27.7-keV Level in I^{129} and Some Remarks about Its Use in Mössbauer Experiments

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The properties of the first excited state of I^{129} have been studied with a mass-separated Te^{129m} source. The energy of this state, as determined from the conversion-electron spectrum, is $E_\gamma=27.72\pm0.06$ keV. This differs considerably from the often quoted value of 26.8 keV, but it agrees very well with the value recently published by Bemis and Fransson. An accurate half-life value $T_{1/2}=16.8\pm0.2$ nsec was determined from delayed βe^- coincidences. A total conversion coefficient $\alpha=5.3\pm0.3$ was obtained from the relative intensities of the 27.7-keV gamma rays and the 27.4-keV x rays that accompany the isomeric transition in Te^{129}. The contributions of these rays were separated by comparing Mössbauer spectra obtained with the 70-min and 33-day activities of Te^{129}. Some remarks are made about the relative merits of these activities for use in Mössbauer sources.

1. INTRODUCTION

THE lowest energy gamma transition in I^{129} has been used in Mössbauer investigations of iodine and its compounds.[1-4] Accurate knowledge of energy and half-life of this transition is important for the interpretation of some of the results of such investigations. Until recently the energy has been indicated as 26.8 keV, as measured by Graves and Mitchell,[5] but a higher value, $E_\gamma=27.72\pm0.06$ keV, results from our measurements with a mass-separated source. A more accurate half-life value $T_{1/2}=16.8\pm0.2$ nsec is also reported in this paper. From these data, a natural width $2\Gamma=2(\hbar \ln 2/T_{1/2})(c/E_\gamma)=0.059\pm0.001$ cm/sec follows for the resonance absorption line. A value $\alpha=5.3\pm0.3$ was found for the total conversion coefficient of the 27.7-keV level. The method for measuring α differs from more common methods in that the Mössbauer effect of the 27.7-keV transition was used as a means for determining the intensity ratio of the 27.7-keV gamma rays and the 27.4-keV x rays present in the decay of Te^{129m}. Since the decay scheme is known sufficiently well, α can be derived from this ratio.

2. SOURCE PREPARATION

The Te source was produced by irradiating about 100 mg of Te^{128}, enriched to 93%, in the DIDO reactor at Harwell for one month in a flux of 1.5×10^{14} neutrons/cm^2 sec. The resulting source, which has a specific activity of about 200 μCi/mg was mass-separated to produce a high-specific-activity Te^{129m} source.

The Te ions were collected on a 5-μ thick aluminum backing with a 50-kV acceleration voltage applied to the ion source. An activity of 95 μCi of Te^{129m} was deposited on an area of 3.5×40 mm^2. A 2×2-mm^2 piece taken from this activity served as our spectrometer source.

The resolving power of the mass separator, defined as $(DM)/b_{1/2}$, in which D is the distance between the positions of neighboring masses, $b_{1/2}$ is the width at half-maximum of the mass distribution and M is the separated mass, was of the order of 800. It is estimated from this that the amount of stable Te^{128} deposited at the position of the Te^{129m} source is less than a few μg/cm^2.

3. ENERGY OF THE FIRST EXCITED STATE

The energy of the first excited state was determined from the conversion-electron spectrum measured with a magnetic-lens spectrometer (Fig. 1). The conversion lines $L28$ and $M28$ are clearly separated. The lines $K106$, $L106$, and $M106$ are the conversion lines from the isomeric transition in Te^{129}.

The spectrometer was calibrated with a Th$(B+C)$ source. The positions of the calibration lines as well as those of the Te^{129} and I^{129} conversion lines were determined with an accuracy of about 0.1% as the intersections of the tangents to the flanks of the lines. A possible shift due to a contribution of L_{II} and L_{III} (or $M_{II}-M_V$) lines under the L_I (M_I) conversion lines was considered. The error caused by this contribution does not amount to more than 0.1%.

As a result of penetration of the Te^{129m} nuclei into the aluminum foil the conversion electrons lose a little of their energy. The most probable penetration depth of 50-keV Te^{129m} ions into Al is about 8 μg/cm^2.[6] According to Bonacalza, Erman, and Rossi[7] the electron stopping power is given by $(dE/dx)/\rho=94.6/E^{0.9}$ eV/(μg/cm^2 Al) (E in keV), yielding an energy loss of about 45 eV for the L conversion electrons and about 40 eV for the M conversion electrons of the 27.7 keV transition.

Taking into account this correction and the errors

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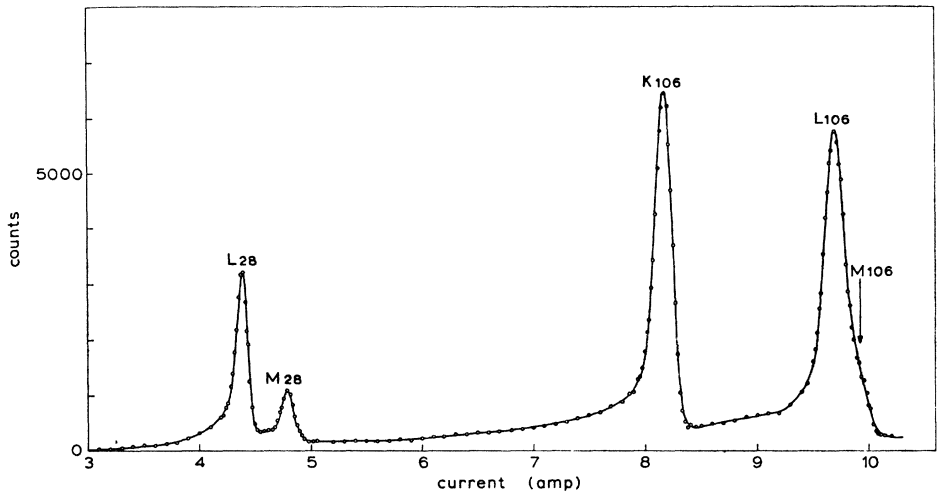

FIG. 1. The conversion-electron spectrum of Te^{129m}.

discussed above, a transition energy

$$E_{\gamma 1}=27.72\pm0.06 \text{ keV}$$

is obtained.

Our value differs considerably from the value 26.8 keV given by Graves and Mitchell.[5] This difference may be a consequence of the thickness of their source. After completion of our investigation we received a communication from Bemis and Fransson[8] in which they report $E_{\gamma 1}=27.78\pm0.05$ keV for this level, in excellent agreement with our result.

The energy of the isomeric transition in Te^{129}, determined in the same way, is

$$E_{\gamma 2}=106.0\pm0.3 \text{ keV},$$

in good agreement with earlier measurements.[5,9,10] Bemis and Fransson[8] report a slightly lower and more accurate value:

$$E_{\gamma 2}=105.62\pm0.06 \text{ keV}.$$

4. HALF-LIFE OF THE 27.7-keV STATE

Half-life values of the 27.7-keV state have been derived by a number of investigators from delayed $\beta\gamma$ or $\gamma\gamma$ coincidence measurements,[11–16] a lower limit was derived from Mössbauer spectra.[1,3] We remeasured the half-life from delayed βe^- coincidences between β particles that feed this level and L conversion electrons by which it decays. In Fig. 2 all measurements have been summarized.

The source was placed in a magnetic-lens spectrometer focused on the L conversion line of the 27.7-keV transition. These electrons (with an energy of 22.5 keV) where detected in a 1-mm thick NE102 plastic scintillator, coupled to an EMI-9514AS photomultiplier. Behind the source another plastic scintillator, mounted on a 56AVP photomultiplier, detected the β particles. The β channel was set to accept β particles with energies above 300 keV. The time spectrum, measured with a time-to-pulse-height converter of the Green and Bell type covering a range of 500 nsec, was recorded on a 256-channel analyzer. An accurate time calibration was performed with the radio-frequency technique described by one of the authors at the 1961 Gatlinburg Conference.[17] Some changes were, however, made in the calibration equipment to make it suitable for lifetime measurements of low-energy states in the time range of 10-100 nsec.

A typical delayed coincidence curve is shown in

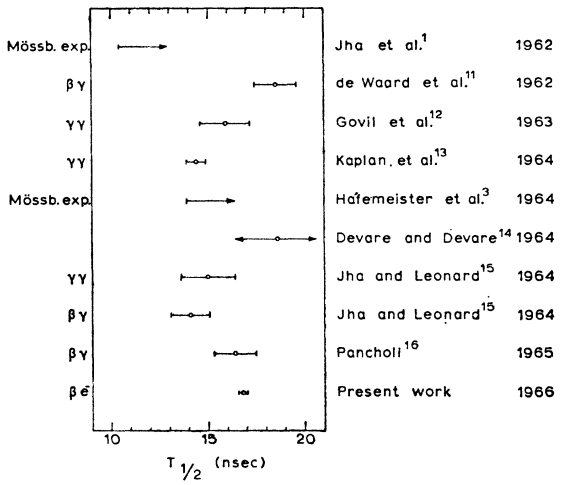

FIG. 2. Survey of experimental half-life values of the 27.7-keV level in I^{129}.

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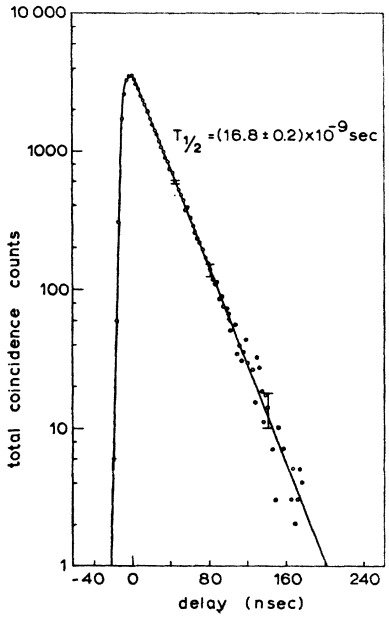

FIG. 3. Delayed coincidence curve of the 27.7-keV level of I^{129}.

Fig. 3. From several of such curves a half-life

$$T_{1/2}=(16.8\pm0.2)\times10^{-9}\text{ sec}$$

is derived.

The 27.7-keV transition in I^{129} is predominantly an l-forbidden $M1$ transition. Combination of our half-life and energy values with the total conversion coefficient and the $E2/M1$ mixing ratio, reported in the next section, leads to a retardation factor of 162±11 with respect to Moszkowski's estimate for an $M1$ transition.[18]

5. CONVERSION COEFFICIENT OF THE 27.7-keV TRANSITION

In Mössbauer experiments with sources that contain the Te^{129m} activity, the resonance-absorption effect is diluted by the 27.4-keV K_α x rays accompanying the 106-keV transition. In a NaI(Tl) scintillation spectrometer operated with a broad channel these will be detected with the same efficiency as the 27.7-keV gamma rays. This circumstance suggests a method for determining the conversion coefficient α of the 27.7-keV transition by comparing the areas of Mössbauer absorption lines obtained with sources of the 33-day Te^{129} isomeric-state activity and the 70-min ground-state activity.

Denote by f the fraction of 106-keV transitions accompanied by K_α x rays, by f_1 the fraction of Te^{129} beta transitions leading to the 27.7-keV state in I^{129} (either directly or through intermediate levels); likewise by f_2 the fraction of beta decays from the isomeric state that go through the 27.7-keV state, and by a the fraction of isomeric-state decays that go to the 70-min state. Let the ratio of the areas of Mössbauer absorption lines obtained with Te^{129} and Te^{129m} sources be ϵ. We easily find:

$$1+\alpha=(\epsilon-1)[f_1+((1-a)/a))f_2]/f. \quad (1)$$

The quantities a, f_1 and f_2 follow from the decay schemes of Te^{129m} and Te^{129} that have been extensively studied by several groups (see Fig. 4). In general, there exists agreement on the level structure, but there are also some differences. One of them, that affects our value of f_2, needs some discussion. From the recent investigations of Devare and Devare[19] and Ramayya *et al.*[20] we derive $a\approx0.7$, $f_1=0.99\pm0.01$ and $f_2<0.01$. However, the level scheme suggested by Bornemeier *et al.*[21] would lead to $f_2=0.2$, because it gives a 698-keV gamma transition to the 27.7-keV state fed by a 8.5% beta branch from the isomeric state in Te^{129}. The only argument that this transition leads to the 27.7-keV state is the observation of a line with an energy higher by about 27 keV in the gamma spectrum as measured with a lithium-drifted germanium detector. Hurley and Mathiesen,[22] who also studied the gamma spectrum with such a detector, but with a slightly better energy resolution, found lines at 697 and 730 keV, differing by 33 keV. Moreover, their coincidence measurements do not show the presence of a 697–27-keV cascade. The same negative conclusion can be drawn from the work of Ramayya *et al.* and that of Devare and Devare. In view of these results, we believe that

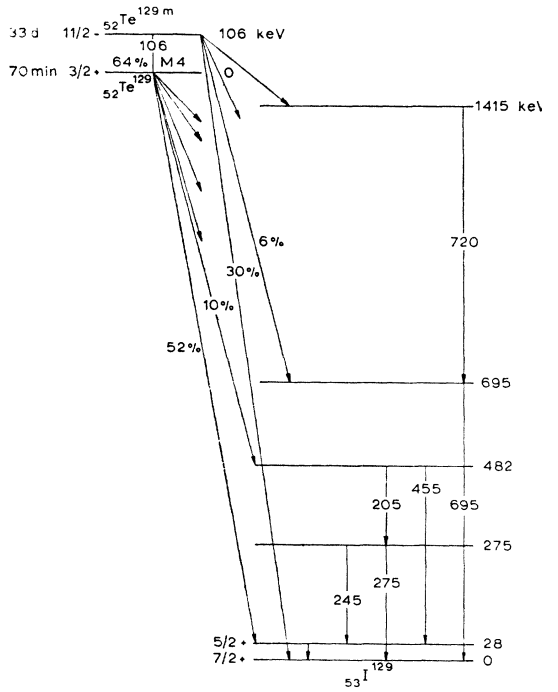

FIG. 4. Relevant part of the decay scheme of Te^{129m}, according to Devare and Devare (Ref. 19).

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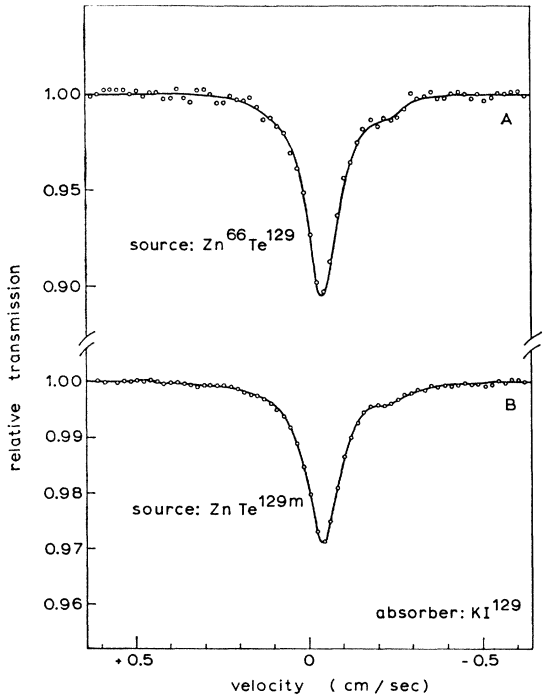

FIG. 5. Mössbauer absorption spectra, (A) obtained with a 70-min Zn^{66} Te^{129} source and (B) with a 33-day $ZnTe^{129m}$ source. The absorber is KI^{129}. Source and absorber temperature about 100°K.

$f_2=0.01$ is a safe upper limit for the fraction of the beta decay from the isomeric Te^{129} state through the 27.7-keV state in I^{129}.

Mössbauer spectra of the 33-day and 70-min tellurium activities, obtained with zinc-telluride sources and one and the same KI^{129} absorber are shown in Fig. 5. Source and absorber temperatures were equal within about 5°K for both measurements. Corrections for background due to the I^{129} in the absorber and to higher energy gamma rays were made. The first source of background had been minimized by inserting a 0.1-mm-thick indium foil between absorber and detector (cf. Hafemeister *et al.*[3]). This foil also cuts out the K_β x rays that accompany the 106-keV transition. Thus, a value $\epsilon=3.56\pm0.11$ is obtained for the ratio of the areas of the absorption peaks.

Finally, a value for $f=\omega_K\alpha_{1K}/\alpha_1$ can be found from the relevant tables (Wapstra *et al.*'s tables[23] give $\omega_K=0.855$ for the K-shell fluorescent yield from Rose's tables[24] of conversion coefficients we derive $\alpha_{1K}/\alpha_1=0.474$ for the 106-keV $M4$ transition).

Inserting these values in Eq. (1) we have

$$\alpha=5.3\pm0.3.$$

This is a little higher than the value $\alpha=4.5\pm0.5$ measured by Devare and Devare.[19] From Rose's tables[24] $\alpha=4.8$, if the transition is pure $M1$. From the value of the total conversion coefficient conclusions about a possible $E2$ admixture can be drawn. Because of the large $E2$ conversion coefficient, α is very sensitive for this admixture. From our experimental value, combined with Rose's theoretical data, it follows that the $E2$ admixture $\delta^2=E2/M1=(1.7\pm1.0)\times10^{-3}$. This is in fair agreement with the value $\delta^2=(2.80\pm0.22)\times10^{-3}$ which Bemis and Fransson[8] derived from L subshell ratios. Recently Gupta and Saha[25] concluded $\delta^2=0.016\pm0.011$ from angular-correlation measurements.

6. RELATIVE MERITS OF THE 33-DAY Te^{129m} AND 70-MIN Te^{129} ACTIVITIES FOR USE IN MÖSSBAUER SOURCES

The larger depth of the absorption peaks obtained with sources of the 70-min activity has led to its preferred use in Mössbauer experiments.[2-4] However, the short half-life restricts its applicability to laboratories not too far from a reactor. We would like to point out that despite the smaller effect obtained with sources of the 33-day activity, this activity can be used to good advantage in many cases. Sources of both activities can easily be made of sufficient strength (about 1 mCi), to yield 10^4 cps (or more) in a NaI(Tl) scintillation spectrometer set on the 27.7-keV gamma line and placed in good geometry (solid angle subtended by the crystal about 0.5%). To avoid large dead-time losses it is advisable to use a Mössbauer spectrometer with the multichannel analyzer operated in the multiscaler mode.[26] In this mode, typical analyzer dead times are about 10 μsec. If a spectrum is stored in 200 channels at an initial rate of 10^4 cps, a 3-h run with a source of the 70-min activity will yield about 2.5×10^5 counts per channel, corresponding to a statistical accuracy of 0.2% for each point of the spectrum. Little is gained by counting for a longer period of time since after 3 h only about one-sixth of the activity is left. Because of the smaller relative depth of the absorption lines obtained with the 33-day activity the same *relative* accuracy is achieved there for about 2.5×10^5 $\epsilon^2\approx2.5\times10^6$ counts per channel. This number can be obtained by counting at a rate of 10^4 cps for about 15 h. When the 70-min activity is used, the ultimate accuracy can of course be improved by using a number of 70-min sources in succession but such a procedure is tedious when using a cryostat and only practicable in the immediate vicinity of a reactor.

Our method of preparing the 33-day $ZnTe^{129m}$ sources differs from that used for the 70-min sources (see Refs.[2,3]) in that the compound is formed with activated tellurium. An enriched Te^{128} sample of about 100 mg, irradiated at high flux (10^{14} neutrons/cm^2 sec or more) for a month is dissolved and oxidized in a

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little concentrated HNO_3, the solution is then evaporated to dryness and dissolved in 10 ml 25% HCl at 60°C. About 5 ml of a 25% K_2SO_3 solution are added to reduce the oxide. The tellurium is centrifuged and dried. It is then weighed into a small quartz tube with an equivalent amount of pure zinc. The tube is evacuated, sealed off and placed in an oven that is brought to 700°C, at which temperature ZnTe is rapidly formed by a vapor-phase reaction. The tube is opened after it has cooled slowly. The brick-red zinc telluride is usually scraped off the wall of the tube under some toluene. This requires some care, but it can be done almost quantitatively.

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$W^{182}(d,p)W^{183}$ Reaction at 7.5 and 12 MeV: An Investigation of the Stripping Process on a Deformed Heavy Nucleus*

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The $W^{182}(d,p)W^{183}$ reaction has been studied at 7.5 and at 12 MeV with a broad-range magnetic spectrograph. At 12 MeV, angular distributions have been obtained from 5° to 145° for the transitions to the ground state and to the levels at excitations of 46, 99, 208, 292, 412, and 453 keV. In addition, the scattering of deuterons on W^{182} and protons on W^{183} has been measured at 12 MeV. The elastic scattering has been analyzed in terms of the nuclear optical model. A serious ambiguity in the deuteron parameters has been observed. For inelastic deuteron scattering leaving W^{182} in its first excited state, a distorted-wave Born-approximation (DWBA) analysis based on a deformed complex potential leads to a deformation parameter $\beta=0.23$ for W^{182}. The angular distributions of the $W^{182}(d,p)W^{183}$ reaction have been compared with DWBA calculations with different distorting potentials, and spectroscopic factors have been extracted. The ratios of the experimental spectroscopic factors agree quite well with those predicted by the Nilsson model, when band mixing is included in the calculation of the theoretical spectroscopic factors. Absolute spectroscopic factors, on the other hand, may disagree by as much as a factor of 2–3. The data have also been compared with the DWBA calculations of Penny and Satchler, which include "two-step" processes. Our results indicate that "two-step" processes are probably unimportant for the reaction studied.

I. INTRODUCTION

THE investigation of deformed heavy nuclei by means of charged-particle reactions [in particular with (d,p) and (d,t) reactions] has only recently become possible through the use of the tandem Van de Graaff accelerator in combination with magnetic spectrographs. So far only a few angular distributions have been published,[1–4] and none of these have been compared with the predictions of the distorted-wave Born approximation (DWBA) theory utilizing measured distortion parameters. In view of the large static deformation of the rare-earth and the actinide nuclei, such a test of the DWBA theory seems of interest, since one might expect inelastic-scattering (strong coupling) effects[5,6] to be significant. In particular, it is desirable to investigate how accurately spectroscopic information can be obtained from (d,p) and (d,t) reactions on these nuclei.

For our investigation, we have chosen the W^{182}-$(d,p)W^{183}$ reaction. The energy-level scheme of W^{183} (up to approximately 500 keV) has been extensively studied.[7,8] The levels (Fig. 1) which we observe in the (d,p) reaction are the $[510]\frac{1}{2}^-$, $[512]\frac{3}{2}^-$, and $[503]\frac{7}{2}^-$ intrinsic states[9] and the various rotational levels built

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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[9] The intrinsic states are labeled with the asymptotic quantum numbers $(Nn_z\Lambda\Omega\pi)$, where N is the total oscillator quantum number, n_z is the number of oscillator quanta along the symmetry axis, Λ is the component of the total orbital angular momentum along the symmetry axis, and Ω is the component of total angular momentum along the symmetry axis.