Nuclear Electric Monopole Transition in Ca^{42}†

N. BENCZER-KOLLER,* M. NESSIN, AND T. H. KRUSE
Columbia University, New York, New York

(Received February 23, 1961)

The 0^+ assignment to the 1.836-Mev, second-excited state in Ca^{42} has been confirmed by the observation of electric monopole electron-positron pairs and internal conversion electrons corresponding to the cross over transition to the ground state. The shape of the continuous positron spectrum from the $E0$ pairs, as well as the ratio $R=9.0\pm1.8$ of pairs to $E0$ conversion electrons are consistent with theoretical predictions for an $E0$ transition. 0.305-Mev internal conversion electrons were observed corresponding to the transition between the 1.836-Mev and the 2^+, 1.523-Mev, first excited state. The ratio of 1.836-Mev to 0.305-Mev electron yields is 1.03 ± 0.10. From these and other data the monopole strength parameter ρ was determined to be 0.41.

INTRODUCTION

NUCLEAR electric monopole transitions between two 0^+ states occur mainly by the emission of internal conversion electrons, or electron-positron pairs, since single gamma-ray emission is absolutely forbidden and double gamma decay is extremely improbable. The determination of the matrix elements of electric monopole transitions is of particular interest to the study of nuclear structure because these matrix elements are very sensitive to the nuclear model chosen to describe the interaction.[1] The absolute transition probability W for $E0$ conversion or pair emission can be written in terms of an electronic factor Ω independent of nuclear properties, and a "strength parameter" ρ which contains the nuclear matrix elements:

$$W_{e^-}=\Omega_{e^-}\rho^2 \quad \text{or} \quad W_{e^+e^-}=\Omega_{e^+e^-}\rho^2.$$

The reduced electric monopole transition probability Ω has been computed by several authors[1–4] for various models of the nuclear charge distribution, and is rather insensitive to the details of the model. For Ca^{42} ($Z=20$) Ω varies by less than 20% in going from a "Coulomb model" to a "uniform charge model." An experimental determination of the absolute transition probability W_{e^-} or $W_{e^+e^-}$ will therefore yield directly the nuclear strength parameter ρ.

The energy level spectrum of Ca^{42} (Fig. 1) is well known from studies of the decay of K^{42},[5] and the magnetic spectrograph analysis of charged particles inelastically scattered in the $Ca^{42}(p,p')Ca^{42*}$ reaction,[6] or produced in the $K^{39}(\alpha,p)Ca^{42*}$ reaction[7] and the $Sc^{45}(p,\alpha)Ca^{42*}$ reaction.[8] However, the spins of all levels but the ground state and the first excited state at 1.52 Mev were undetermined. It was assumed that the two lowest levels would have spin and parity assignments 0^+ and 2^+, respectively, consistent with the systematics of even-even nuclei. The analysis of the γ-ray spectrum emitted in the decay of K^{42} indicates that the 1.84-Mev second-excited state of Ca^{42} decays by γ-ray emission to the first excited state, but not to the ground state. The spin and parity of the 1.84-Mev state were tentatively assigned as 0^+ or 4^+, both values being consistent with the β-decay selection rules.

Recently, various investigators[9] measured the γ-γ angular correlation of the cascade γ rays and conclusively established that the spin of this second excited state is zero. The parity, however, cannot be determined from γ-γ angular correlation measurements.

If the parity is even, the level will de-excite to the ground state through three possible channels, emission of $E0$ conversion electrons, $E0$ pairs, or two γ rays (a very improbable mode which will be assumed negligible),[9a] and to the first excited state by a radiative electric quadrupole transition and by $E2$ internal con-

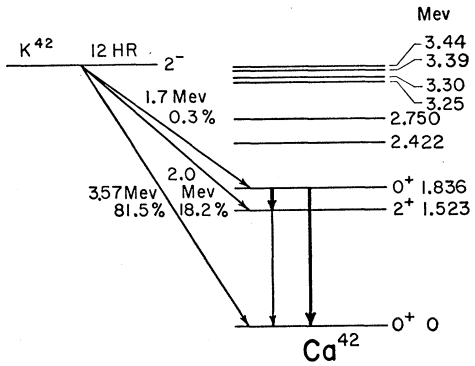

FIG. 1. Decay scheme of K^{42} and low-lying excited states of Ca^{42} as determined from the magnetic spectrograph analysis of the $Ca^{42}(p,p')Ca^{42*}$ reaction.

† This work partially supported by the U. S. Atomic Energy Commission.

* Present address: Department of Physics, Rutgers University, New Brunswick, New Jersey.

[1] E. L. Church and J. Weneser, Phys. Rev. **103**, 1035 (1956).
[2] R. Thomas, Phys. Rev. **58**, 714 (1940).
[3] A. S. Reiner, Physica **23**, 338 (1957).
[4] R. E. Mills and R. M. Kloepper, Los Alamos Scientific Laboratory Report LAMS-2359 (unpublished).
[5] Ch. L. Koerts, thesis, Columbia University, New York, 1955 (unpublished). J. D. McCullen and J. J. Kraushaar, Phys. Rev. **122**, 555 (1961).
[6] C. M. Braams, thesis, 1956 (unpublished). P. M. Endt and C. M. Braams, Revs. Modern Phys. **4**, 683 (1957).
[7] J. P. Schiffer, Phys. Rev. **97**, 428 (1955).
[8] W. W. Buechner and M. Mazari, Rev. mex. fis. **7**, 117 (1958).
[9] H. Morinaga, N. Mutsuro, and M. Sugarawa, Phys. Rev. **114**, 1146 (1959). I. Asplund and T. Wiedling, Phys. Rev. **116**, 741 (1959). H. Einbinder and C. S. Wu, Columbia University Report CU(PNPL)-203, 1960 (unpublished). J. D. McCullen and J. J. Kraushaar, Bull. Am. Phys. Soc. **5**, 10 (1960).
[9a] H. Ryde, P. Thieberger, and T. Alväger, Phys. Rev. Letters **6**, 475 (1961).

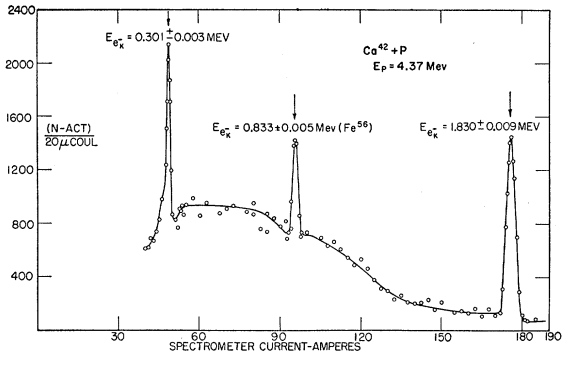

FIG. 2. Corrected spectrum of electrons emitted in the de-excitation of the 1.836-Mev level in Ca^{42}. The line at 0.833 Mev corresponds to internal conversion electrons emitted in the decay of the first excited state of the Fe^{56} in the target backing foil. The energies indicated are those of the electron conversion lines.

version electrons. The measurement of the relative transition probabilities of the four major modes of decay of the second excited state, together with that of its mean life, yield the value of the absolute transition probability of any one of the four modes, in particular W_{e^-} or $W_{e^+e^-}$, which in turn determines the value of ρ.

The lifetime of the 0^+ state excited in the β^- decay of K^{42} was measured by delayed coincidence techniques to be $\tau_{\text{mean}}=(4.8\pm0.3)\times10^{-10}$ sec.[10]

EXPERIMENTAL METHODS

The 1.84-Mev state of Ca^{42} was excited by bombarding an enriched $CaCO_3$ (82.5% Ca^{42}) target with protons from the Van de Graaff generator. The target was prepared by depositing a few $\mu g/cm^2$ of $CaCO_3$ in powder form on a Deltamax foil[11] backing 0.000125 in. thick. The powder was glued to the Deltamax backing with a drop of very dilute glyptol. The Deltamax foil was chosen because of its flat background in the region of interest.

Electron and positron spectra were measured in the intermediate image spectrometer using a detector and charge selection baffle system previously described.[12]

The electron spectrum (Fig. 2) exhibits three strong lines: the line at 0.833±0.005 Mev, which appeared with equal intensity when the Deltamax backing alone was bombarded, corresponds to the de-excitation by internal conversion of the 0.845-Mev first-excited state of Fe^{56}; the lines at 0.301±0.003 and 1.830±0.009 Mev correspond to the internal conversion electrons emitted in the cascade transition from the second to the first excited state of Ca^{42}, and in the crossover transition to the ground state, respectively.[13]

The ratio r of intensities of the two Ca^{42} lines was $r=[I(0.301)/I(1.830)]=1.03\pm0.10$ and remained constant at several proton bombarding energies between 3.9 and 5.2 Mev. This result supports the above conclusion that both the 0.301-Mev and the 1.830-Mev electron lines are emitted in the de-excitation of the same state.

The positron spectrum is characterized by a continuous distribution having an end point at 0.800±0.030 Mev. This spectrum was observed at a bombarding energy of 4.37 Mev, below the first resonance for production of 3.35-Mev monopole pairs from Ca^{40}.[14]

In both the electron and positron measurements the activity background count with the beam stopped was observed immediately after each measurement. The electron activity was very low and practically negligible. However, there was a strong continuous background spectrum of positrons with an end point around 1 Mev, which decayed with a half-life of about 10 min. This background was tentatively attributed to the $C^{13}(p,n)N^{13}\xrightarrow{\beta^+}C^{13}$ reactions. An attempt was consequently made to prepare a target with a minimum of carbon. Two targets, one on Deltamax, the other on gold backing, were prepared by overlaying the $CaCO_3$ powder with a very thin gold foil, and without using glyptol. Such targets withstood bombardment for several hours; they were frequently checked by remeasuring the intensity of the strong 1.830-Mev line. However, little improvement in reducing the positron activity background was achieved. Hence to avoid an intolerable buildup of activity, the beam was allowed on the target for about 30 sec at intervals of about 8 min,

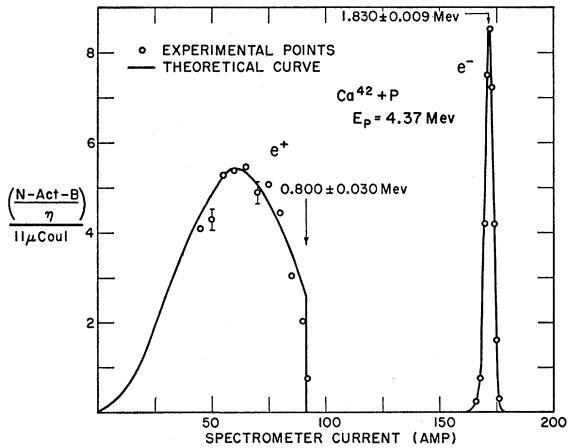

FIG. 3. Positron spectrum observed in the de-excitation of the 1.836-Mev level of Ca^{42}, corrected for activity, prompt background, and spectrometer resolution, and the 1.830-Mev internal conversion line similarly corrected.

[10] P. C. Simms, N. Benczer-Koller, and C. S. Wu, Phys. Rev. **121**, 1169 (1961).

[11] The main constituent of Deltamax is iron. The foil was kindly supplied to us by Arnold Engineering, Marengo, Illinois.

[12] K. Eklund, thesis, Columbia University, Columbia Report CU-196, New York, 1960 (unpublished). M. Nessin, K. Eklund, and T. H. Kruse, Bull. Am. Phys. Soc. 4, 278 (1959). M. Nessin, thesis, Columbia University, Columbia Report CU(PNPL)-201, New York, 1960 (unpublished).

[13] The binding energy of the K electron is 7 kev in iron and 4.0 kev in calcium.

[14] R. D. Bent and T. H. Kruse, Phys. Rev. **109**, 1240 (1958).

and measurements with "beam off" were performed before and after each "beam on" point.

Another source of background was attributed mainly to neutrons and γ rays. It was observed with the "beam on" as a fairly constant background above the end point of the positron spectrum. Since neither the origin of this prompt background nor its true distribution under the positron spectrum is known, it was assumed constant from the positron spectrum end point down to zero energy. The observed positron spectrum corrected for activity, prompt background, and spectrometer resolution is shown in Fig. 3, together with the 1.830-Mev internal conversion line also corrected in the same fashion.

DISCUSSION

The positron spectrum of Fig. 3 agrees well with the theoretical distribution (solid curve) calculated from Thomas[2] expression, and normalized to fit the experimental points. In order to estimate the relative rates of nuclear pairs to K conversion electron emission, the area under the normalized theoretical positron distribution was compared to the area under the conversion electron line. The observed ratio must be corrected for the fact that the K and L conversion lines were not resolved since they are only 3.6 kev apart. According to an expression given by Church and Weneser the ratio of K to L_{I} conversion transition probabilities for a transition of 1.836 Mev is 6.78, and L_{II}, L_{III}, and M conversion are negligible. Further corrections corresponding to the effect of the finite dimension of the nuclear charge distribution and screening by atomic electrons need to be considered. The finite size effect on the probability of either electron or pair emission is negligible for $Z=20$. The screening correction to the bound wave functions, however, is appreciable and is different for the K and L shells. The probability for K conversion is depressed by a factor of 0.91 only, while the probability for L conversion is depressed by a factor of 0.61.[15] The effect of screening on the continuum electron wave function is negligible, but the probability for pair emission is enhanced by about 2.5%.[16] The ratio of positrons to K electron yields calculated from the observed spectra becomes

$$R_{\mathrm{exp}}=W_{e^+e^-}/W_{eK^-}=9.0\pm1.8.$$

This ratio compares favorably with the theoretical value for electric monopole transitions corrected for screening effects in the K shell:

$$R_{\mathrm{theor}}=7.9,$$

where the expressions used for W_{eK^-} and $W_{e^+e^-}$ are those given by Thomas. The error assigned to the observed value of the ratio R stems principally from the difficulty in estimating the background for the positron spectrum.

The approximate theoretical value expected for R, assuming the second-excited state has 4^+ spin and parity assignments, is $R=[W_{e^+e^-}(E4)/W_{eK^-}(E4)]=(5\times10^{-5}/6.4\times10^{-5})=0.8$,[17] and the ratio of the intensities of the 0.310-Mev $E2$ conversion line to that of the 1.836-Mev $E4$ conversion line would be $[e_{E2}{}^-(0.310)/e_{E4}{}^-(1.836)]=5\times10^{10}$, this last value being computed from the single-particle estimates of the partial lifetimes of an assumed 4^+ second-excited state.

The assignment of zero spin and even parity to the second excited state in Ca^{42} is confirmed by the electric monopole nature of the radiations observed in the decay of this state, namely the shape and end point of the positron spectrum, and the intensity ratio of 1.836-Mev conversion electrons to the positron component of the pairs.

The nuclear strength parameter ρ can be obtained directly from the computed value of the reduced matrix elements $\Omega_{e^+e^-}$ or Ω_{e^-}, the experimentally observed mean life τ, and the ratios r and R:

$$\tau_{\mathrm{mean}}=\frac{1}{W_{e^+e^-}(E0)+W_{eK^-}(E0)+W_{\gamma}(E2)+W_{eK^-}(E2)}$$

$$=\frac{1}{W_{eK^-}(E0)[1+[W_{e^+e^-}(E0)/W_{eK^-}(E0)]+[W_{eK^-}(E2)/W_{eK^-}(E0)](1+1/\alpha)]}.$$

The conversion coefficient α of the 0.313-Mev $E2$ transition has been calculated theoretically[18] but has not been measured. Assuming the theoretical value of $\alpha=3.2\times10^{-3}$, the transition probability for $E0$ internal conversion in the K shell is given by $W_{eK^-}(E0)=1/(332\tau_{\mathrm{mean}})=\Omega_{eK^-}\rho^2$ and $\rho=0.41\pm0.04$. The uncertainty in ρ was calculated solely from the statistical errors in the lifetime measurement and in the determination of the decay branching ratios and includes a 10% error in α which arises from the difficulty of interpolating the actual value of α from Rose's tables. There appears to be a significant difference between the ρ values of Ca^{40} ($\rho=0.15$),[19] a doubly magic nucleus, and of Ca^{42} consisting of a doubly magic core with two additional

[18] M. E. Rose, G. H. Goertzel, and C. L. Perry, Oak Ridge National Laboratory Report ORNL-1023, Oak Ridge, Tennessee, 1951 (unpublished).

[15] N. Brysk and M. E. Rose, Oak Ridge National Laboratory Report, ORNL-1830, Oak Ridge, Tennessee, 1955 (unpublished).

[16] J. R. Reitz, Phys. Rev. **77**, 10 (1950).

[17] R. Wilson in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. XX, p. 636.

[19] R. M. Kloepper, R. B. Day, and D. A. Lund, Phys. Rev. **114**, 240 (1959).

neutrons, while no such discrepancy occurs between the ρ value of the germanium isotopes, Ge^{70} ($\rho=0.09$)[20] and Ge^{72} ($\rho=0.11$).[21] ρ depends mainly on the mean life of the 0^+ state and the conversion coefficient α. If there is no large error in either of these terms, the difference in the value of the two matrix elements may reflect a structural difference in the two nuclei.

[20] D. E. Alburger, Phys. Rev. **109**, 1222 (1958).
[21] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

ACKNOWLEDGMENTS

We wish to express our appreciation to Professor C. S. Wu for stimulating discussions. We also thank Mr. E. Hadjimichael for his help in the early stages of this experiment.

PHYSICAL REVIEW VOLUME 123, NUMBER 1 JULY 1, 1961

Coulomb Barrier in a Highly Excited Nucleus

D. W. LANG
Department of Theoretical Physics, Australian National University, Canberra, Australia
(Received February 9, 1961)

Experiments involving alpha emission spectra from nickel and rhodium bombarded with protons are analyzed using the statistical model. It is shown, using values calculated by Igo for the cross sections for alpha absorption, that the experimental data are consistent with a constant value for the potential barrier.

EXPERIMENTS by Fulmer and Goodman[1] in which the alpha emission spectrum of a nucleus, formed by bombardment with high-energy protons, have been interpreted by these authors as showing that the Coulomb barrier in a highly excited nucleus is lower than in a ground state. This result is in apparent conflict with the theoretical work of Lane and Parker[2] on this topic, and will be shown, using values of the alpha-particle capture cross section calculated by Igo,[3] to be unnecessary.

According to Weisskopf,[4] the number of particles in an energy range dE of the emission spectrum of a compound nucleus should be $N(E)dE=\omega(U-Q-E)E\sigma_c(E,U-Q-E)dE$ where E is the energy of the emitted particle, Q its binding energy, U the excitation energy of the compound nucleus, ω the level density as a function of the excitation energy in the residual nucleus, and σ_c the cross section for the inverse reaction [i.e., capture of an α particle with energy E by the residual nucleus at an initial excitation energy $(U-Q-E)$]. The assumption under question, which is implicit in Igo's work, is that σ_c is a function of E only and not of the residual excitation energy $(U-Q-E)$.

The experimental data for various values of the bombardment energy were plotted by Fulmer and Goodman in the form $N(E)$ against E. Using Igo's σ_c, these data, replotted in the form $\log[N(E)/E\sigma_c(E)]$ against E, are shown in Fig. 1 for rhodium and nickel. If the level density function had the form $\omega(U-Q-E)=\omega(U-Q)\exp(-E/\tau)$, and if no alpha particle which followed any other emission were included, then the plots should yield straight lines. If the plots are approximately straight lines, then a value for τ may be derived from each, using points near the maximum value of $N(E)$ in each case. The relation $U=a\tau^2-2.5\tau$ may then be used as in Le Couteur and Lang[5] to derive a value of the parameter a. Values of τ and a are listed in Table I.

Examination of Fig. 1 reveals that the plots are not in fact straight lines. In the case of rhodium, a straight

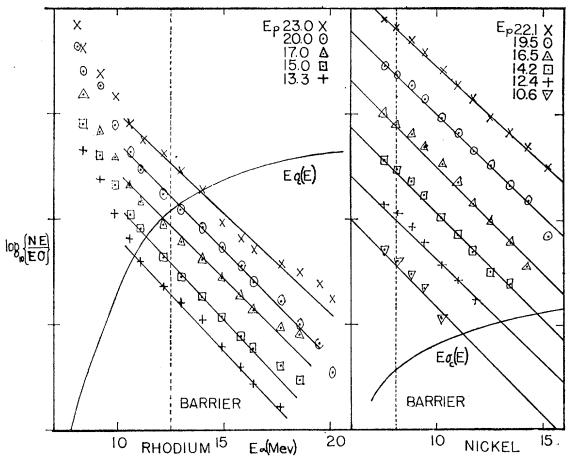

FIG. 1. Alpha-particle spectrum from Fulmer and Goodman[1] for (p,α) in (a) rhodium and (b) nickel, plotted in the form $\log_{10}\{N(E)/[E\sigma_c(E)]\}$ versus E using values for $\sigma_c(E)$ from Igo.[3] A plot of $\log_{10}\{E\sigma_c(E)\}$ versus E is also given. The vertical scale interval is 2.0.

[1] C. B. Fulmer and C. D. Goodman, Phys. Rev. **117**, 1339 (1960).
[2] A. M. Lane and K. Parker, (to be published).
[3] G. Igo, Phys. Rev. **115**, 1665 (1959).
[4] V. F. Weisskopf, Phys. Rev. **52**, 295 (1937).
[5] K. J. LeCouteur and D. W. Lang, Nuclear Phys. **13**, 32 (1959).