{55}(p,p'\gamma)$. The neutron yield of the Mn^{55} reaction is sufficiently low at 1.8-Mev proton energy so that no severe background effects were present.

Nickel ($Z=28$)

A solid nickel target was bombarded for 102 milliampere hours with 3.7-Mev protons. One nuclear gamma-ray line was observed on the nuclear emulsion at 67.40 kev. A gamma ray at 70 kev has been observed in Ni^{61} in the course of electric excitation experiments[7] with separated isotopes of this element. The 67.40-kev line is therefore identified with the first excited level in Ni^{61}. The rather long exposure time necessary to observe this line supports the above assignment since the natural abundance of Ni^{61} is only 1.2%.

The (p,n) reaction in Ni^{61} produces Cu^{61} which decays to Ni^{61} with a half-life of 3.3 hours by positron emission. It is known[8] that the positron decay of Cu^{61} populates a level at about 70 kev in Ni^{61}. The presence of large amounts (~several millicuries) of Cu^{61} on the target substantially enhances the intensity of the observed gamma if, as is likely, the level populated by the decay of Cu^{61} is the same line observed in the electric excitation of Ni^{61}. No neutrons are produced from 3.7% abundant Ni^{62} or 26.2% abundant Ni^{60}, since the thresholds for the (p,n) reactions in these isotopes are above 3.7 Mev. Neutrons from the (p,n) reaction in 1% abundant Ni^{64} can contribute to the observed background. The effects due to 67.9% abundant Ni^{58} are not known.

Copper ($Z=29$)

The gamma rays observed from the copper backings of evaporated metal targets have been described in reference 1. A pure copper target was exposed to the 3.7-Mev proton beam for 17 milliampere hours. Three nuclear gamma rays at 53.93, 61.20, and 115.09 kev were observed. These gamma rays are caused by the reaction $Cu^{65}(p,n\gamma)Zn^{65}$ which has a threshold energy of 2.17 Mev. The observed lines are in good agreement with the proposed decay scheme given by Bernstein and Lewis.[9] According to this level scheme, the 53.93-kev gamma ray is the transition from the first excited level to the ground state, the 115.09-kev line is the transition between the second excited level and the ground state and the gamma ray at 61.20 kev is the cascade transition between these levels. The energies shown in Table III should be compared with the measurements of the same gamma rays given in reference 1, where these lines were encountered as an important background effect. The good agreement between the present energies and those obtained previously is another indication of the reliability of the measurements.

Two neutron-producing reactions, $Cu^{65}(p,n)Zn^{65}$ with a threshold of 2.17 Mev and $Cu^{63}(p,n)Zn^{63}$ with a threshold at about 4 Mev, are observed when copper is bombarded with the high-energy proton beam from the A-48. [The $Cu^{63}(p,n)Zn^{63}$ threshold is slightly above the rated energy of the machine but the energy spread of the beam is sufficient to cause an appreciable number of reactions.] The $Cu^{65}(p,n)Zn^{65}$ and $Cu^{65}(p,n\gamma)Zn^{65}$ reactions have been studied in some detail. It has been shown[10] that the ground state of Zn^{65} and the 115.09-kev level in this isotope are about equally populated by the (p,n) reaction. The gamma-ray-to-neutron ratio is, therefore, sufficiently high to permit successful observation of the gamma rays. The $Cu^{63}(p,n)Zn^{63}$ reaction probably does not contribute substantially to the background, since not all protons in the beam are effective in producing the reaction.

Germanium ($Z=32$)

A germanium target was bombarded with 3.7-Mev protons for 24 milliampere hours. One nuclear gamma-ray line at 67.03 kev was observed. A nuclear gamma ray at 67.8 kev has been observed in the electric excitation experiments with separated germanium isotopes.[10] The 67.03-kev level is, therefore, identified with the first excited level in 7.8% abundant Ge^{73} on the basis of previous work. The exposure time necessary to observe this line is consistent with this interpretation.

An excited level at 67.4 kev in Ge^{73} has been observed[11] in the decay of As^{73}. This level decays by the cascade emission of two gamma rays of 53.9 and 13.5 kev. No evidence of the presence of the 67.4-kev crossover gamma ray has been found. Temmer and Heydenburg[12] have pointed out that this 67.4-kev level is not the level observed at about the same energy in Ge^{73} by electric excitation. It follows, therefore, that the 76-hour As^{73} activity on the target does not contribute to the intensity of the observed line. No evidence of the 53.9-kev gamma ray reported in reference 11 was observed. This can be explained in terms of the long half-life of As^{73}, which results in source strengths at the target not sufficient for succesful exposures.

Selenium ($Z=34$)

A selenium target was bombarded for 13.6 milliampere hours with 3.7-Mev protons. One nuclear gamma-ray line was observed at 37.05 kev. The most probable origin of this line is the reaction $Se^{80}(p,n\gamma)Br^{80}$ on 49.9% abundant Se^{80}. The threshold of the (p,n) reaction is about 2 Mev. A decay scheme for Br^{80} has been established.[13] The ground-state spin of Br^{80} is 1^+. The first excited level in Br^{80} is at 37 kev and has a spin of 2^- and the second excited level is at 86 kev with a spin of 5^-. The second level decays by emitting a 49-kev gamma ray to the first level with a half-life of 4.5 hours, and the first level then decays promptly to the ground state by emitting a 37-kev gamma ray. The $Se^{80}(p,n\gamma)Br^{80}$ reaction can readily populate the first excited level in Br^{80}, since the largest spin change in the reaction is 2. The observed 37.05-kev gamma ray is, therefore, assigned to the first excited level in Br^{80}. No gamma ray at 49 kev was observed. This is not surprising since the large spin change (5) involved makes it difficult to populate the second level in Br^{80}. Further work on this reaction should be done to confirm this assignment.

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