Resonance Scattering of Nickel Capture γ Rays from a Natural Tellurium Target

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The complex spectrum of resonantly scattered nickel neutron-capture γ rays from a natural tellurium target is shown to be predominantly associated with transitions from a 7.538-MeV excited level in ^{130}Te to several low-lying levels. The experiments were performed at a tangential-beam-tube facility of the IRR-2 reactor, using a nickel source placed adjacent to the reactor core. A large-volume lithium-drifted germanium detector was used to measure the γ spectrum. Coincidence measurements were performed using two sodium iodide crystals.

INTRODUCTION

WHEN monoenergetic neutron capture γ rays strike a target, nuclear resonant scattering occurs[1–5] if the energy of the capture γ line (after correction for target recoil) happens to overlap a nuclear level in the target nucleus. This phenomenon provides a powerful tool for the study of nuclear levels of stable nuclei.

Despite the "hit-or-miss" element in exciting a particular nuclear level, the possible use of many high-intensity neutron capture γ-ray sources and the availability of high-resolution germanium diodes now permit studies of these excitations in practically any high-mass stable nucleus.

In previous work[2] we examined 57 target elements, using 22 capture γ sources, and found some 50 different resonances. Inelastic transitions from resonant capture states have been studied by the coincidence technique[3] and in favorable conditions it was possible to identify the particular isotope responsible for the resonance from a knowledge of the level schemes. However, in view of the low neutron (and hence low capture γ) fluxes available for our previous experiments these studies were only possible for the strongest resonances, where there is a considerable scattered intensity. In the present work an improved experimental facility was used to study the tellurium levels, with nickel as the capture γ source. The new facility gives a γ flux about two orders of magnitude higher than the old one, thus permitting the use of lithium-drifted germanium counters to study both elastic and inelastic transitions.

EXPERIMENTAL FACILITY

The experimental facility (see Fig. 1) utilizes an 11-in.-diam tangential beam tube of the IRR-2 research reactor. The nickel capture γ source is irradiated adjacent to the reactor core at a thermal neutron flux of $2\times10^{13}n/\text{cm}^2$ sec. In order to reduce the neutron flux depression, the 7-kg source is made of five separated disks, 10 cm in diam and 2 cm thick, screwed into a water-cooled aluminum base. The whole source assembly can be separated from the main plug assembly after irradiation and replaced with a different source for a new experiment, using a special beam-plug loading machine. The beam plug is provided with lead collimators as well as borated aluminum and paraffin shielding to reduce neutron contamination at the exit of the beam. A 150-cm-long section of the beam tube can be used as a water switch to switch off the beam when necessary. The tangential beam tube was used for two different experiments at the same time, each occupying one end of the beam tube. In the second experiment, the capture γ source was iron, which contaminated the nickel capture γ beam, giving in effect a more complex incident spectrum; however, the additional lines did not disturb the present experiment and were actually used for energy calibration.

In order to permit convenient manipulation of the beam plugs and sources, the scattering chamber as well as the beam catcher and lead and water shielding were placed on a large trolley. Any one of six scattering targets could be selected by rotating a circular target holder. A sliding holder containing four absorbing samples, used for self-absorption experiments,[6] was

* Present address: McMaster University, Hamilton, Canada.
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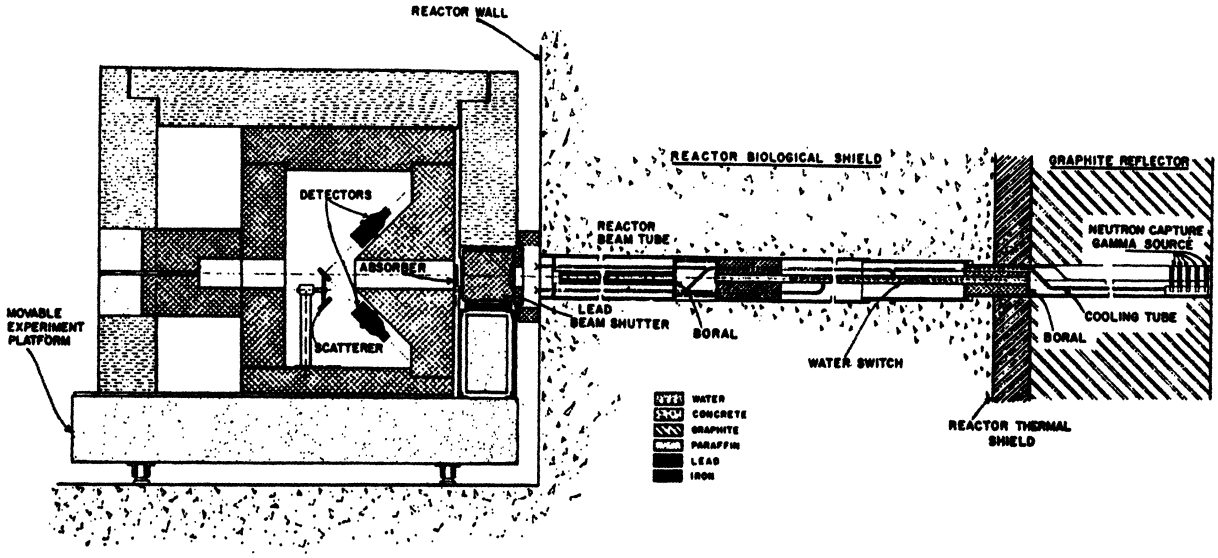

FIG. 1. Vertical section of the experimental facility.

TABLE I. Nickel capture γ rays above 5 MeV.

Present experiment		Kinsey *et al.*[b]		Adyasevich *et al.*[b]	
Energy (MeV)	Intensity of new lines[a] (%)	Energy (MeV)	Intensity (%)	Energy (MeV)	Intensity (%)
10.580					
8.998		8.997	26	8.996	28
8.535		8.532	11	8.505	12.3
8.123		8.119	2.5	8.095	2.5
7.820		7.817	6	7.825	6
7.696	0.55				
7.538		7.528	4	7.575	5.1
7.260		7.22	0.4	7.19	0.7
7.092		7.05	0.6	7.015	0.6
6.838		6.839	9	6.842	10.8
6.718	0.32				
6.680	0.21			6.639	2.8
6.584		6.58	2		
6.329		6.34	1	6.314	1
6.109		6.10	1.3	6.135	1.6
6.036	0.17			6.030	1.3
5.974		5.99	0.4		
5.819		5.82	3	5.842	2.6
5.696		5.70	0.6	5.725	>1.3
5.441	0.30				
5.327		5.31	1.3	5.312	>1.6

[a] Intensities obtained by interpolation from Kinsey *et al.*

[b] Reference 7.

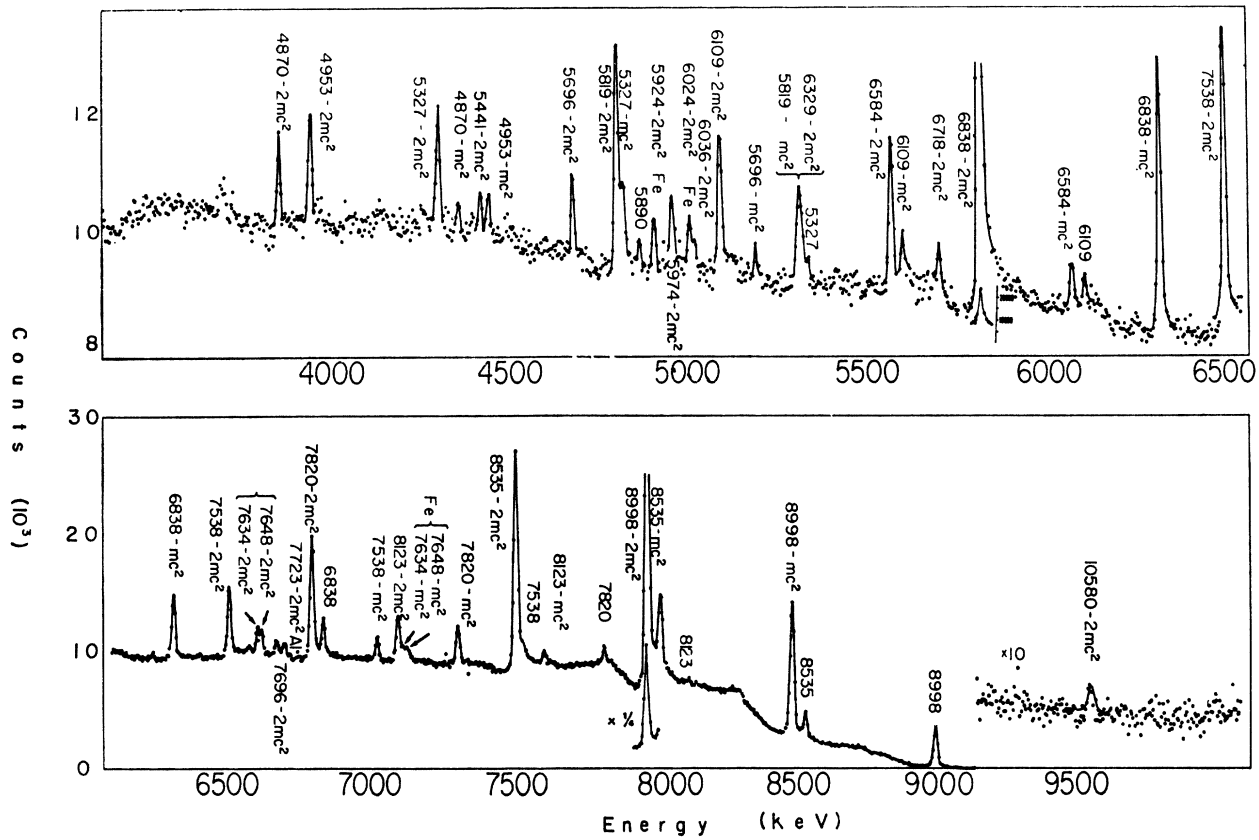

FIG. 2. Capture γ spectrum from nickel.

placed at the entrance to the scattering chamber. Scattering targets and absorbing samples could be automatically selected in any desired sequence. The detectors used for the singles spectra were 10-cc and 30-cc germanium detectors (Princeton Gamma-Tech), and for coincidence experiments 5×5-in. and 3×3-in. sodium iodide (Tl) crystals. The spectra were recorded using a 1001 TMC 1024-channel analyzer.

EXPERIMENTAL RESULTS

(a) Direct Spectrum of Nickel

The nickel capture γ ray spectrum incident on the scattering target was measured with a 30-cc lithium-drifted germanium diode, using a 3-mm-diam beam collimated through a 60-cm-long lead block (see Fig. 2). Table I shows the energy and intensity of the γ lines as measured in this experiment, compared with published data.[7] The energy calibration of the detector was carried out with reference to the 7.820-MeV line in the nickel capture γ spectrum. The first and second escape peaks of the stronger lines served to measure the differential gain over the whole energy region. The resolution at 7 MeV was 12 keV full width at half-maximum (FWHM) for this detector. In order to calibrate the intensities, the number of counts under each peak was normalized to the intensities appearing in Kinsey's[7] tabulation. The intensities of the new lines not hitherto reported were obtained by interpolation.

(b) Resonance Scattering of Ni Capture γ Rays from a Natural Te Target

The scattering target was 650 g of metallic tellurium powder of natural isotopic abundance, enclosed in a thin perspex container. The scattered spectrum was measured with a 30-cc lithium-germanium detector at an angle of 130° to the incident beam (Fig. 3). The γ lines observed are listed in Table II. Although the absolute energies are accurate only to within about 6 keV, the energy differences between the γ lines are known to within better than 2 keV for a 1 MeV separation. It can be seen that the only lines which occur

[7] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D.C. 20025).

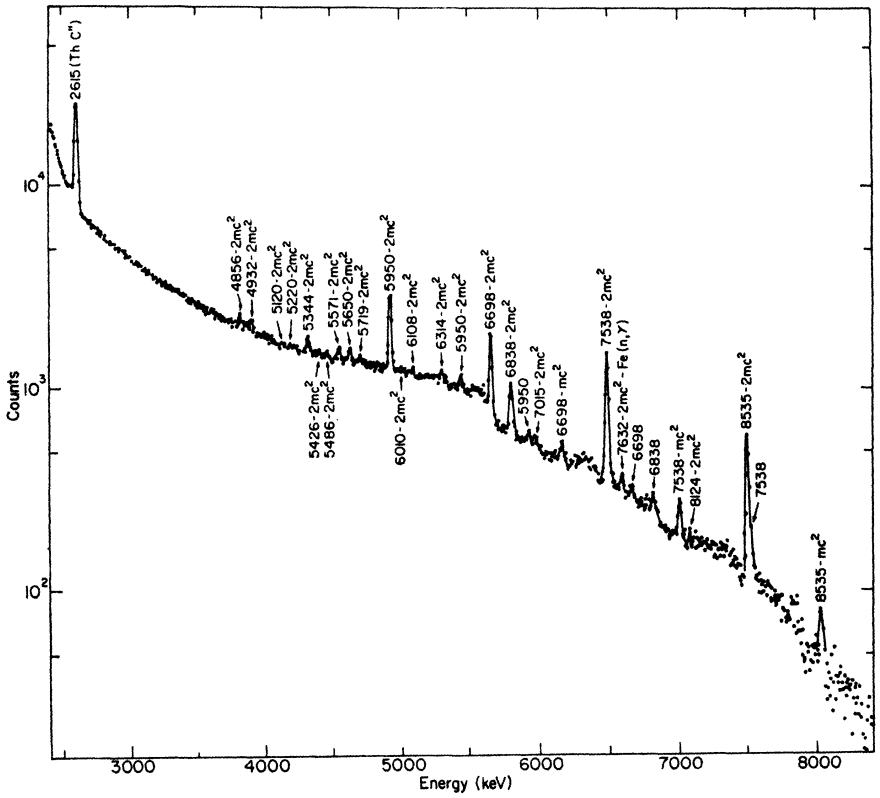

FIG. 3. Spectrum of nickel capture γ rays scattered from a Te target.

in both the direct and scattered spectrum are at 8.535, 7.538, and 6.838 MeV. It is assumed that these lines are emitted in transitions from nuclear levels at these energies to the ground state, while the other lines are emitted in transitions from these levels to low-lying states. A study of the reported decay schemes of the different Te isotopes[8,9] shows that ^{130}Te is the only one having known low-lying levels which can account for the inelastic components from the 7.538-MeV level. The suggested decay scheme is shown in Fig. 4.

In order to verify the interpretation of the stronger transitions in the above decay scheme, coincidence measurements were carried out using two NaI detectors—a 5×5 in. for energies above 5 MeV and 3×3 in. for lower energies. Using a fast ($2\tau=40$ nsec) coincidence circuit and a conventional routing technique, the spectra in the large detector coincident with different low-energy regions were recorded simultaneously. Figure 5(a) shows the noncoincident spectrum which was recorded for calibration purposes. Figure 5(b) shows the spectrum coincident with the 748-keV line, Fig. 5(c) with the 840-keV line, and Fig. 5(d) with the 1588-keV line. It can be seen that the 6.698-MeV line is in coincidence only with the 840-keV line, while the 5.950-MeV line is in coincidence with both the 840- and 748-keV lines—which is consistent with the suggested decay scheme of Fig. 4. From Fig. 5(d) it can be concluded that if there is a two-stage cascade transition ($1^{\pm}$) 5950 keV (2^+) 1588 keV (0^+), it is at least an order of magnitude weaker than the three stage ($1^{\pm}$) 5950 keV (2^+) 748 keV (2^+) 840 keV (0^+). Owing to the low intensities, it was not possible to check the other transitions by the coincidence technique.

For similar reasons, it is difficult to measure the inelastic components of the resonances at 8.535 and 6.838 MeV and to identify unambiguously the tellurium isotopes to which these levels belong.

The relative intensities of the different γ lines shown in Table II were estimated by comparison with a spectrum taken with a 5×5-in. NaI crystal, using the known NaI response functions for monoenergetic γ's.

In order to determine the multipolarities of the three strong transitions at 7.538, 6.698, and 5.950 MeV, the angular distributions were measured. A 5×5-in. NaI detector was used to measure the angular distribution of the 7.538-MeV ground-state transition relative to the incident beam. The distribution was found to be consistent only with a dipole transition. This is in agreement with all other reported angular distributions

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[9] R. L. Robinson, P. H. Stalson, F. K. McGowan, J. L. C. Ford, and W. T. M. Iner, Nucl. Phys. **74**, 281 (1964).

for photo-excited nuclear levels in this energy region.[10,11] The spin of the 7.538-MeV resonant level is therefore equal to 1. The parity of this level is being measured by a double scattering experiment,[12,13] and will be reported elsewhere. The 30-cc germanium detector was used to measure the intensities of the 6.698- and 5.950-MeV transition relative to the 7.538-MeV line, at angles of 90°, 126°, and 145° to the incident spectrum. The standard deviation of the relative intensities was 4%.

Both angular distributions were consistent with the form $1+0.05P_2(\cos\theta)$, in agreement with dipole transitions for the spin sequence $0\rightarrow1\rightarrow2$. This permits an assignment of spin 2 for both the excited levels populated by the 6.698- and 5.950-MeV transitions. This is in agreement with the previous reported[8] value of spin 2 for the 840-keV level. There is, however, disagreement with the value of spin for the 1588-keV level, which was previously reported[8] as having a spin of 4^+. The fact that the 5.950- and 6.698-MeV transitions have roughly equal strength is additional confirmation that the spin of the 1588-keV level is not 4^+. However, the uncertainty in the angular distribution of the 5.950-MeV line permits us to set an upper limit of 30% of this transition to an unresolved 0^+ level at 1588 keV.

TABLE II. γ lines observed in scattered spectrum from tellurium.

Energy (keV)	Relative intensity[a]
8535[b]	51±5
7538[b]	100
7015 (complex peak)	2±1
6838[b]	38±5
6698	113±10
6314	6±2
6108[c] (complex peak)	12±3
6010	7±2
5950	125±20
5719	5±2
5650	13±3
5571	14±3
5486	6±2
5344	18±4
4932	14±5
4856	14±5
4656	9±4
4192	12±4

[a] These intensities refer to an uncooled nickel source at a temperature of 450°C.
[b] Resonance levels.
[c] Probable resonance levels.

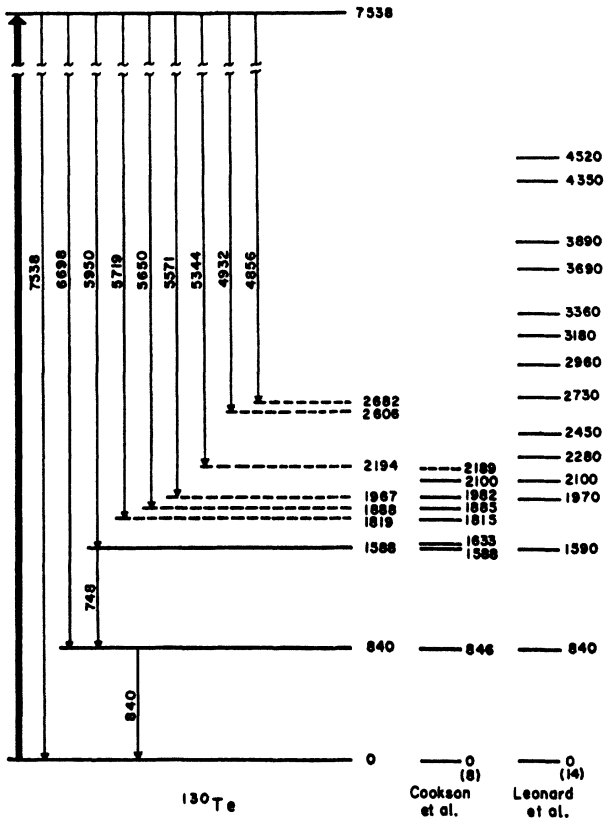

FIG. 4. Decay scheme of ^{130}Te excited by nickel capture γ rays.

The angular distribution of the elastically scattered 8.535- and 6.838-MeV lines were also found to be of the dipole form, and therefore correspond to scattering from spin-1 levels.

The effective cross section[6] for resonant scattering by a particular nuclear level can be used to estimate the level width if the branching ratio, level spins, and energy separation between the resonant level and γ line are known from independent experiments. The effective cross section for the 7.538-MeV level in ^{130}Te is equal to 190 mb. Since the isotope identification is not definite for the other two resonant levels, the effective cross section is evaluated per atom of natural tellurium. It is equal to 12 mb for the 8.535-MeV level, and 10 mb for the 6.838-MeV level. It should be noted that both these latter cross sections are strongly temperature-dependent, and refer to an uncooled source at 450°C and a tellurium scatterer at room temperature.

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[11] R. Moreh and G. Ben-Yaacov, Israel Atomic Energy Commission Report No. NRCN-180, 1967 (unpublished).
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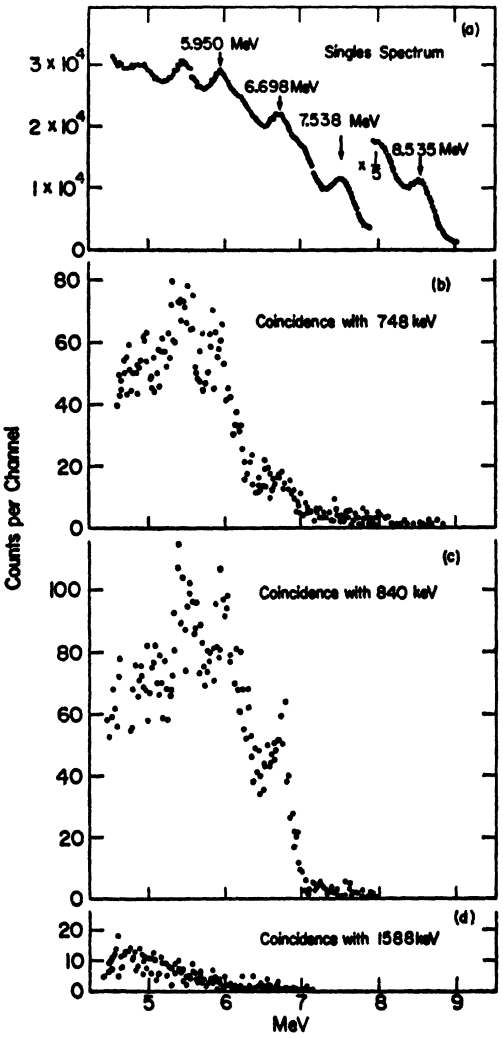

FIG. 5. Scattered spectrum of nickel capture γ rays from a Te target using a 5×5-in. NaI detector. (a) Noncoincident spectrum. (b) Spectrum coincident with 748 keV (single-channel window 600–760 keV). (c) Spectrum coincident with 840 keV (single-channel window 800–900 keV). (d) Spectrum coincident with 1588 keV (single-channel base line 1500 keV).

DISCUSSION

The level scheme suggested in Fig. 4 could only partly be confirmed by coincidence measurements because of intensity limitations, and we have therefore assumed that all the observed transitions correspond to scattering from the strongly excited 7.538-MeV level in ^{130}Te. The possibility should not be discounted that some of these transitions may correspond to inelastic scattering of a different nickel source line from a level where the inelastic component is much stronger than the elastic component, which is too weak to be observed experimentally in this work. However, owing to the high resolution of the germanium diode and the known energies of the low-lying levels, it was possible in most cases to identify the particular transitions. Most of the low-lying levels have been previously reported by several authors,[8,9,14] and the energies are in good agreement with our values. However, as mentioned above, there is disagreement regarding the spin of the 1588-keV level. This spin has been deduced[8] from data on inelastic proton scattering which favors excitation of low-lying collective states. The authors carried out their measurements over a large range of even isotopes of tellurium and cadmium and derived the spin of the two-phonon triplet using the empirical intensity rule, namely $\sigma(2^+)>\sigma(4^+)>\sigma(0^+)$. Their results for the low-lying levels of Te isotopes are shown in Fig. 6.

The low-lying levels of the Te isotopes have been attributed to quadrupole surface vibrations of the nearly spherical nuclei about their equilibrium state.[15] The simple harmonic oscillator model predicts a first excited one-phonon state of spin 2^+, with a higher two-phonon triplet with spins 0^+, 2^+, and 4^+ at twice the excitation energy of the first state. In the experimental work referred to above[8] a consistent difference between the isotopes of Te and Cd was found: For the Cd isotopes the 4^+ two-phonon state lies above the 2^+, while for the Te this order is reversed. Various refinements of the Bohr theory[16] were unable to explain this difference in order, and in fact predict that the order ought to be 2^+ above 4^+ for both the tellurium and cadmium isotopes.

However, the present work shows that the spin assignment of the 1588-keV level in ^{130}Te is definitely 2 and not 4 as shown in Fig. 6. In contrast to this result, similar measurements in progress in this laboratory using other capture γ sources have excited levels in other tellurium isotopes and the results confirm the spin assignments previously reported for the 1422-keV 2^+ level in ^{126}Te, and the 1522-keV 2^+ level in ^{128}Te. Hence if the 1588- and 1633-keV levels in ^{130}Te are the higher spin components of the two-phonon

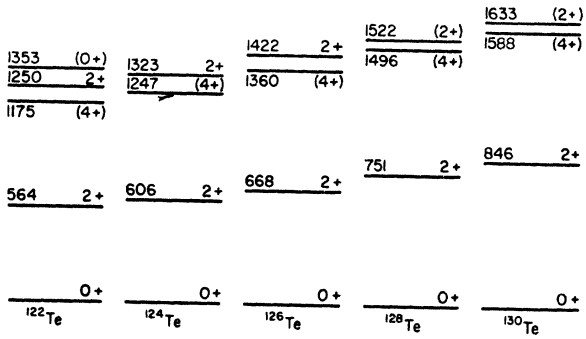

FIG. 6. Low-lying levels of even tellurium isotopes according to Cookson and Darcey (Ref. 8).

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[15] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **26**, No. 14 (1952).
[16] A. S. Davydov and A. A. Chaban, Nucl. Phys. **20**, 499 (1960).

triplet, then it is possible that for this isotope the order of spins shown in Fig. 6 is actually reversed. This figure in fact shows a gradual decrease of the separation between the 4^+ and 2^+ levels with increasing mass number, and this trend could be compatible with a change in spin order in ^{130}Te, that is 4^+ for the 1633-keV level, and 2^+ for the 1588-keV level.

The 0^+ two-phonon state was not found either in this study or in the earlier work on ^{130}Te. While in the (p, p') reaction excitation of the 0^+ level has a small probability, in the present case deexcitation to the 0^+ level would be expected to have a large probability, comparable with that of the 2^+ level. The fact that the transitions to the ground state and first two excited states are very prominent and approximately of the same intensity indicates that one can view the 7.538-MeV state as consisting of dipole vibration applied to the ground state and on both excited 2^+ states in equal amounts. However, owing to the expected near degeneracy of the 0^+ and 2^+ two-phonon states, they are probably admixed in similar amounts in the 7.538-MeV level. Should the 0^+ and 2^+ two-phonon states be closer than 2 keV, they would not be resolved under the experimental conditions in this work.

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Decay Study of Bromine-75*

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The radioactive decay of bromine-75 has been studied with a 16-cc Ge(Li) detector and a standard scintillation spectrometer. The bromine isotope was produced with carbon-12 ions (3.9 MeV/nucleon) on natural copper targets. The following γ rays, decaying with a half-life of 95.5±1.5 min, have been found: 110±1, 140±1, 286±1, 378±1, 426±1, 430±1, 569±1, 606±1, 654±1, 728±1, 788±1, 900±1, 940±1, 948±1, and 1233±2 keV. Coincidence measurements were performed, and a tentative decay scheme for bromine-75 is given.

1. INTRODUCTION

BROMINE-75 was first described in 1948 by Woodward, McCown, and Pool,[1] who found a half-life of 102 min. Fultz and Pool[2] made a magnetic-spectrometer investigation of bromine-75 in 1952 and found four positron transitions with the following end-point energies: 1700, 800, 600, and 300 keV. Beydon *et al.*[3] studied the γ-ray transitions and found a 285-keV line with a half-life of 95±5 min for bromine-75. In 1961 Baskova *et al.*[4] again investigated the $\beta+$ energies of bromine-75 and reported end point energies of 1720, 1100, and 650 keV. Besides that, they reported a half-life of 100±5 min, the already known γ ray of 285 keV, and a new γ ray of 620 keV. Lobkowicz and Marmier[5] investigated the level scheme of selenium-75 via the reaction $As^{75}(p, n)Se^{75}$ using several 2×2-in. NaI(Tl) crystals. They observed levels of 110, 285, 420, 615, 670, 750, 860, 1030, and 1160 keV and the corresponding γ rays, more than 14 in number. A recent thesis by Tubbs[6] also reports new levels in Se^{75} via the $As^{75}(p, n)Se^{75}$ reaction.

Comparing the above data, it seemed interesting to investigate the decay of bromine-75 with a high-resolution Ge(Li) spectrometer, especially to confirm the levels in selenium-75. The availability of carbon-12 ions (10 MeV/nucleon) at the Yale heavy-ion accelerator made these studies possible.

2. EXPERIMENTAL

A. Source Preparation

Thin natural copper foils (1.5 mg/cm^2) were bombarded with a degraded carbon-12 ion beam for about

* Work supported by the U.S. Atomic Energy Commission.

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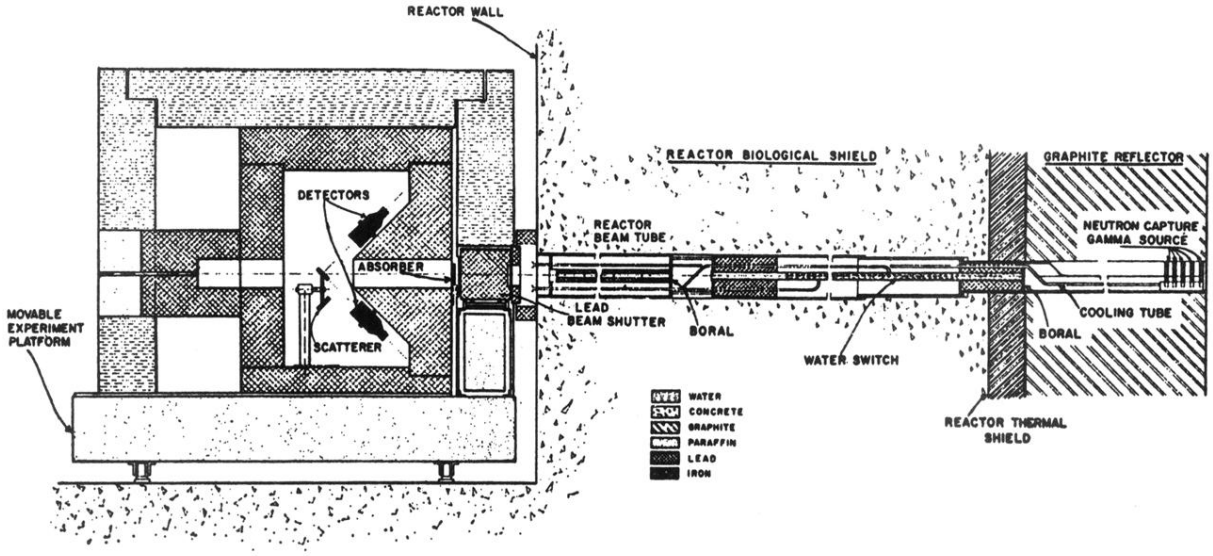

FIG. 1. Vertical section of the experimental facility.