$Q'(Yb^{173})=3.3\pm0.2$ b from the level $6s6p\ ^3P_1$, the error coming from the uncertainty of the wave function used.

The mean of the two values is $Q'(Yb^{173})=3.1\pm0.2$ b. If the shielding correction $\Delta(6s6p)=-0.1$ is assumed,[10] one obtains for the quadrupole moment

$$Q(Yb^{173})=2.8\pm0.2 \text{ b}.$$

If one assumes a strong coupling between the unbalanced nucleon and the nuclear surface, our spectroscopic quadrupole moment yields, according to the formula given by Bohr,[11] the intrinsic quadrupole moment $Q_0(Yb^{173})=8.0$ b. This is in good agreement with the value 7.8 b obtained from the Coulomb excitation investigation by Elbek, Nielsen, and Olesen.[12]

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Recoilless Nuclear Resonant Absorption in I^{129}†

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Recoilless resonant absorption has been observed with the 26.8-keV gamma ray of I^{129} using the parent, Te^{129m}, as a source. With a ZnTe source and $NaI\cdot 2H_2O$ absorber the absorption spectrum has a structure which is interpreted in terms of quadrupole splitting in the absorber. The field gradient $q(1-\gamma)$ at the iodine nucleus is experimentally found to be $-2.3a_0^{-3}$. The broader spectrum which is obtained with a Te metal source appears to contain many unresolved lines. It is interpreted as resulting from simultaneous quadrupole splitting in source and absorber. From the observed linewidth, the first-excited state of I^{129} is estimated to have a mean life of 1.5×10^{-8} sec. The small observed percentage effects result, at least in part, from dilution by x rays emitted by the source and the absorber.

INTRODUCTION

ALTHOUGH the Mössbauer effect has already found applications in many branches of physics, its use is still limited by the fact that Fe^{57},[1] Sn^{119},[1] Tm^{169},[2] and[1] Dy^{161} are the only isotopes which show really large effects at easily available temperatures. It would be useful to have a beta-emitting isotope with large Mössbauer effect at room temperature. Such a source, in a ferromagnetic host, would make possible the parity and time-reversal experiments suggested by Morita.[3] In a search for such an isotope, we have studied the Mössbauer effect of the 26.8-keV gamma ray of I^{129}, using Te^{129m} as the source. Unfortunately, the magnitude of the effect is still small, but a structure has been observed which can at least tentatively be explained on the basis of known nuclear properties. A somewhat unique and annoying feature of this experiment is the radioactivity of the absorber.

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‡ This work is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Carnegie Institute of Technology.

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EXPERIMENT

1. Source and Absorber

The sources of Te^{129m} were prepared by the irradiation of Te^{128}, 97% enrichment, in the Oak Ridge Research reactor for one week. The irradiated samples were dissolved, purified to remove iodine contamination, and reprecipitated in the metallic form.

The ZnTe sources used in some of the experiments were prepared by heating Zn and the radioactive Te in an evacuated Pyrex tube until the characteristic red ZnTe compound was formed.

The absorber material used for these experiments was fission-produced I^{129}, supplied by Oak Ridge National Laboratory in the form of sodium iodide dissolved in basic sodium sulphite solution. It contained 86% I^{129} and 14% I^{127}. The absorber was prepared by drying this solution on a polystyrene disk. The thickness was 40 mg/cm^2 of iodine. The absorber is assumed to be in the form of $NaI\cdot 2H_2O$, which is triclinic.

I^{129} is unstable, decaying by beta emission (3×10^7 yrs; 150 keV) followed by a 40-keV gamma ray which is strongly converted. Thus, the absorber emitted 29-keV xenon x rays which were not resolved from the 26.8-keV gamma ray of the source; this caused some dilution of the observed Mössbauer effect.

2. Measurement of the Absorption Spectrum

In order to maximize the observed effect all measurements were made with both source and absorber at liquid-nitrogen temperature. In a preliminary experiment, whose purpose was merely to detect resonance absorption, a Te metal source was fastened to a loud speaker and driven at 60 cps. The counting rate was determined at various speaker amplitudes, the amplitudes being measured by means of a traveling microscope. The effect was detected: The minimum transmission, which occurred at zero amplitude, was found to be 3% smaller than the transmission at very large amplitude, before correction for dilution.

Next a mechanical drive, with the conventional three-step linear cam, was employed. With Te metal as a source, a maximum effect of 8% was noted; because of the long counting times involved, the absorption curve was not taken with good velocity resolution. For some unknown reason, it has never been possible to obtain again such a high percentage effect with a metallic source. This difficulty may be caused by the appearance of an amorphous phase in the Te. By the time subsequent experiments were performed, this original source was no longer usable.

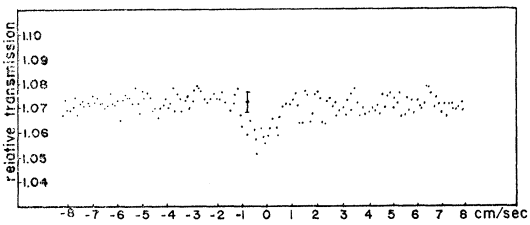

FIG. 1. Resonance absorption spectrum: Te metal source, $NaI \cdot 2H_2O$ absorber. Positive velocities correspond to the source approaching the absorber.

Most of the data were taken using the standard arrangement of sinusoidal source motion, velocity to pulse-height conversion, and accumulation in a multichannel pulse-height analyzer.[1] A weighting curve was obtained simultaneously in order to take account of the distortions which sinusoidal drive and analyzer dead time introduce. In all these experiments the detector was placed as far from the absorber as possible, consistent with reasonable counting rates. This tended to reduce the relative intensity of x radiation from the absorber.

EXPERIMENTAL RESULTS

The transmission vs velocity data are shown in Figs. 1–3, all measurements being made with both source and absorber at liquid nitrogen temperature. The fraction of the counts in the 27 keV window which was attributable to absorber radiation was about 30% in each case. Approximately 60% of the remaining counts were caused by Te x rays from the source; these arise from the internal conversion process in the isomeric transition of Te^{129m} (see Fig. 4) and are estimated as follows. The direct beta decays of Te^{129m} can be neglected because they do not appreciably feed the 26.8-keV state of I^{129}, nor do they produce Te x rays. About half of the 106-keV isomeric transitions result in K conversion, and the K fluorescence yield is about 0.9. Almost all of the isomeric transitions eventually feed the 26.8-keV I^{129} state, whose calculated[4] L conversion coefficient is about 5. In this calculation, and in the analysis of the absorption spectrum, we make the reasonable assumption that the 26.8-keV transition is predominantly $M1$. Thus, each isomeric transition produces on the average 0.2 of the desired 26.8-keV gamma rays, and 0.45-keV Te x rays, which are not resolved from them. Only about 1/5 of the counts in the 27-keV window then correspond to gamma rays from the desired transition, and the observed percentage effects must be multiplied by five.

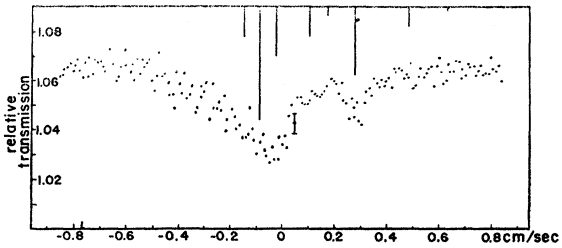

FIG. 2. Resonance absorption spectrum: ZnTe source, $NaI \cdot 2H_2O$ absorber. The vertical lines at the top of the figure represent the calculated relative absorption intensities in the pattern which results from quadrupole interaction. Positive velocities correspond to the source approaching the absorber.

The spectra obtained using the metallic Te source are not well resolved, but the resonance absorption was definitely detected. Figure 2 shows the structure of the spectrum using ZnTe source, and Fig. 3, taken with a higher velocity range, verifies it and shows that there are no other prominent absorption lines.

DISCUSSION

In ZnTe, which is cubic, no quadrupole interaction will occur at a normal lattice site. The beta decay of

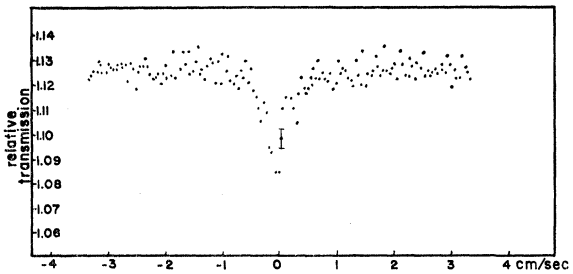

FIG. 3. Resonance absorption spectrum: ZnTe source, $NaI \cdot 2H_2O$ absorber. Positive velocities correspond to the source approaching the absorber.

[4] *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), p. 834.

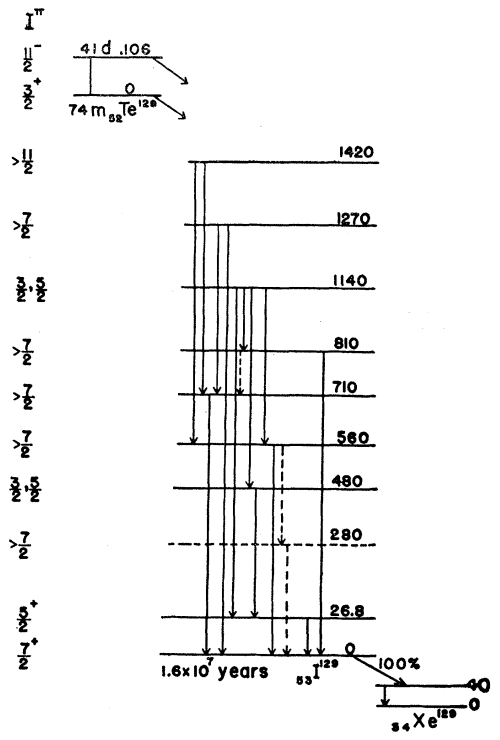

FIG. 4. Decay scheme of 41-day Te^{129m}, S. Jha, R. K. Gupta, H. G. Devare and S. Srinivasa Raghavan, in *Proceedings of the Rutherford Jubilee Conference, Manchester*, edited by J. B. Birks (Academic Press Inc., New York, 1961), p. 22.

Te^{129} gives rise to a maximum recoil energy of about 16 eV, and an average recoil energy of roughly only half of this. While these are small compared with the 25 eV or more which is typically required to produce atomic displacements, the present situation is complicated by the electronic excitation which results from the sudden increase in nuclear charge. A satisfactory explanation of the observed spectrum in terms of absorber splitting alone is possible. We, therefore, make the simplifying assumption that no appreciable number of gamma rays come from nuclei in interstitial positions, hence, that the source is unsplit. Using a line absorber, it should be possible to check this assumption and thus add to the growing list of solid-state applications of Mössbauer effect studies.

The absorber material, $NaI \cdot 2H_2O$, has a triclinic structure with two formula units per unit cell. While the detailed arrangement of the atoms within the unit cell is not known, it is almost certain that such a structure has a center of inversion. This implies that the neighborhoods of the two iodine atoms differ only that one is the inverse of the other, and thus that they are equivalent with respect to quadrupole interaction and nuclear volume effect.

The nuclear electric quadrupole interaction energy is given by

$$E=[e^2q(1-\gamma)Q/4I(2I-1)][3m^2-I(I+1)],$$

where q is the electric field gradient produced by all parts of the lattice except the ion in question, Q is the nuclear quadrupole moment, γ is the Sternheimer factor, and m and I refer to the nuclear spin. The ground $(7/2^+)$ state of I^{129} is known to have a quadrupole moment of about -0.4 b.[5] We may estimate the quadrupole moment of the excited $(5/2^+)$ state to be about -0.7 b by assuming that it is not much different from that of the ground state of I^{127}, which has been measured.[5] Because the structure of $NaI \cdot 2H_2O$ has not been determined, the magnitude and the sign of $q(1-\gamma)$ are not known for this substance. This means that, accepting the above values of the quadrupole moments, the energy scale and the sense of the predicted spectrum are not determined. Because of the possibility of nuclear volume effect, even the zero of the scale cannot be predicted. We therefore regard $q(1-\gamma)$ as an unknown, and determine it by making a fit to the experimental data. The absorption spectrum results from differences between two terms of the type shown above, one for the excited state $(5/2^+)$ and one for the ground state $(7/2^+)$ of the nucleus. In Fig. 2 the fit is made: The vertical lines at the top of the figure show the positions and relative intensities of the absorption lines. In Fig. 5 is shown the corresponding energy-level diagram, together with an indication of the transitions which are allowed in the $M1$ gamma emission. The

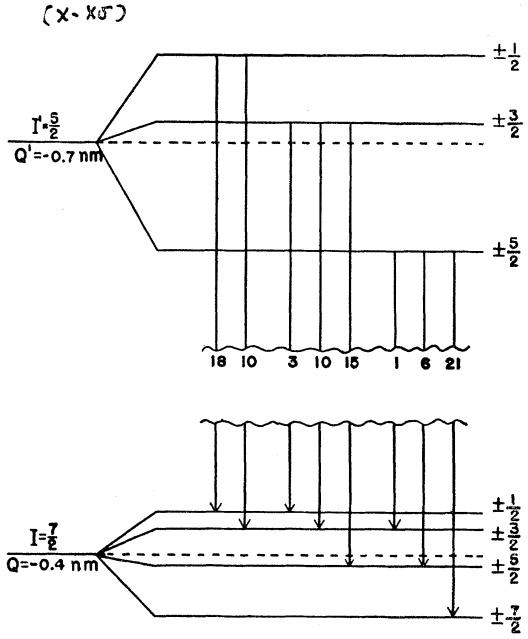

FIG. 5. Energy-level diagram of I^{129}, showing the effect of quadrupole interaction. The ratio of the ground and excited state quadrupole moments is taken to be 4/7. The transitions allowed in magnetic dipole radiation are shown, and their relative weights are indicated. Read 36 instead of 18.

[5] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. 30, 585 (1958).

value determined for $q(1-\gamma)$ is $-2.3a_0^{-3}$, where a_0 is the Bohr radius.

The spectra which were observed with the Te metal (hexagonal) source are interpreted as resulting from the simultaneous quadrupole splitting of source and absorber. These spectra are roughly twice as wide as those obtained with the ZnTe source.

According to the above interpretation, the peak on the right of Fig. 2 results from an unsplit line. The full width at half maximum of this line is approximately 0.1 cm/sec; the corresponding mean life of the state is 1.5×10^{-8} sec. Because of the possibility of line broadening (particularly in the source) this result is a lower limit. It is, however, of the order of the mean lives of the 24-keV state of Sn^{119} and the 35-keV state of Te^{125}, both of which also decay by $M1$ transition.

Using the Debye model, the Lamb-Mössbauer factor[1] of ZnTe at 78°K is 0.8. The Debye temperature of $NaI\cdot 2H_2O$ is not known, but it is probably less than that of NaI, whose Lamb-Mössbauer factor, f', is 0.4 at nitrogen temperature. We may use this to calculate an upper limit to the expected percentage resonant absorption. Taking $f'=0.4$ and a calculated L conversion coefficient of 4, the absorber thickness for $1/e$ transmission is 20 mg/cm² of I^{129}, before taking account of the quadrupole splitting. The peak on the right of Fig. 2 should, according to our previous interpretation, result from a single transition whose statistical weight is about 1/4 of the total. Thus, when this resolved line is on resonance, the thickness for $1/e$ transmission is about 80 mg/cm². The actual absorber thickness is 35 mg/cm² of I^{129} and thus about 0.35 of the resonant gammas should be absorbed. When account is taken of the estimated source recoilless fraction (0.8) and the dilution factor (0.2), the predicted fractional effect is 0.06. This figure, which is an upper limit, is to be compared with the observed fractional effect, which is 0.02 for the resolved line. The agreement is as good as could be expected, considering the roughness of the calculation and the doubtful utility of the Lamb-Mössbauer factor in the case of solids which are composed of chemical compounds.[6]

ACKNOWLEDGMENTS

Our grateful thanks are due to Professor S. De-Benedetti and Dr. R. Ingalls of this institution, and Dr. B. Craven of the University of Pittsburgh for many stimulating and helpful discussions.

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Ranges of Be^9 Ions in Gold and Aluminum*

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The ranges of Be^9 ions in gold and aluminum have been measured in the energy range 2 to 21 MeV. Pulse height measurements of Be^9 recoils, degraded by various thicknesses of gold or aluminum foil, served as the basis for construction of range-difference curves. These curves were extrapolated to zero energy and transformed into the more useful range-energy relationships.

INTRODUCTION

THE advent of accelerators which generate beams of heavy ions has produced a need for more complete information on the range-energy relationship in various materials for ions heavier than He^4. An increasing interest in heavy ions as products of nuclear reactions has amplified this need. Recently, Northcliffe[1] has determined range-energy relationships for He^4, B^{10}, B^{11}, C^{12}, N^{14}, O^{16}, F^{19}, and Ne^{20} ions in aluminum in the energy range 1 to 10 MeV per nucleon. A complementary study of the ranges of the same ions in oxygen and nickel has been made by Roll and Steigert.[2] Heckman *et al.*[3] have measured the range-energy relationship for C^{12}, N^{14}, O^{16}, Ne^{20}, and Ar^{40} ions in emulsions at energies up to 10 MeV per nucleon. Detailed information for the ranges of N^{14} ions in nickel and aluminum is available.[4] Other determinations of range-energy relationships for heavy ions include the work of Burcham[5] on C^{12} in aluminum; Oganesyan[6] on C^{12}, N^{14}, O^{16} in aluminum, copper, and gold; Barkas[7] on Li^8 and B^8 in emulsions; and Schambra, Rauth, and Northcliffe[8] on C^{12}, O^{16}, and

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