Coulomb Excitation of Tellurium and Silver

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Coulomb excitation has revealed gamma rays at 159, 274, 342, 436, and 504 kev in Te^{123}; 435 and 633 kev in Te^{125}; 319 and 419 kev in Ag^{107}; and 306 and 412 kev in Ag^{109}. Interpretation of these results in conjunction with excitation curves and coincidence measurements is discussed in terms of proposed energy level schemes. In the case of Te^{123} it is concluded that three levels are independently excited. Values are given for the quadrupole moments, Q_0, based on the Bohr-Mottelson unified model and for the reduced transition probabilities for excitation, $B_e(E2)$.

I. INTRODUCTION

IN view of the successful application of the Bohr-Mottelson unified model[1] to nuclei well removed from closed shells, it is of interest to study nuclei near closed shells in order to determine the extent to which the model applies. Considerable attention has been given to the nuclei in the neighborhood of $Z=50$.[2–5] Among these nuclei, those with ground-state spin $\frac{1}{2}$ are of added interest because the energy level spacing predicted by the model depends on the structure of the wave function of the last odd nucleon.[6] The study of four such nuclei, Te^{123}, Te^{125}, Ag^{107}, and Ag^{109} is reported here.

II. EXPERIMENTAL TECHNIQUES

Coulomb excitation of these nuclei was produced by using protons and alpha particles from the NRL 5-Mev Van de Graaff accelerator. Tellurium targets were made by compressing the isotopically enriched metallic powders into cylindrical cups of pure tin, an element which does not exhibit gamma rays due to Coulomb excitation. In most of the experiments on tellurium, the gamma rays from the target traversed the target thickness and the 0.020-inch end wall of the tin cup. The silver targets, semithin to protons and thick to alpha particles, were made by electrodeposition of isotopically enriched silver onto platinum backings 0.001-inch thick. The isotopic enrichments were: 48.58% Te^{123} (with 8.19% Te^{125}), 81.65% Te^{125} (with 2.46% Te^{123}), 96.8% Ag^{107}, and 99.9% Ag^{109}.†

The gamma-ray scintillation counter consisted of a 2-inch NaI(Tl) crystal and an RCA 6342 photomultiplier. Pulse-height spectra were obtained with a 20-channel pulse-height analyzer. Ba^{133}, Sb^{125}, and Na^{22} sources were used for calibration. Coincidence spectra were examined with an arrangement consisting of two NaI scintillation counters separated by a 30-degree lead wedge which prevented coincidences due to Compton scattering. A 20-channel pulse-height analyzer in the first channel of the coincidence circuit was gated by pulses above a desired bias setting in the second channel. Gamma-ray coincidences could be determined by observing the effect on the coincidence spectrum in the first channel when the pulses in the second channel due to gamma rays of different energies were successively biased out.

Since the second excited states of the nuclei studied were more easily excited by proton bombardment, the proton spectra were more complete than those obtained with alpha particles. On the other hand, since alpha particles generally produced measurable excitation only in the first excited states, they were used to determine gamma-ray yields and excitation curves of these states. Thus it was possible in almost all cases to determine the gamma-ray yields under conditions such that contributions from higher energy states were negligible. Absolute gamma-ray yields were measured using an experimental photopeak efficiency curve. Points on this curve were obtained using standard sources[7] and the yield from the Coulomb excitation[8] of the 137-kev level in Ta^{181}. Background effects were subtracted from the peak in question by fitting to it a Gaussian curve which corresponded to those observed with radioactive sources. Angular distribution effects were estimated to be small and were neglected. For thick targets the reduced transition probabilities, $B_e(E2)$, are obtained by numerical integration of the cross section for $E2$ excitation given by Alder and Winther.[9] The values of dE/dx used in the integrations were determined from the well-known relation

$$dE/dx=4\pi Z_1^2NZ_2e^4L/mv_i^2, \qquad (1)$$

where Z_1 and Z_2 are the charges of the incident particle and target nucleus respectively, N the number of target atoms per cubic centimeter, v_i the velocity of the incident particle, and m the electron mass. The empirical

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[2] N. P. Heydenburg and G. M. Temmer, Phys. Rev. 95, 861 (1954).
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[5] P. H. Stelson and F. K. McGowan, Phys. Rev. 99, 112 (1955).
[6] B. R. Mottelson (private communication).
† The Te was furnished by ORNL and the Ag targets by Professor B. Waldman, University of Notre Dame.

[7] Standard sources of I^{131} and Na^{22} were obtained from the National Bureau of Standards.
[8] A value of 7.5×10^{-24} cm^2 was taken for the Q_0 of Ta^{181}.
[9] K. Alder and A. Winther, Phys. Rev. 96, 237 (1954).

relation, $L=1.55\ v_i\hbar/(e^2Z_2^{\frac{1}{3}})$ is given by Lindhard and Scharff.[10]

The probable error of the gamma-ray energy measurements is approximately $\pm 1\%$. Absolute values of $B_e(E2)$, excluding possible errors in the internal conversion coefficients used, are considered accurate to about $\pm 30\%$.

III. RESULTS AND DISCUSSION

The Te^{123} spectrum resulting from proton bombardment is shown in Fig. 1. Gamma rays were observed at 159, 274, 342, 436, and 504 kev. Comparison of the excitation curve for the 436-kev radiation with the theoretical curve and with the curve obtained from a target deliberately contaminated with NaCl showed that some but not all of the radiation was due to inelastic scattering from Na^{23}. Furthermore, although 511-kev gamma rays due to positron annihilation could be observed following bombardment, it was possible to make this contribution to the 504 peak small by using very short bombardments spaced at 10 minute intervals. Coincidence studies showed that both the 274- and 342-kev gamma rays were in coincidence with the 150-kev radiation, but not with each other. Accordingly, the energy level scheme shown in Fig. 1 is proposed for Te^{123}. Inspection of this scheme indicates the possibility of a transition from the 504- to the 436-kev level yielding a 68-kev gamma ray. Such a gamma ray was not detected although absorption and internal conversion should not have been sufficient to prevent observation. Failure to observe this gamma ray in addition to other intensity considerations led to the conclusion that the 436- and 504-kev levels were independently excited. Thus three states were excited directly, whereas in general $E2$ Coulomb excitation in odd-A nuclei reaches only two states. Therefore it

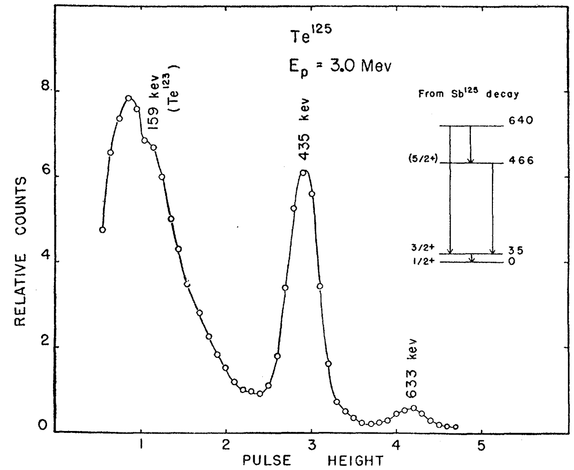

FIG. 2. Pulse-height spectrum from Te^{125} bombarded with 3.0-Mev protons. The broad peak at the low-energy end is due to proton bremsstrahlung. The small hump in this peak at 159 kev is due to a slight contamination of Te^{123}.

would seem, in terms of the unified model, that a state from a rotational scheme other than that associated with the ground state is being excited. However, a strict interpretation in terms of rotational level schemes may not be possible, because the extent to which rotational levels exist in nuclei so close to a closed shell has not been determined. The spins and parities shown for the upper two states in the energy level scheme in Fig. 1 are based on the fact that the excitation is electric quadrupole in nature. Angular distribution measurements should enable determination of the spins of the two upper states. The spin and parity of the first excited state, known from the study[11] of isomerism in Te^{123}, agrees with that predicted by the unified model for a rotational state in a nucleus whose ground-state spin is 1/2.

The spectrum obtained from proton bombardment of Te^{125} is presented in Fig. 2. Gamma rays were observed at 435 and 633 kev. By the same method as with Te^{123} it was established that only a small percentage of the 435-kev gamma ray was due to inelastic scattering from Na^{23}. From the study[12] of the radioactivity of Sb^{125}, levels in Te^{125} at 640 and 466 kev are known to decay predominantly by cascade to a third level at 35 kev, giving rise to four strong gamma rays of 605, 431, 174, and 35 kev. Excitation curves are not sensitive enough to determine whether the 435- and 633-kev gamma rays are cross-over radiations or cascade radiations to a 35-kev state. Although tentatively it is reasonable to associate the 435-kev gamma ray with the 431-kev radiation in Sb^{125} decay, such an association cannot be made for the 633-kev gamma ray. It is clearly distinguishable in energy from the 605-kev radiation in Sb^{125} decay and, furthermore, no 174-kev radiation is

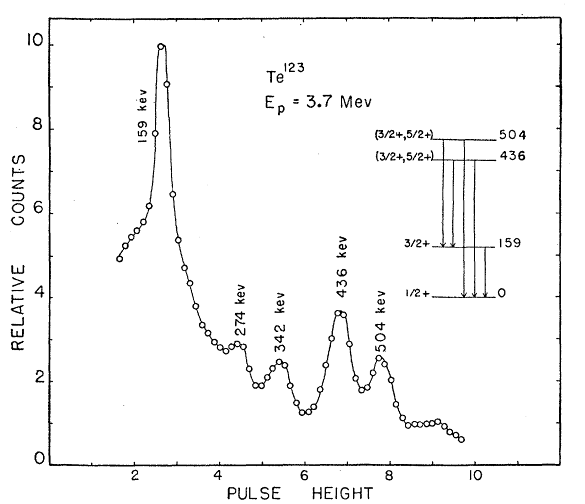

FIG. 1. Pulse-height spectrum from Te^{123} bombarded with 3.7-Mev protons.

[10] J. Lindhard and M. Scharff (private communication).

[11] R. D. Hill, Phys. Rev. 76, 333 (1949).

[12] M. Goldhaber and R. D. Hill, Revs. Modern Phys. 24, 179 (1952).

TABLE I. Values of Q_0 and $B_e(E2)$, the reduced transition probability for excitation, are given along with the bombarding particle, the internal conversion coefficient, α_T, and the level used in their determination. Both values of Q_0 and $B_e(E2)$ for Te^{125} were calculated assuming a spin and parity of $5/2^+$ for the excited state. Values of a are also given. Because of the possible ambiguity in second excited states in the case of tellurium, the value of a appropriate to each possible state, given in parentheses in kev, is shown.

Isotope	Level (kev)	α_T	Bombarding particle	E (Mev)	Q_0 (10^{-24} cm^2)	$B_e(E2)e^2$ (10^{-48} cm^4)	a
Te^{123}	159	0.21	alpha	4	0.7	0.018	−0.02 (436) −0.13 (504)
Te^{125}	466	0.01	proton	3	2.7	0.44	−0.76 (466)
	668	0.00	proton	3.5	2.1	0.26	−0.83 (668)
Ag^{107}	319	0.02	alpha	4	2.0	0.16	+0.68
	419	0.01	proton	3	2.0	0.23	
Ag^{109}	306	0.02	alpha	4	2.2	0.18	+0.66
	412	0.01	proton	3	2.3	0.31	

observed. Therefore the 633-kev gamma ray is due to a level either at 633 kev or at 668 kev, the latter decaying through the 35-kev level. From a comparison with the 159-kev state in Te^{123}, it is reasonable to expect that the 35-kev level in Te^{125} should also be reached by Coulomb excitation. However, the 35-kev radiation is 93% converted,[13] and the conversion x-rays are completely hidden by the x-rays produced from charged particle bombardment of the target. Thus this gamma ray was not observed despite many attempts using scintillation counters, photon proportional counters, and x-ray absorption techniques. Although coincidences were observed between conversion x-rays and the 431-kev gamma ray with an Sb^{125} source, such coincidences could not be found in the Coulomb excitation of Te^{125} because of the high accidental rate from x-rays caused by the proton bombardment. The spin and parity of the 466-kev level shown in Fig. 2 are based on intensity considerations, identification of the 435-kev radiation with the 431-kev radiation in Sb^{125} decay, and the fact that the excitation is electric quadrupole. The spin and the parity of the first excited state, determined by other methods,[13] agrees with the predictions of the unified model for a rotational state in a nucleus whose ground-state spin is 1/2. Based on the quadrupole nature of the excitation, assignments for the level[14] associated with the 633-kev radiation should be $3/2^+$ or $5/2^+$. Angular distribution measurements here also should make possible the determination of the spins and parities of the two upper levels.

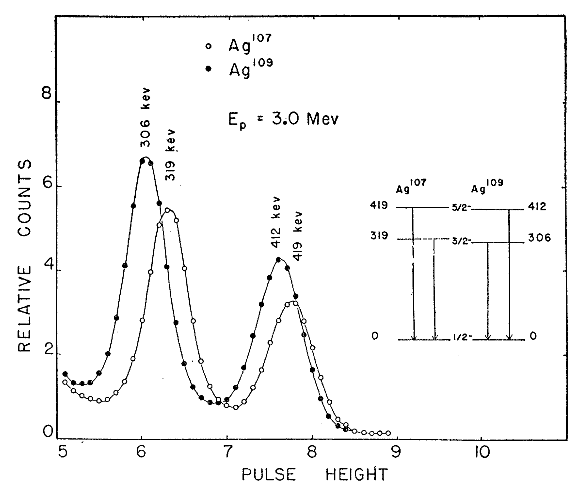

FIG. 3. Pulse-height spectra from Ag^{107} and Ag^{109} bombarded with 3.0-Mev protons.

In Fig. 3 the spectra obtained from the proton bombardment of silver show gamma rays at 319 and 419 in Ag^{107} and at 306 and 412 kev in Ag^{109}. An alpha-particle excitation curve for the 319-kev radiation in Ag^{107} indicated that the radiation came from a level at 319 kev. The spin assignments shown in Fig. 3 have have been established by angular distribution measurements[15] and agree with those predicted by the unified model for rotational levels in a nucleus whose ground-state spin is 1/2. The ratio of reduced transition probabilities for the 400- and 300-kev radiations respectively was also found to be in agreement with that predicted by the unified model for rotational levels with the spin sequence shown. The results of the study on silver reported here agree with those of previous investigations.[16]

The values of the transition probability for excitation and the ground state quadrupole moments of all nuclei studied are given in Table I. The calculations of Q_0 were based on the unified model using relationships which apply only to transitions in a ground state rotational band. Different quadrupole moments were obtained using the 435- and 633-kev gamma rays in Te^{125}. This difference may be due to the fact that one or possibly both of these levels does not belong to a ground state rotational band. The quadrupole moments shown in Table I cannot be measured spectroscopically because all the nuclei studied here have ground state spin $\frac{1}{2}$.

When rotational levels exist for nuclei with this ground-state spin, the Bohr-Mottelson theory predicts

[13] J. C. Bowe and P. Axel, Phys. Rev. **85**, 858 (1952).

[14] This level is not shown in Fig. 2 due to the ambiguity in its location.

[15] F. K. McGowan and P. H. Stelson, Phys. Rev. **99**, 127 (1955).

[16] N. P. Heydenburg and G. M. Temmer, reference 2; T. Huus and A. Lunden, Phil. Mag. **45**, 996 (1954); Mark, McClelland, and Goodman, reference 3; and P. H. Stelson and F. K. McGowan, reference 5.

states of energies

$$E_I=\frac{\hbar^2}{2\mathcal{I}}[I(I+1)+a(-1)^{I+\frac{1}{2}}(I+\tfrac{1}{2}) -\{I_0(I_0+1)+a(-1)^{I_0+\frac{1}{2}}(I_0+\tfrac{1}{2})\}], \quad (2)$$

where I and I_0 are the excited-state and ground-state nuclear spins respectively, and $\mathcal{I}$ is the nuclear moment of inertia. The decoupling parameter, a, reflects the structure of the wave function of the last odd nucleon. Values of a found using Eq. (2) and the energies of the first two excited states are given in Table I. It is of interest to note the trends exhibited in the odd isotopes of even-Z nuclei near closed shells in the light of the unified model. In tellurium, a particularly good example, the spin and parity of the first excited states of the odd isotopes near $A=121$ is $\frac{3}{2}+$. The position of these states starting at $A=121$ decreases monotonically with increasing A until the ground state spin becomes $\frac{3}{2}+$ instead of $\frac{1}{2}+$. Equation (2) is consistent with this behavior if a decreases as A increases. If this equation applies, competition in the filling of the $3s_{\frac{1}{2}}$ and $2d_{\frac{3}{2}}$ independent-particle neutron shells should be reflected in the values of a for the odd Te isotopes because a depends on the amount of admixture of the competing states.

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Neutron-Capture Gamma-Ray Spectra of V, Co, Ti, Fe, Cr, Au, Mn, and I†*

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An experiment has been performed on the neutron-capture gamma spectra of eight elements in the region of about 100 kev to 2.5 Mev using NaI crystals. Wherever possible, the data have been compared with the results of previous experiments and existing energy level schemes.

I. INTRODUCTION

THE study of energy levels in nuclei by measuring the prompt gamma rays resulting from thermal neutron capture is a relatively recent approach to the problem of nuclear spectroscopy. The techniques used in some of the early measurements[1–3] limited the information obtained to a general picture of the decay scheme. However, structural details were rarely obvious. A very fruitful technique using a pair spectrometer[4] has given excellent information in the region from about 3 Mev up to the binding energy. The low-energy component of the spectrum has generally been investigated by the use of NaI crystals.[5–9] Motz[10–11] used a lens spectrometer to measure the energy of the electrons emitted by a photoelectric converter exposed to the capture gamma-ray beam in the region from 300 kev to 3 Mev.

Although the construction of a level scheme is most easily performed with the high-energy data, low-energy information is needed not merely as supplementary data, but to remove the ambiguities inherent when there are more than one capturing isotope and to give a more complete picture regarding the multiplicity of the decay. The experiment reported here covers the region from about 100 kev to 2.5 Mev.

II. APPARATUS

The target and spectrometer were located opposite an experimental hole which yielded a flux of about 10^6 n/cm^2 sec, on the west face of the Brookhaven reactor. Figure 1 shows a schematic of the experiment. The upper surface of those targets for which the capture cross section is not large compared with the scattering cross section was covered with an aluminum box containing lithium fluoride in order to prevent neutrons which are scattered from the target from being captured in the surrounding equipment and detectors.

Spectroscopy was performed by means of a 3 cm ×3

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* A brief summary of this work was presented at the Washington meeting of the American Physical Society, April 29, 1954.

‡ Submitted in partial fulfillment of the requirements for the Ph.D. degree at New York University.

§ Now at Westinghouse Atomic Power Division, Pittsburgh, Pennsylvania.

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