Lifetime of the 1.52-MeV Level in Ca^{42}†

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Nuclear resonance fluorescence from the first excited state of Ca^{42} has been observed. The K^{42} beta decay provided the recoil needed to restore the resonance condition. To fully utilize this recoil, a gaseous source of K^{42} iodide was used. The measured cross section for resonance scattering corresponds to a width $\Gamma=(4.8\pm1.1)\times10^{-4}$ eV for the 1.52-MeV 2^+ level in Ca^{42}, or a mean life of 1.4×10^{-12} sec. In arriving at this result, the coefficient λ in the beta-neutrino angular correlation function $W(\theta)=1+\lambda(v/c)\cos\theta$ was assumed to have the value $\frac{1}{3}$. The error quoted above for the width Γ takes into account the possibility that λ may range from $-\frac{1}{3}$ to $+1$. The reduced $E2$ transition probability corresponding to the measured width, $B(E2, 2\rightarrow0)=74e^2F^4$, is eight times larger than the Weisskopf estimate, and more than 20 times larger than the prediction of a recent calculation by Bertsch.

I. INTRODUCTION

THE spherical shell model cannot satisfactorily explain the existence of the 1.84-MeV 0^+ state and the 2.42-MeV 2^+ state in Ca^{42}. The presence of these states, and the anomalously large $E2$ transition probability[1] of the 0.32-MeV transition from the 1.84-MeV 0^+ state to the first 2^+ state at 1.52 MeV, indicate that deformed components play an important role in the description of Ca^{42} as they seem to do in the oxygen isotopes.[2] Bertsch[3] has recently investigated collective excitations in the calcium isotopes, taking into account the core polarization by the valence particles. He predicted, among other things, the transition probability for the ground-state transition from the first 2^+ state in Ca^{42}. His value for the reduced transition probability, $B(E2, 2\rightarrow0)=3.2e^2$ F^4, is approximately one-third of the Weisskopf estimate,[4] and corresponds to a mean life of 3.1×10^{-11} sec. Experimentally, Pancholi and Saha[5] had reported a mean life of $(1.4\pm0.6)\times10^{-9}$ sec. However, a later experiment,[6] also using the delayed-coincidence technique, showed that the mean lifetime of the 1.52-MeV state must be shorter than 1.4×10^{-10} sec. A determination of the actual lifetime was clearly needed, and this paper is a report on such a determination using the resonance-fluorescence method.[7]

Since 12.5-h K^{42} populates the 1.52-MeV level in Ca^{42} and is readily available, it received first consideration as the source of the exciting γ radiation. The portion of the decay scheme[8] of K^{42}, which is relevant to the use of this isotope in a resonance-fluorescence experiment, is reproduced in Fig. 1. The energy given there for the endpoint of the β spectrum leading to the first excited state, $E_{\beta2}=2.01$ MeV, was obtained by combining the average of the most accurate reported values[9,10] for the energy of the β transition to the ground state of Ca^{42} with the energy[11] $E_\gamma=1.524$ for the γ transition, and averaging the result with an independent determination[12] of the endpoint of the inner spectrum. Since $E_{\beta2}$ exceeds the γ-ray energy by a confortable margin, resonant γ rays could be expected from K^{42}, provided that effective use was made of the β recoil. At this point, the low abundance (0.6%) of Ca^{42} in natural calcium represented the major obstacle to the contemplated experiment. This obstacle was removed once a loan of 20 g of highly enriched Ca^{42} from the Cross Section Research Pool of the U. S. Atomic Energy Commission was assured.

In what follows, the preliminary experiments with a liquid-K^{42} source, and the procedures used in the

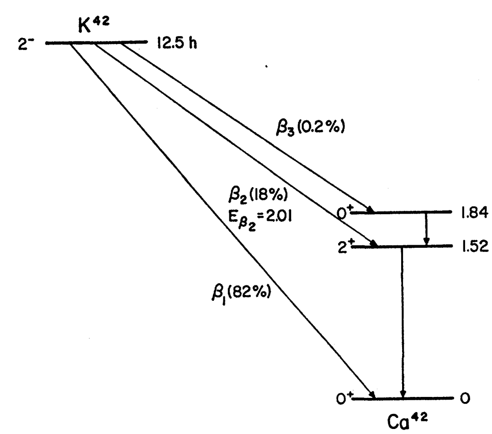

FIG. 1. Portion of the decay scheme of K^{42} relevant to this study. Energies are given in MeV.

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preparation of the gaseous source and in the actual scattering experiments, will be described. The evaluation of the experimental data in terms of the lifetime of the 1.52-MeV state will then be discussed,[13] and the results will be compared with various theoretical predictions.

II. EXPERIMENTS

For a resonance experiment utilizing the recoil of the preceding radiation, the use of a gaseous source is imperative if the lifetime of the excited state is as long as Bertsch's[3] estimate for the 1.52-MeV state in Ca^{42} indicated. In a liquid or solid source, the β recoil would be dissipated prior to the γ emission, and none of the γ rays would be resonant with the 1.52-MeV level. If the lifetime were somewhat shorter, e.g., of the order of 10^{-12} sec, some of the recoils might still be left with velocities sufficient to compensate for the recoil energy losses which, in this case, amount to 59 eV. However, unless the lifetime of the excited state were considerably shorter than 10^{-13} sec, the evaluation of the scattering experiment with a liquid or solid source would be rather uncertain because of the complexity of the slowing down process.

Although the use of a gaseous source was clearly indicated for the 1.52-MeV level in Ca^{42}, a first experiment was carried out with a liquid source. The purpose of this measurement was to obtain a rough estimate of the lifetime, and to check on the nonresonant scattering and the possible leaking of γ radiation through the shielding. The geometry designed for the final experiment, and depicted in Fig. 2, was used. The source consisted of 4 cm^3 of K_2CO_3 in aqueous solution, the total activity being 150 mCi. The scatterers, approximately 50 g each of natural $CaCO_3$ and of $CaCO_3$ enriched to 94.42% in Ca^{42}, were in the form of right cylinders, $2\frac{1}{2}$ in. in length and $1\frac{3}{32}$ in. in diameter, contained in $\frac{1}{64}$ in. aluminum. These scatterers were placed 2 in. from the face of a 3×3 in.-NaI(Tl) detector, the pulses from which were fed into an RIDL 400-channel analyzer.

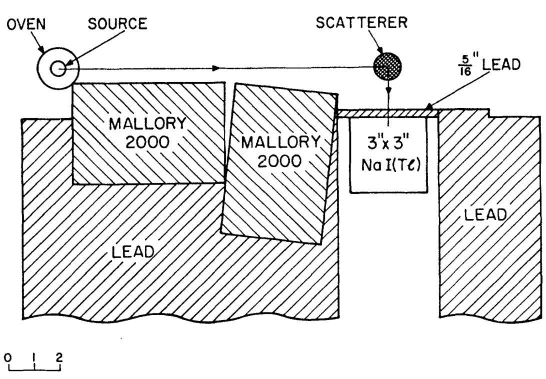

FIG. 2. Typical geometry for the scattering experiment. Of course, the detector was covered with several inches of Pb.

Using the liquid source and the scatterers described above, resonance scattering from Ca^{42} was indeed observed, the counting rate in the region of the 1.52-MeV peak being about 20% larger for the enriched scatterer than for the scatterer fabricated from natural $CaCO_3$. From a comparison with similar cases reported by Ofer and Schwarzschild,[14] it was concluded that the observed scattering represented approximately 2% of the scattering that would be observed in the absence of collisions in the source, and that the mean life of the 1.52-MeV level was about 10^{-12} sec. This meant that an easily observable effect could be expected with a much weaker gaseous source. This was fortunate, since the chemically less active compounds of potassium have low vapor pressures at technically feasible temperatures, and, therefore, impose severe restrictions on the amount of potassium, and thus on the K^{42} activity, that can be kept in the gaseous phase in a given volume. The experiment with the liquid source furthermore showed that leakage through the shielding was negligible, and that the geometry (Fig. 2) did not have to be modified.

For the experiment with the gaseous source, a sample of 1 mg of KI, enriched to 99.5% in K^{41}, was sealed into a quartz ampoule and irradiated in the hydraulic facility of the Oak Ridge Research Reactor for a period of 36 h in a flux of 2.8×10^{14} neutrons per cm^2/sec. Upon receipt, this ampoule was introduced into a vacuum system, broken under vacuum, and a good fraction of the KI distilled into a quartz ampoule 2 in. in length and $\frac{1}{2}$ in. in diameter. This source ampoule, containing approximately 15 mCi of K^{42}, was then placed into an oven consisting of quartz tubing wound with Nichrome wire and insulated with asbestos tape. Using a $\frac{3}{32}$ in. wide and 5 in. long Pb slit, the distribution of the activity over the length of the ampoule was measured at several temperatures. It was found that the activity was uniformly distributed over the volume of the ampoule as long as the temperature was above 1025°C. To be sure that no condensation would take place, the scattering experiments were carried out with the source at 1080°C.

With the geometry as shown in Fig. 2, and another geometry in which the scatterers were placed at a distance of 4 in. from the front face of the detector, pulse-height distributions were registered with the scatterers exchanged every 10 min. In Fig. 3, the pulse-height distributions obtained in the geometry of Fig. 2 are shown. The 1.46-MeV radiation from natural K^{40} in the building material of the room is seen to present a special background problem in this case. Nevertheless, the resonant scattering from the 1.52-MeV level of Ca^{42} is rather prominent in the region of channels 74 to 79 which were used for the evaluation.

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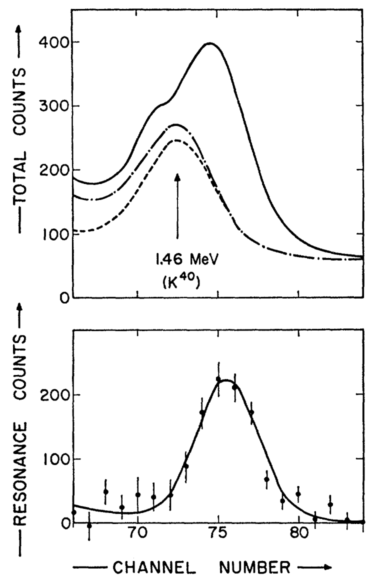

FIG. 3. Pulse height distributions measured in the geometry depicted in Fig. 2. In the upper portion of the figure, the counts per channel measured with the enriched $Ca^{42}CO_3$ scatterer (——) are compared with the counts observed with a scatterer of natural $CaCO_3$ (—·—·—), and with the background counts (- - - -) registered when the source and scatterers were removed. In the lower portion the differences of the $Ca^{42}CO_3$ and $CaCO_3$ counts are plotted. The smooth curve represents the best fit using the shape expected for 1.52-MeV γ radiation.

The strength of the K^{42} source was determined by placing the oven with the source at a distance of 113 in. from the front face of the detector and registering the pulses for a few minutes. A small fraction of the source was used to determine the variation with distance of the solid angle subtended by the detector in the region occupied by the scatterer.

III. EVALUATION AND RESULTS

For an incident γ radiation with an energy distribution which is much broader than the width of the absorption line, the resonant scattering may be written as[7]

$$N_{sc} = N(E_r) g \pi^2 \lambda\!\!\!^{-2} \Gamma G, \qquad (1)$$

where $N(E_r) = F(E_r) N_{total}$ is the number per unit energy interval of γ rays having the resonant energy E_r, $g = (2J_{exc}+1)/(2J_{gs}+1)$ is the ratio of the statistical weights of the excited state and the ground state, $\lambda\!\!\!^{-}$ is the wavelength of the γ radiation divided by 2π, Γ the total width of the level, and G a factor describing the geometry. In arriving at Eq. (1), it was assumed that the direct γ decay to the ground state is the only mode of de-excitation for the level, i.e., that $\Gamma_0 = \Gamma$. This condition is fulfilled for the 1.52-MeV state in Ca^{42} since it is the first excited state and the internal conversion is negligible. To the extent that the resonant attenuation of the incoming beam in the scattering material is appreciable, the geometrical factor G depends on Γ. For the Ca^{42} scatterer used in these experiments, the reduction of the scattering due to the resonant attenuation of the incident beam may be represented by a factor $\mu = 1 - 14.8\Gamma_{eV}$ which, for a lifetime of 10^{-12} sec ($\Gamma = 6.6\times10^{-4}$ eV), is 0.99. To calculate G, the scatterer was subdivided into 21 sections, and the solid angles, the angular distribution factors, the attenuations of the incoming and the outgoing radiations, etc., were calculated for each of these sections.

There remained the calculation of the fraction $F(E_r)$ of incident gamma rays falling into a one eV interval at the resonant energy or, more generally, the calculation of the shape of the 1.52-MeV γ line emitted by a gaseous KI source. This shape depends on the β-neutrino and β-γ angular correlations for the β branch to the 1.52-MeV level. The β-γ angular correlation is known[15,16] to be small. The β-neutrino correlation, on the other hand, has not been studied for this decay. For the purpose of this paper, we assume the β-neutrino angular correlation to have the form $W(\theta) = 1 + \lambda(v/c)\cos\theta$, where v is the velocity of the electron, and θ the angle between the directions of motion of the electron and the neutrino, with λ ranging from $-1/3$ to $+1$.

The momentum distribution of the recoils was calculated for the values $\lambda = -\frac{1}{3}$, $+\frac{1}{3}$, and $+1$. Since the recoil energy necessary for the restoration of the resonance condition is much larger than the binding energy of the KI molecule, and the iodine atom several times heavier than the potassium atom, the main effect of the use of KI molecules is a reduction of the recoil energy by the binding energy of the KI molecule which has been reported[17] as (3.31 ± 0.04) eV. From the momentum distributions which had been corrected for the effect of the molecular binding, the energy distributions of the γ radiation were obtained. They are shown in Fig. 4 for the vicinity of the absorption line.

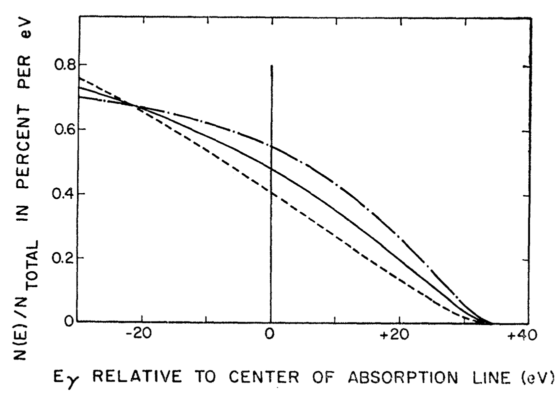

FIG. 4. Shape of the 1.52-MeV emission line from gaseous $K^{42}I$ in the region of the absorption line. The three curves shown correspond to the values $\lambda = -\frac{1}{3}$(- - - -), $\lambda = +\frac{1}{3}$(——), and $\lambda = +1$(—·—·—) of the parameter in the angular correlation function $W(\theta) = 1 + \lambda(v/c)\cos\theta$. The center of the emission line is located at $-E_\gamma^2/Mc^2 = -59$ eV.

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TABLE I. $B(E2, 2 \rightarrow 0)$ values for the 1.52-MeV transition in Ca^{42}, in units e^2 F^4. For the estimate in column 2, a radius $R=1.2A^{1/3}$ F was used. The value[a] given in column 3 is for an effective charge of $0.5e$.

Experiment	Weisskopf estimate[b]	$(f_{7/2})^2{}_{2+} \rightarrow (f_{7/2})^2{}_{0+}$	Bertsch[c]
74 ± 17	8.8	4.6	3.2

[a] We thank Dr. T. A. Hughes for this result.
[b] See Ref. 4.
[c] See Ref. 3.

With the value $N(E_r)=4.8\times10^{-3}N_{\text{total}}$ for $\lambda=+\frac{1}{3}$, taken from Fig. 4, the average scattering observed in the two geometries leads to a width $\Gamma=(4.8\pm0.4)\times10^{-4}$ eV. If allowance is made for the range $-\frac{1}{3}<\lambda<+1$, the result of our study may be summarized as

$$\Gamma=(4.8\pm1.1)\times10^{-4}\text{ eV},$$

corresponding to a mean life of 1.4×10^{-12} sec. This experimental result is compared in Table I with various theoretical estimates.

Clearly, the 1.52-MeV transition in Ca^{42} is quite collective. If, e.g., it is attributed to the recoupling of two $f_{7/2}$ neutrons, the observed rate would imply the large value of $2e$ for the effective charge of an $f_{7/2}$ neutron. The transition is considerably more collective than was expected on the basis of Bertsch's calculations, and this presumably[3] calls for stronger mixing between deformed and undeformed wave functions.

ACKNOWLEDGMENTS

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$Si^{28}(d,p\gamma)Si^{29}$ Angular Correlations from 4 to 6 MeV*

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A study of the (p,γ) angular correlations involving the 1.28- and 2.03-MeV states in Si^{29} populated by the $Si^{28}(d,p)Si^{29}$ reaction has been carried out at five deuteron bombarding energies between 4 and 6 MeV. Angular-correlation measurements were carried out in the reaction plane and in that plane perpendicular to the reaction plane which contains the incident-beam direction. The data were analyzed by means of the distorted-wave stripping formalism. Statistical tensors, describing the orientation of the intermediate excited nuclear states, were calculated at each energy. Since the reaction-plane measurements on the 2.03-MeV state alone were sufficient for determining the statistical tensors describing the correlation over the sphere, comparison has been made between the measured perpendicular-plane correlations and the correlations predicted from these statistical tensors. In addition, a combined set of statistical tensors has been calculated utilizing data from the reaction-plane and perpendicular-plane correlations. The magnitudes of the proton polarizations have also been calculated for the 2.03-MeV excited-state reaction using the combined set of statistical tensors. The observed correlations are in agreement with the predictions of a distorted-wave theory and not with those of the plane-wave theory.

I. INTRODUCTION

THIS paper reports on the investigation of the $(d,p\gamma)$ angular correlations on Si^{28} through the first (1.28 MeV) and second (2.03 MeV) excited states in Si^{29}. These investigations are an extension to lower deuteron bombarding energies of the work of Kuehner, Almqvist, and Bromley[1] at Chalk River, Canada.

The general validity of the distorted-wave Born approximation (DWBA) in describing deuteron stripping reactions is now well accepted. The proton and deuteron wave functions used in the Born approximation are calculated from optical-model potentials whose parameters have been determined over wide energy ranges from fits to elastic-scattering angular distributions. Using these optical potentials and distorted-wave functions in describing incident deuterons and outgoing nucleons, reasonable fits to the angular distribution of the emitted nucleon in stripping reactions can be obtained. Current efforts in improving the DWBA description of stripping reactions involve the nature of the spin dependence of the deuteron and nucleon potentials. A number of theoretical investigations have been done in

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