

in Fig. 3 along with the theoretically expected correlation function of a 2-2-0 spin sequence and pure quadrupole-quadrupole transitions. The observed anisotropy at 180° , 0.14, is greater than would be expected for such a cascade of transitions. Accordingly, a theoretical correlation function with the first emitted gamma ray a mixture of $E2$ in $M1$ to the extent of 99.56%, has been plotted and appears to agree well with the observed correlation function corrected for finite angular resolution. Thus it is concluded that the 480-kev gamma ray is a mixture of $E2$ in $M1$ with the

aforementioned percent of mixture. The mixing ratio was found to be positive, corresponding to a phase difference of 180° between the matrix elements of the two types of transition.

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Gamma Radiation from Inelastic Scattering of Fast Neutrons by Isotopes of Tellurium, Nickel, and Copper*

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Gamma radiation from 4.4 ± 0.1 Mev neutron bombardment of separated isotopes was observed with a single crystal NaI(Tl) spectrometer. Gamma rays assigned to inelastic scattering are (energies in Mev): Te^{126} , 0.68 ± 0.02 , 1.38 ± 0.04 ; Te^{128} , 0.76 ± 0.02 ; Te^{130} , 0.83 ± 0.02 ; Ni^{58} , 1.01 ± 0.01 , 1.46 ± 0.02 ; Cu^{68} , 0.65 ± 0.01 , 0.97 ± 0.01 , 1.34 ± 0.03 , 1.43 ± 0.05 ; Cu^{65} , 1.12 ± 0.02 . A 1.35 ± 0.02 Mev gamma ray is assigned to Ni^{60} by elimination. Relative yields of the gamma rays are given and their assignment to various excited states of the target nuclei is discussed.

INTRODUCTION

THE study of fast neutron scattering by observations of the de-excitation gamma rays has received considerable attention in the past few years. The technique has proved useful for monoisotopic elements with widely spaced excited states, so that the various gamma rays can be resolved with the commonly used scintillation counters. The use of enriched isotopes as scatterers now makes possible the study of polyisotopic elements for which the gamma rays from the various isotopes in an elemental scatterer cannot be resolved because of instrumental overlap. The isotopic assignments that can be made allow more positive

correlations of these gamma rays with quantities measured by other experimental methods.

Gamma ray energies and yields can be used, together with general arguments based on nuclear systematics, to locate the excited states. These assignments cannot be unambiguous unless other data on the approximate location of the levels, preferably from measurements of the scattered neutron spectra, are available. The gamma ray energies can then be used to locate these levels accurately.

EXPERIMENTAL

The experimental method has been described previously.¹ Neutrons of energy 4.4 ± 0.1 Mev were

TABLE I. Isotopic composition (percent) and weight (grams) of tellurium samples.^a

Isotope	Te^{125} Sample No. 1 ^b	Te^{125} Sample No. 2 ^c	Te^{126} Sample No. 1 ^d	Te^{126} Sample No. 2 ^e	Te^{128} Sample No. 1 ^f	Te^{128} Sample No. 2 ^g	Te^{130} Sample No. 1 ^h	Te^{130} Sample No. 2 ⁱ	Normal Te
Te^{120}	...	<0.030	<0.001	0.045	0.042	<0.1	0.013	0.039	0.090
Te^{122}	0.1	0.112	0.096	0.055	0.097	<0.1	0.020	0.032	2.47
Te^{123}	0.3	0.140	0.034	0.043	0.027	<0.1	0.020	0.020	0.89
Te^{124}	1.4	1.98	5.60	0.247	0.480	<0.1	0.052	0.030	4.74
Te^{125}	87.9	80.53	0.661	1.33	0.502	0.2	0.077	0.051	7.03
Te^{126}	6.8	12.66	89.68	93.46	12.84	1.5	0.513	0.164	18.72
Te^{128}	2.4	3.36	3.32	3.95	82.32	94.4	21.07	1.88	31.75
Te^{130}	1.1	1.19	0.609	0.852	3.69	3.9	78.23	97.78	34.27
Weight	1.58	1.27	4.35	3.19	8.72	5.67	4.65	3.35	45.7

^a Other elements are present in negligible amounts. ^b Oak Ridge National Laboratory Lot No. CA296(ar). ^c FE644(a). ^d DX510(a). ^e FE645(a) DX511(a). ^f CA298(a). ^g DX512(a). ^h FE647(a).

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¹ R. M. Sinclair, Phys. Rev. **99**, 1351 (1955).

TABLE II. Isotopic composition (percent) and weight (grams) of nickel samples.^a

Isotope	Ni ⁵⁸ sample ^b	Normal Ni
Ni ⁵⁸	99.94	67.8
Ni ⁶⁰	0.06	26.2
Ni ⁶¹	...	1.2
Ni ⁶²	...	3.7
Ni ⁶⁴	...	1.1
Weight	21.182	45.5

^a Other elements are present in negligible amounts.
^b Oak Ridge National Laboratory Lot No. FJ669(a).

TABLE III. Isotopic composition (percent) and weight (grams) of copper samples.^a

Isotope	Cu ⁶³ sample ^b	Cu ⁶⁵ sample ^c	Normal Cu
Cu ⁶³	99.5	2.60	69.09
Cu ⁶⁵	0.5	97.41	30.91
Weight	32.682	9.953	43.5

^a Other elements are present in negligible amounts.
^b Oak Ridge National Laboratory Lot No. GT849(a).
^c GT850(a).

produced by the bombardment of a deuterium gas target by deuterons accelerated in the Westinghouse electrostatic generator. A 1½ in. × 1½ in. cylindrical NaI(Tl) crystal, 6292 photomultiplier, and conventional electronics measured gamma radiation from various scatterers. The crystal was shielded from the neutron source by a 10-in. tungsten wedge. This spectrometer was calibrated with gamma rays of known energy from radioactive sources: Na²² (0.511 Mev and 1.277 Mev), Cs¹³⁷ (0.662 Mev), and Sb¹²⁴ (1.71 Mev).²⁻⁴ In each

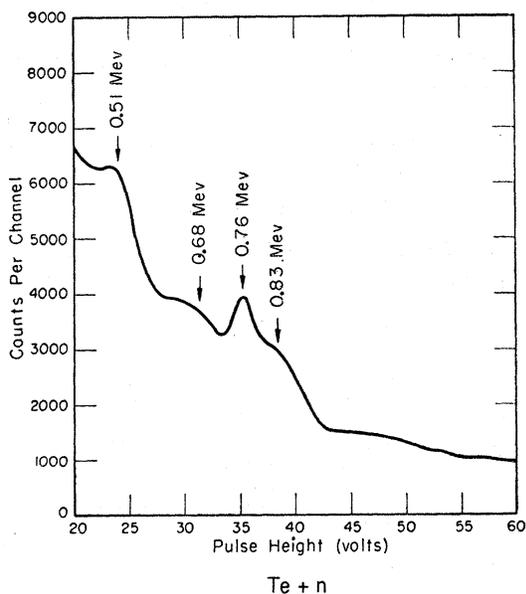


FIG. 1. Pulse-height curve obtained with normal tellurium sample. Neutron energy = 4.4 ± 0.1 Mev. Analyzer channel width = 1.0 volt.

² Muller, Hoyt, Klein, and DuMond, Phys. Rev. **88**, 775 (1952).

³ D. E. Alburger, Phys. Rev. **76**, 435 (1949).

⁴ N. H. Lazar, Phys. Rev. **95**, 292 (1954).

case, gamma rays were chosen on each side of the one being measured, and the spectrometer calibration curve was interpolated linearly.

Relative yields of the gamma rays were obtained by comparing the photopeak areas and correcting for the isotopic abundances, scatterer masses, and the energy-dependent photopeak efficiency of the spectrometer.⁵ No corrections were made for multiple neutron scattering or possible anisotropy of the gamma rays.

Isotopically enriched samples of tellurium, nickel, and copper were obtained on loan from the Stable Isotopes Research and Production Division, Oak Ridge National Laboratory. Each sample was in the elemental form, as a block 1 in. × 1 in. with a thickness determined by the amount and density. In the cases when two samples of a given isotope were furnished, they were

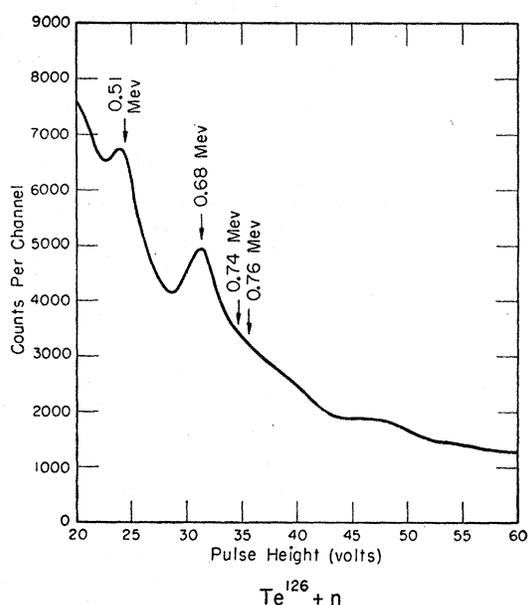


FIG. 2. Pulse-height curve obtained with Te¹²⁶ samples. Neutron energy = 4.4 ± 0.1 Mev. Analyzer channel width = 1.0 volt.

placed together to form a thicker 1 in. × 1 in. scatterer. The sample having the greater enrichment of the isotope being studied was placed nearer the NaI(Tl) crystal. Tables I-III give the results of mass spectrographic analyses of the samples, as reported by Oak Ridge National Laboratory. Also shown are the compositions and weights of normal isotopic scatterers used for comparison.

RESULTS

Figures 1-4 show typical pulse-height curves obtained with the normal and enriched tellurium samples. No gamma rays could be detected from the small Te¹²⁵ sample.

Table IV lists the energies and yields of the gamma rays assigned to neutron inelastic scattering. Radiation

⁵ Woodbury, Tollestrup, and Day, Phys. Rev. **93**, 1311 (1954).

of ~ 0.51 Mev was observed from all the samples, and is presumably annihilation radiation. No other gamma rays were detected. Some weakly excited gamma rays reported previously^{6,7} could not be observed from these small samples. The figures for the relative isotopic cross section for production of each gamma ray are normalized for each element. Errors quoted are twice the probable errors of the average of a number of measurements, to allow for systematic errors.

DISCUSSION
Tellurium

Other observers using normal tellurium report gamma rays of energy 0.72, 1.10, 1.43, and 2.30 Mev.⁶ All the curves using Te scatterers, a C scatterer, and those using no scatterer showed a peak at ~ 1.05 Mev in the

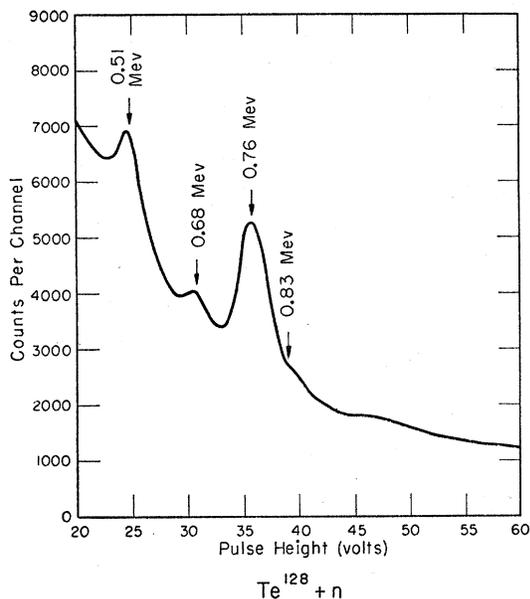


FIG. 3. Pulse-height curve obtained with Te¹²⁸ samples. Neutron energy = 4.4 ± 0.1 Mev. Analyzer channel width = 1.0 volt.

present work, which is ascribed to neutron interactions in the NaI.⁶ Another background peak at ~ 1.7 Mev, present on all the curves, masked any radiation from the second states in Te¹²⁸ and Te¹³⁰.

The gamma rays from Te¹²⁶ correspond in energy to ground-state transitions from the first and second excited states, which are known from studies^{8,9} of the decay of I¹²⁶. This other work has shown, however, that when the second level is formed by electron capture, it decays to the first state by emission of a 0.74-Mev gamma ray about ten times as often as by the cross over

⁶ Scherrer, Allison, and Faust, Phys. Rev. **96**, 386 (1954).

⁷ R. B. Day, International Conference on Peaceful Uses of Atomic Energy, A/Conf.8/P/581, 1955 (to be published), and references cited therein.

⁸ M. L. Perlman and Joan P. Welker, Phys. Rev. **95**, 133 (1954).

⁹ Koerts, Macklin, Farrelly, van Lieshout, and Wu, Phys. Rev. **98**, 1230 (1955).

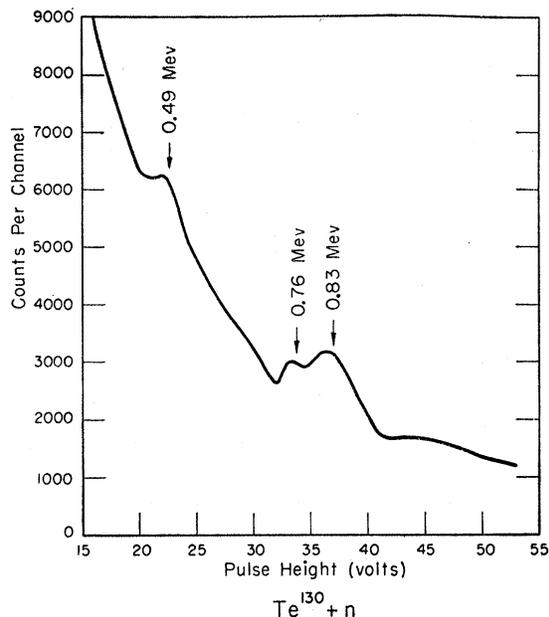


FIG. 4. Pulse-height curve obtained with Te¹³⁰ samples. Neutron energy = 4.4 ± 0.1 Mev. Analyzer channel width = 1.0 volt.

to the ground state. In the present work, this 0.74-Mev radiation would be expected to be $(0.2/0.6) \times 10 \approx 3$ times as intense as the 0.68-Mev gamma ray. The photopeak from the latter has only a small tailing on the high side, which can be accounted for by the Te¹²⁸ present in the sample. Any 0.74-Mev gamma ray from Te¹²⁶ can be, at most, a few percent as intense as the 0.68-Mev radiation. This suggests that the 1.38-Mev gamma ray observed here is not a transition from the 2+ second state in Te¹²⁶. Yet there is no *a priori* reason why the excitation of the 2+ second state in Te¹²⁶ by fast neutrons should not be comparable to that of the 2+ first state. The reason for this anomaly is not apparent.

The 0.76- and 0.83-Mev gamma rays from Te¹²⁸ and Te¹³⁰ are assigned to transitions from the first excited states. These agree with the values of 0.75 Mev and 0.85 Mev for these states found by Coulomb excitation

TABLE IV. Gamma radiation from neutron inelastic scattering.

Isotope	Gamma ray energy (Mev)	Relative isotopic cross section (normalized to the most intense gamma ray from each element)
Te ¹²⁵	None detected	...
Te ¹²⁶	0.68 \pm 0.02	0.6 \pm 0.1
	1.38 \pm 0.04	0.2 \pm 0.1
Te ¹²⁸	0.76 \pm 0.02	0.7 \pm 0.1
Te ¹³⁰	0.83 \pm 0.02	1.0 \pm 0.3
Ni ⁵⁸	1.01 \pm 0.01	0.33 \pm 0.03
	1.46 \pm 0.02	1.0 \pm 0.1
Cu ⁶³	0.65 \pm 0.01	0.4 \pm 0.1
	0.97 \pm 0.01	1.0 \pm 0.1
	1.34 \pm 0.03	0.6 \pm 0.2
	1.43 \pm 0.05	0.2 \pm 0.1
Cu ⁶⁵	1.12 \pm 0.02	0.9 \pm 0.2

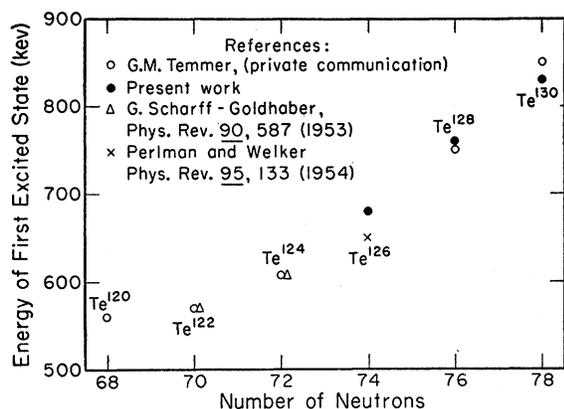


FIG. 5. Energy of the first excited state of the several tellurium isotopes.

using 6.5 Mev alpha particles.¹⁰ Figure 5 shows the energy of the first levels of the various tellurium isotopes, as determined by these and other experiments, and illustrates the behavior expected as the number of neutrons approaches 82.¹¹

Nickel

The previously reported^{6,7,12} 1.35-Mev and 1.46-Mev gamma rays were both observed from a normal nickel

¹⁰ G. M. Temmer (private communication).

¹¹ P. Stähelin and P. Preiswerk, *Nuovo cimento* **10**, 1219 (1953); G. Scharff-Goldhaber, *Phys. Rev.* **90**, 587 (1953).

¹² R. M. Kiehn and C. Goodman, *Phys. Rev.* **95**, 989 (1954).

sample, while only the latter was emitted by the Ni⁵⁸ sample. The 1.46-Mev gamma ray is therefore assigned to Ni⁵⁸ and the other, by elimination, to Ni⁶⁰. These confirm assignments⁷ made on the basis of energy comparison with the known first levels in Ni⁵⁸ at 1.453 Mev¹³ and Ni⁶⁰ at 1.3325 Mev.¹⁴ The 1.01-Mev gamma ray, detected from both the normal nickel and Ni⁵⁸ samples, is tentatively assigned to the second-first state transition in Ni⁵⁸.

Copper

The gamma rays observed from Cu⁶³ and Cu⁶⁵ have been reported previously.^{6,7} The present isotopic assignments again confirm those made by energy comparison⁷ as ground-state transitions from known states in Cu⁶³ at 0.669, 0.968, 1.326, and 1.410 Mev¹³ and in Cu⁶⁵ at 1.12 Mev.¹⁵

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¹³ Schiffer, Windham, Gossett, and Phillips, *Phys. Rev.* **99**, 621(A) (1955).

¹⁴ Lindström, Hedgran, and Alburger, *Phys. Rev.* **89**, 1303 (1953).

¹⁵ K. Siegbahn and A. Ghosh, *Phys. Rev.* **76**, 307 (1949).

Decay of Rn²²⁰ and Rn²²²†

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A gamma ray of energy 510 ± 2 kev and approximate intensity 7×10^{-4} quanta per decay is emitted in the alpha decay of Rn²²². A gamma ray of energy 542 ± 2 kev and approximate intensity 2.5×10^{-4} quanta per decay is emitted in the alpha decay of Rn²²⁰. The intensities are considered accurate only to within a factor of two.

THE alpha spectra of the radium and thorium emanations have been reported as simple, and no gamma rays were observed in the decay of these isotopes. Presuming that weak gamma rays, if present, might easily have escaped previous observations, we investigated the decay of Rn²²⁰ and Rn²²² by the following arrangement. The emanation was left to accumulate in an air volume of a few cubic centimeters above a solution containing about one millicurie of radiothorium or radium, respectively. In the case of radiothorium, owing to the short half-life of the emanation (54.5 seconds) it was important to spread the solution

in a thin layer on the bottom of a wide vessel, to allow the emanation to diffuse out of the liquid before decay. By opening a stopcock, the emanation could be quickly transferred through a long capillary tube to a previously evacuated, flat glass vessel placed immediately above an NaI(Tl) crystal 2 in. in diameter and 1 in. thick. Visual examination and photographs of the pulses on an oscilloscope screen immediately revealed in either case a gamma-ray photopeak of about 0.5-Mev energy.

With Rn²²⁰, the gamma ray decayed with the half-life of the emanation, indicating that it was emitted either in its decay, or in the decay of the short-lived (0.14-second) daughter nucleus, Po²¹⁶. To distinguish between

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