$Q_0=-506$ keV with a standard deviation of 3 keV. Since the average value for Q_0 may still contain systematic uncertainties such as flight path, the position of the γ-ray peak for the determination of zero time in the flight-time measurements, proton energy, and target thickness, we have adopted an error for Q_0 which is typical of that for an individual determination. Thus we deduce $Q_0=-506\pm7$ keV. However, the errors in the excitation energies of Table I are smaller because certain systematic errors tend to cancel.

Our value for Q_0 disagrees with that of -529 ± 10 keV quoted by Chasman *et al.*[6] Their value was derived from the Q value for the first excited state ($Q=-660\pm10$ keV) which was measured by Johnson and quoted by Mattauch *et al.*[16] and from the measurement of the energy of the first excited state by a Ge(Li) γ-ray detector. Since our excitation energies agree with those of Chasman *et al.*,[6] the disagreement then arises from the Q-value measurement of Johnson. We also disagree with the value of -534 ± 15 keV given by McMurray *et al.*[7] The value given by Mattauch *et al.*[17] in their systematic analysis of nuclear-reaction energies for the determination of masses ($Q_0=-493\pm12$ keV) is in good agreement with the present determination.

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Nuclear Resonance Fluorescence in Cu^{65}†

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The Coulomb fragmentation of $Zn^{65}I_2$ molecules was utilized as the means of producing γ rays which are resonant with the 1.116-MeV level in Cu^{65}. A study of the resonant self-absorption led to a mean lifetime $\tau=(3.80\pm0.25)\times10^{-13}$ sec for this level. From the angular distribution of the resonant radiation, the mixing amplitude δ for the $M1+E2$ 1.116-MeV ground-state transition was determined as $\delta=-0.437\pm0.015$.

I. INTRODUCTION

THE situation with regard to the lifetime of the 1.116-MeV level in Cu^{65} and the multipole mixing of the 1.116-MeV ground-state transition has been summarized in a paper[1] which reported resonance-fluorescence results obtained through the use of gaseous sources of Ni^{65}. A disturbing aspect brought out by that summary was the discrepancy between the $E2/M1$ mixing amplitudes reported on the basis of the angular distribution of γ rays following Coulomb excitation[2,3] and the mixing amplitudes obtained from studies of the angular distribution of resonant γ rays[1] or from a comparison[1] of the best $B(E2)$ and $B(M1)$ values. The Coulomb-excitation angular distribution measurements[2,3] led to an average $\delta=-0.22\pm0.06$. The other experiments combined to give $\delta=-0.51\pm0.03$. The ratios δ^2 of the $E2$ and $M1$ transition rates, derived from the two sets of experiments, thus differed by a factor of about 5. This difference, in turn, made the total lifetime deduced from the Coulomb-excitation experiments[3] approximately 5 times shorter than the lifetime estimated on the basis of Doppler shift[4] and resonance-fluorescence[1] studies.

The short half-life (2.56 h) of the radioisotope Ni^{65} made it difficult to improve over the accuracy obtained in the previous resonance-fluorescence experiment[1] as long as this isotope had to be used. However, a marked improvement appeared to be feasible if an efficient way of obtaining resonant 1.116-MeV γ rays from the long-lived (245-day) isotope Zn^{65} could be found. The recent observation[5] of the large velocities resulting from the Coulomb fragmentation of the $Cu^{65}Cl_2$ molecule following K capture in Zn^{65} indicated a way of producing resonant γ rays from gaseous Zn^{65} compounds. The suggested analysis[5] of the $Zn^{65}Cl_2$ experiments made it probable that $Zn^{65}I_2$ sources would provide an even larger fraction of resonant γ rays. It was, therefore,

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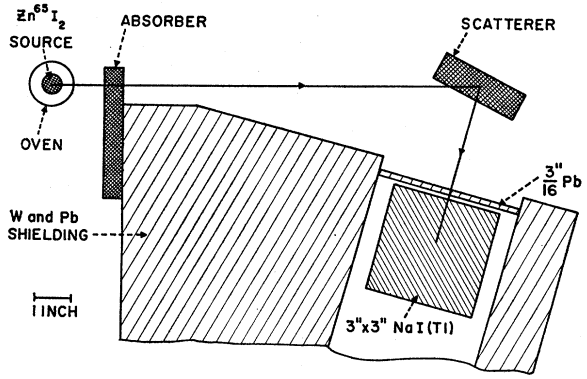

FIG. 1. Geometry used for the self-absorption experiment.

decided that a ZnI_2 source should be prepared and its effectiveness as a source of γ rays resonant with the 1.116-MeV level of Cu^{65} determined. In view of the discrepancy in the reported δ values and of the advantages of Zn^{65}-halide sources for accurate resonance-fluorescence experiments, the previous[1] self-absorption and angular distribution studies were repeated. In what follows, the study of $Zn^{65}I_2$ as a source of resonant 1.116-MeV γ rays will be described first. Then a report will be given on the self-absorption and angular distribution measurements carried out with this new source. Finally, the results of these studies will be interpreted in terms of the lifetime of the 1.116-MeV level in Cu^{65} and of the mixing in the $M1+E2$ ground-state transition.

II. COULOMB FRAGMENTATION OF $Zn^{65}I_2$ MOLECULES

A. Source Preparation

Approximately 3.5 mg of high specific activity (5 mCi/mg) Zn^{65} metal and 50 mg of elemental iodine were heated together in a quartz-Pyrex system, and the resulting ZnI_2 was sealed into a 5-cm^3 quartz ampoule after the excess iodine had been removed by distillation. By scanning the ampoule with a Pb slit it was ascertained that all the activity was in the gaseous phase, provided the temperature was above $\simeq$730°C. The resonance-fluorescence experiments were performed with the source at 760°C. Experiments carried out two weeks and many room-temperature–to–760°C cycles apart indicated that less than 1% change, if any, occurred in the fraction of resonant γ rays emitted by the source; i.e., apart from the radioactive decay of Zn^{65}, there was no deterioration of the source.

B. Determination of $F(E_r)$ for the ZnI_2 Source

The usefulness of a given source for resonance-fluorescence studies is measured by $F(E_r)=N(E_r)/N_{\text{total}}$, the fraction of the emitted γ rays falling into a unit energy interval at the position E_r of the absorption line. If the same isotope serves as the source and as the scattering material, E_r differs by $\Delta E_r=E_\gamma^2/Mc^2$ from the energy of the center of the emission line, where Mc^2 is the rest energy of the resonating nucleus. For the 1.116-MeV level in Cu^{65}, this energy difference is $\Delta E_r=20.6$ eV. If the natural width of the level is known, $F(E_r)$ can be determined via a resonance-scattering experiment. The number N_{sc} of γ rays resonantly scattered by a thin slab of material may be written[6] as

$$N_{sc}=C\int N(E)\sigma(E)dE, \tag{1}$$

where C is a factor describing the geometry, $N(E)$ is the spectrum of the incident γ rays, with $\int N(E)dE=N_{\text{total}}$, and $\sigma(E)$ the scattering cross section[6] for which

$$\int\sigma(E)dE=g\tfrac{1}{4}\lambda^2\Gamma, \tag{2}$$

where $g=(2I_{exc}+1)/(2I_{gs}+1)$ is the ratio of the statistical weights of the excited state and the ground state, λ the wavelength of the γ radiation, and Γ the total width of the level. In arriving at Eq. (2), $\Gamma_0/\Gamma=1$ was assumed.

If $N(E)$ is slowly varying compared with $\sigma(E)$, Eq. (1) may be replaced by

$$N_{sc}=CN(E_r)\int\sigma(E)dE=CN(E_r)g\tfrac{1}{4}\lambda^2\Gamma \tag{3}$$

or

$$N_{sc}/N_{\text{total}}=C\cdot F(E_r)g\tfrac{1}{4}\lambda^2\Gamma. \tag{4}$$

For a thick scatterer, Eq. (4) still holds, but C will depend on the width Γ because of the self-absorption in the scatterer material.

Scattering experiments were carried out with the ZnI_2 source and also with a newly prepared Zn metal source in the geometry used previously[5] for Zn and $ZnCl_2$ sources. This geometry was similar to the one depicted in Fig. 1. The results for all three types of sources are summarized in Table I. The counting rates

TABLE I. Influence of the chemical form of the source on the resonance scattering yield. The counting rates given in column 2 are normalized to the same source strength ($\simeq$15 mCi). The fractions listed in column 3 are based on the value $\Gamma=1.73\times10^{-3}$ eV for the width of the 1.116-MeV level in Cu^{65}.

Source	Resonance effect (counts/min)	Resonant fraction $F(E_r)$ (eV^{-1})
Zn	1.4±0.6	3×10^{-5}
$ZnCl_2$	54 ±3	1.2×10^{-3}
ZnI_2	268 ±8	6.2×10^{-3}

[6] See, e.g., F. R. Metzger, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, Inc., New York, 1959), Vol. 7, p. 54.

given in column 2 of this table were normalized to the same source strength, namely, the strength of the ZnI_2 source. The small, but finite, effect observed with the Zn metal vapor source is attributed to the presence of Zn_2 molecules in the Zn vapor.[7] To calculate the $F(E_r)$ values from the observed scattering effects, the width $\Gamma=1.73\times10^{-3}$ eV, determined in the self-absorption experiment (see Sec. III), was used. The value $F(E_r)$ given in Table I for the $ZnCl_2$ source differs from the previously quoted result[5] by more than a factor of 2. This difference is not the result of new experimental evidence, but is the consequence of a 40% increase in the width used to evaluate the data and of a more accurate evaluation of the scattering geometry.

The fact that linear triatomic molecules were involved makes a quantitative analysis of the breakup difficult. Qualitatively, the large increase observed in the resonance effect in going from $ZnCl_2$ to ZnI_2 is in line with the conclusion[5] that the $1/e$ width of the emission line for $ZnCl_2$ is smaller than the separation of emission and absorption lines. If the charge sharing is not very different for ZnI_2 from what it is for $ZnCl_2$ molecules, a broader emission line and thus a larger value for $F(E_r)$ are expected for ZnI_2, since in the heavier molecule a larger fraction of the available fragmentation energy will go into the kinetic energy of the copper ion.

III. SELF-ABSORPTION EXPERIMENTS

To determine the level width in the absence of information concerning the shape of the γ-emission line, a self-absorption experiment[6,8] had to be performed. The geometry used for the self-absorption studies of the 1.116-MeV level in Cu^{65} is shown in Fig. 1. Cu absorbers, 0.498 and 1.008 in. thick, were used. Ni plates of comparable thicknesses served as the nonresonant comparison absorbers. Of course, the $Zn^{65}I_2$ source was used throughout.

In addition to measurements with the Cu scatterer in which the Cu and Ni absorbers were alternated, experiments using a matched Ni scatterer, and alternating the Cu and Ni absorbers, were carried out. The purpose of these runs was not only to determine the nonresonant background, but to ascertain that the Cu absorbers did not resonantly scatter some 1.116-MeV γ rays into the 3×3-in. NaI detector. Once it had been established that no such scattering-in took place, it was a simple matter to calculate the resonant attenuations from the measured counting rates. In Table II, these attenuations, corrected for the mismatch of the absorbers, are listed in column 2.

To obtain the width Γ from the attenuations, use was made of the fact that as long as the absorption line has the Doppler form,[6] $\sigma(E)=K\exp\{-[(E-E_r)/\Delta]^2\}$, resonant absorption reduces the scattering from a given volume element of the scatterer by a factor

$$\mu(l)=\sum_{m=0}^{\infty}\frac{(-1)^m(nKl)^m}{m!(m+1)^{1/2}}, \tag{5}$$

where l is the path length of resonant material that has to be traversed by the incoming γ rays, n the number of resonant nuclei per cm^3, and K the peak cross section $K=g\lambda^2\Gamma(4\pi^{1/2}\Delta)^{-1}$. In the expression for K, $\Delta=E_\gamma(2kT/Mc^2)^{1/2}$ is the Doppler width of the absorption line, k being Boltzmann's constant and T the effective temperature[6] of the absorber.

For the measurement with the comparison absorber, l is, in general, not zero, because the incoming beam has to traverse l_s cm of scatterer material. If the path length in the absorber is denoted by l_a, the attenuation A_ν for the νth volume element is

$$A_\nu=\mu(l_{a\nu}+l_{s\nu})/\mu(l_{s\nu}). \tag{6}$$

The attenuations measured in the experiment, and listed in Table II, are the averages over the attenuations A_ν of the individual volume elements of the scatterer. Using Eq. (6), the attenuations A_ν were calculated for 15 volume elements of the scatterer for selected values of the width Γ, and the average attenuations obtained from these calculations were compared with the experimental values. This comparison led to the widths Γ listed in column 3 of Table II and to the mean value

$$\Gamma=(1.73\pm0.10)\times10^{-3}\text{ eV},$$

which corresponds to a mean lifetime

$$\tau=(3.80\pm0.25)\times10^{-13}\text{ sec}$$

for the 1.116-MeV level in Cu^{65}.

TABLE II. Results of the self-absorption experiment.

Path length in Cu absorber (cm)	Resonant attenuation	Radiative width Γ (eV)
1.26	0.913±0.006	$(1.62\pm0.13)\times10^{-3}$
2.56	0.809±0.014	$(1.89\pm0.15)\times10^{-3}$

IV. ANGULAR DISTRIBUTION OF RESONANCE RADIATION

Scattering experiments were carried out for scattering angles of 90°, 105°, 120°, 135°, and 146°, again using the ZnI_2 source. The front face of the 3×3-in. NaI detector was placed at a distance of 6 in. from the center of the 3×2.5×0.75-in. scatterer. Typical pulse-height distributions are reproduced in Fig. 2. Although the experiments were carried out in a low-background room,[9] the counting rates observed with the Ni comparison scatterer were mainly due to room background and were thus almost independent of the source

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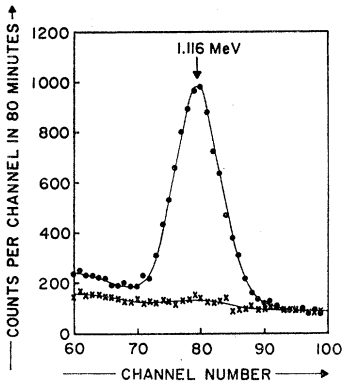

FIG. 2. $Zn^{65}I_2$ source, 135° geometry. Pulse-height distributions of the γ radiation scattered from Cu (circles) and from Ni (crosses), measured with a 3×3-in. NaI detector. The region from 0.93 to 1.31 MeV is depicted.

strength. The geometrical factors [C in Eq. (1)] for the five geometries were calculated using 25 subdivisions of the scatterer and taking into account the self-absorption corresponding to a width $\Gamma=1.73\times10^{-3}$ eV.

A first analysis, in which the coefficients A_2 and A_4 in the angular distribution function $W(\theta)=1+A_2\times P_2(\cos\theta)+A_4P_4(\cos\theta)$ were treated as independent parameters, led to an upper limit for A_4: $A_4\leq0.05$. This restricted $|\delta|$ to values $|\delta|<0.7$. Using the theoretical relationship[10] between the coefficients A_2 and A_4 for a spin sequence $\frac{3}{2}$-$\frac{5}{2}$-$\frac{3}{2}$, the best fit to the experimental data, after correction for the finite angular resolution, was obtained for

$$A_2=0.96\pm0.02,$$

the corresponding A_4 value being $A_4=0.013$.

These values of the coefficients of the Legendre polynomials restrict the $E2/M1$ mixing amplitude δ for the 1.116-MeV transition in Cu^{65} to the range

$$\delta=-0.437\pm0.015.$$

V. DISCUSSION

The mean lifetime $\tau=(3.80\pm0.25)\times10^{-13}$ sec deduced from the self-absorption study agrees quite well with the result $\tau=(4.4\pm1.1)\times10^{-13}$ sec reported by Beard,[1] but disagrees with the lifetime $\tau=(5.3_{-0.3}{}^{+0.4})\times10^{-13}$ sec reported[4] on the basis of a Doppler-shift experiment, and with another self-absorption result[11] [$\tau=(6.5\pm1.6)\times10^{-13}$ sec]. The disagreement with the latter is not considered to be serious in view of the rather large error assigned to it. In this connection it is worth mentioning that the ratio of resonant scattering to background in the present experiment was approximately 20 times better than it was in the experiment reported in Ref. 11. This is, to a considerable extent, due to the use of Zn^{65} rather than Ni^{65} as the source of the resonant γ rays.

As far as the resonance-fluorescence angular distribution experiments are concerned, our reanalysis of the data of Ref. 1, using not freely varying A_2 and A_4 coefficients but coefficients related via the theoretical expressions[10] for a $\frac{3}{2}$-$\frac{5}{2}$-$\frac{3}{2}$ spin sequence, led to a range $A_2=1.03\pm0.06$, which overlaps with our result, $A_2=0.96\pm0.02$. The $E2/M1$ mixing ratio corresponding to $A_2=0.96$ is $\delta^2=0.191\pm0.013$. If this value for the mixing ratio is combined with the observed mean lifetime, a partial $E2$ lifetime $\tau(E2)=(2.37\pm0.21)\times10^{-12}$ sec is obtained. The corresponding reduced $E2$ transition probability is $B(E2)\downarrow=(1.98\pm0.18)\times10^{-50}$ e^2 cm^4. The Coulomb-excitation studies[2,3,12,13] led to an average value $B(E2)\downarrow=(1.92\pm0.14)\times10^{-50}$ e^2 cm^4. The good agreement of these two results is in marked contrast with the disagreement between the δ^2 value deduced above from the angular distribution of the resonance radiation and the value $\delta^2=0.048_{-0.025}{}^{+0.030}$ which follows from the studies[2,3] of the angular distribution of the Coulomb-excited γ rays. Because of the good agreement of the $B(E2)$ values noted above, one is inclined to conclude that the δ^2 value obtained from the angular distribution of the Coulomb-excited γ rays is low and that the errors assigned to it are too optimistic.

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