# Doppler-Shift Measurements of Lifetimes of Low-Lying Levels in $Na^{23}$ †

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Lifetimes of low-lying levels in the nucleus $Na^{23}$ have been measured using the Doppler-shift-attenuation method. Precise level energies have also been deduced. The measured lifetimes or limits on lifetimes $\{E_x(\text{MeV})\ \tau_m(\text{psec})\}$ for a number of levels of $Na^{23}$ are 2.078 ($<0.23$), 2.391 ($0.95\pm0.20$), 2.640 ($0.20\pm0.08$), 2.705 ($0.20\pm0.10$), 2.982 ($<0.07$), 3.678 ($<0.17$), 3.913 ($<0.10$). The decay properties of the 2.640- and 3.678-MeV levels are discussed in terms of the Nilsson model.

## I. INTRODUCTION

MANY of the properties of the low-lying levels of $Na^{23}$ have in the past been successfully explained by unified Nilsson-model calculations.[1] Recent work has pointed out some deficiencies in the application of the model to $Na^{23}$ but has also indicated new areas of agreement. The reports of Howard, Allen, and Bromley[2] and Poletti and Start,[3] between them, give a fairly complete set of references to earlier work and discuss a number of the properties of $Na^{23}$ in terms of the Nilsson model. More recently, Dubois[4] has used the $Ne^{22}(He^3, d)Na^{23}$ reaction at bombarding energies of 10 and 12 MeV to investigate the properties of excited states of $Na^{23}$ up to 9 MeV. He has also derived[4] a set of wave functions for the even-parity states of $Na^{23}$. His calculations include the possibility of band mixing between as many as six bands.

That it is necessary to correctly antisymmetrize the wave function of the $\frac{1}{2}^+$, 2.39-MeV level in order to explain its decay properties has been pointed out by Pelte[5] and discussed by Dubois.[6] Lindgren *et al.*[7] have used the $Na^{23}(\alpha, \alpha'\gamma)Na^{23}$ and $Mg^{26}(p, \alpha\gamma)Na^{23}$ reactions at incident energies of 16.85 and 14.25 MeV, respectively, to examine the decay properties of levels below $E_{ex}=6.65$ MeV. Sowerby, Sheppard, and Olsen[8] have reported on some $\gamma$-ray angular correlation studies in $Na^{23}$ as have Maier, Pronko, and Rolfs.[9] Both groups[8,9] have assigned spins of $\frac{7}{2}$ and $\frac{9}{2}$ to the 2.08- and 2.71-MeV levels, respectively. Rasmussen[10] has reinvestigated the resonance fluorescence excitation of the 2.98-MeV level by the use of bremsstrahlung radiation. The $\gamma$-$\gamma$ angular correlation obtained by Rasmussen, in contrast to the one obtained earlier[11] when $\gamma$ rays from the 2.98-MeV level in $Al^{27}$ were used to excite the level, gives a value for the $E2/M1$ mixing ratio ($J_i=\frac{3}{2}$) which agrees more nearly with that reported by Poletti and Start,[3] who used the $Mg^{26}(p, \alpha\gamma)Na^{23}$ reaction to excite the level. Although Rasmussen's result[10] is preliminary, this agreement together with the width measured by Rasmussen and Khan[11] implies that the 2.98-MeV level is almost certainly $J^\pi=\frac{3}{2}^+$. Rasmussen[10] has also measured the width of the 2.64- and 3.91-MeV levels. Richter and Von Witsch[12] have analyzed the fluctuating yield of the $Mg^{26}(p, \alpha)Na^{23}$ reaction leading to the 2.39-MeV level. Their analysis supports the $J^\pi=\frac{1}{2}^+$ assignment to this level, as does both the direct reaction[4,13] and $\gamma$-ray correlation studies.[3,8,9] A rotational model representation of low-lying excited states in $Na^{23}$ has been given by El-batanoni and Kresnin.[14] Accurate energies of excited states in $Na^{23}$ have been given by Dubois[15] and Hay and Kean.[16]

The aim of the present work was to measure the lifetimes of some of the low-lying states of $Na^{23}$ in order to test further the unified Nilsson-model description of the nucleus. For reference, in Fig. 1, we give a summary of the energies, decay modes, and spin-assignments obtained from a synthesis of the results of the present and previous work. The decay mode and probable spin of the 5.530-MeV level are discussed by Lindgren *et al.*[7] The decay modes given in the figure are those obtained by Poletti *et al.*[17] except for the 3.85- and 4.43-MeV levels. For these

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latter levels the decay modes are obtained from Endt and van der Leun.[18]

## II. EXPERIMENTAL METHOD

Protons with energies ranging from 3.75 to 5.25 MeV, accelerated by the Stanford FN Tandem Van de Graaff accelerator, were used to bombard targets containing $Na^{23}$. The $\gamma$ rays arising from the resulting nuclear reactions [$Na^{23}(p,p'\gamma)Na^{23}$ and $Na^{23}(p,\alpha\gamma)Ne^{20}$, $Q=+2.377$ MeV] were observed with the aid of a Ge(Li) $\gamma$-ray spectrometer system which has been previously described.[19] We did not attempt to detect any of the associated charged particles ($\alpha$'s or $p$'s), but instead recorded the $\gamma$ spectra in singles only. The attenuated Doppler shifts were obtained by measuring the energies of $\gamma$ rays detected with the Ge(Li) detector set alternately at angles of $\theta_\gamma=0°$ and 90° with respect to the beam axis. The energies were measured by fitting a smooth background below the peak of interest (full energy, one- or two-escape peak) and determining the centroid of the remainder. Accurate energies of the detected $\gamma$ rays were determined using a mixed-source technique in which $\gamma$ rays from $Na^{23}+p$ ($E_p=$ 4.75 MeV) were recorded simultaneously with those from $Co^{60}$ and $Th^{228}$ sources. Peak positions determined from the centroid program were used together with a quadratic least-squares-fitted calibration curve to obtain the final energy values which we quote in Table I.

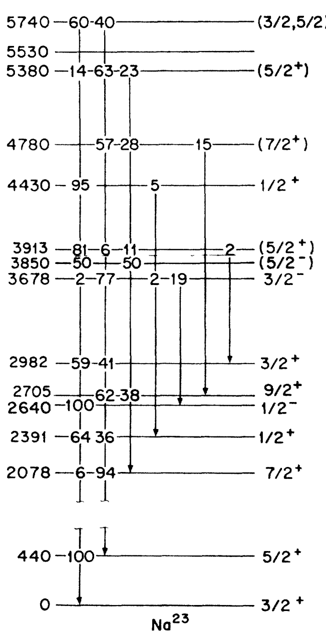


FIG. 1. Summary of energies in keV, spin-parity assignments, and $\gamma$-ray decay modes for the low-lying levels in $Na^{23}$.

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TABLE I. Energies of $\gamma$ rays observed upon bombarding $Na^{23}$ with 5.25-MeV protons.

| Energy (keV) | Assignment[a] |
|---|---|
| 440.15±0.40 | 0.44→0 |
| 627.9±0.4 | 2.70→2.08 |
| 1633.9±0.5 | $Ne^{20}$, 1.63→0 |
| 1950.4±0.7 | 2.39→0.44 |
| 2077.5±1.1 | 2.08→0 [b] |
| 2263.9±1.3 | 2.70→0.44 |
| 2390.1±0.9 | 2.39→0 |
| 2540.2±1.2 | 2.98→0.44 |
| 2639.3±1.4 | 2.64→0 |
| 2980.9±1.5 | 2.98→0 |
| 3237.7±1.6 | 3.68→0.44 |
| 3911.4±2.1 | 3.91→0 |

[a] Transitions in $Na^{23}$ except where specified.

[b] The major decay mode of the 2.08-MeV level in $Na^{23}$ gives rise to a $\gamma$ ray of 1637.4±1.2 keV. This is obscured by the more intense $Ne^{20}$ $\gamma$ ray of 1633.9±0.5 keV.

Two different target materials were used: either metallic Na (scraped clean of any oxide layer and transferred to the target chamber in an inert atmosphere of helium) or anhydrous NaI made by fusing NaI crystals on a tantalum backing at a temperature of 650°C. Both targets were infinitely thick for protons of the bombarding energies used and neither gave rise to any $\gamma$ rays except those from $Na^{23}+p$.

## III. RESULTS

Figure 2 displays two representative spectra obtained at a proton bombarding energy of 5.25 MeV with a thick metallic Na target. Except for $\gamma$ rays from the first two excited states of $Ne^{20}$ formed by the $(p,\alpha)$ reaction on $Na^{23}$, all observed $\gamma$ rays are ascribed to the decay of levels in $Na^{23}$. The $\gamma$ ray from the $Ne^{20}$ second excited state ($E_\gamma=2.616$ MeV) was greatly Doppler-broadened and we could not determine its energy accurately. In Table I, we present the energies (measured as previously described) of the observed $\gamma$ rays together with their assignments. From this table we derive the energies of excited states in $Na^{23}$ and these we list in Table II together with the previously best-known energies. We average the two sets of results and adopt the values listed in Table II, column 3 for the purpose of further discussion.

We have recently described[19] the method used to extract the lifetimes from the experimentally measured difference in the energies of $\gamma$ rays detected at $\theta_\gamma=0°$ and 90° ($\Delta E_{stop}$). The expected full shift

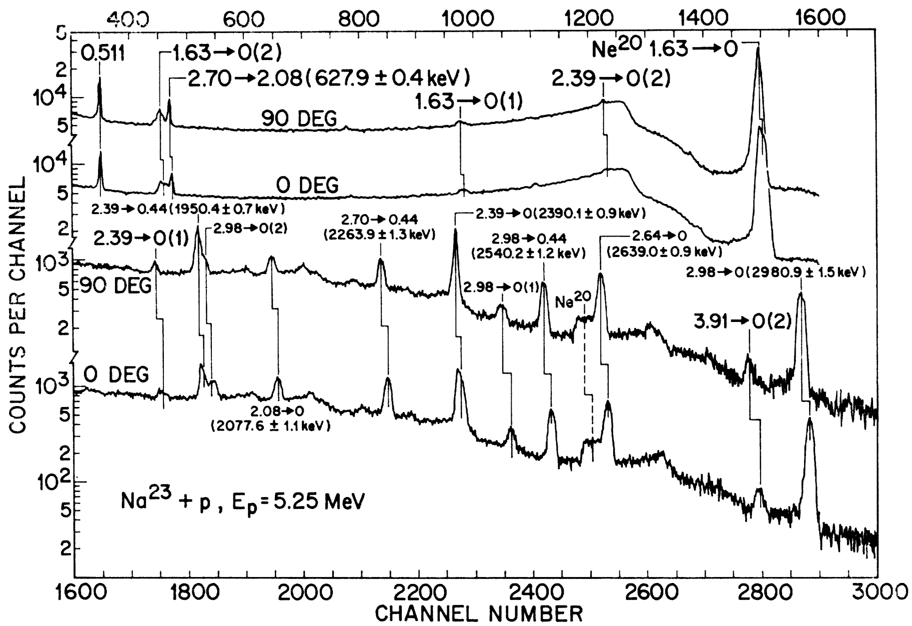


FIG. 2. Partial $\gamma$-ray spectra obtained from the bombardment of a thick metallic Na target with protons of 5.25 MeV. The most prominent peak obtained in such a bombardment—that due to the 440-keV $\gamma$-ray transition from the first excited state of Na[23]—is not shown. All the prominent peaks in the spectrum are labeled on the figure. Except for the peaks at 1.63 and 2.62 MeV, which arise from the decay of levels in Ne[20], all the peaks arise from the $\gamma$ decay of excited states in Na[23]. It can immediately be seen that the lifetime of the 2.39-MeV level is comparable to the characteristic slowing down time.

($\Delta E_{fs}$) was calculated assuming that the recoil velocity $v_z$ in the direction of the $z$ axis could be taken as[20]

$$\langle\beta_z\rangle = \langle v_z/c\rangle = \beta_{\mathrm{c.m.}}[1+\gamma^{-1}\langle\cos\theta_{\mathrm{c.m.}}\rangle],$$

where $\langle\cos\theta_{\mathrm{c.m.}}\rangle$ indicates an average over the differential cross section of the reaction $M_2(m_1, m_4)M_3{}^*$, while $\gamma^{-1}$ is the ratio of the speed of $M_3{}^*$ in the c.m. system to the speed of the center of mass in the laboratory system.[20] Because of the low bombarding energies and the fact that the Doppler-shift measurements were made as close to threshold as possible, we take in the analysis $0\pm0.16$ to be a good *a priori* estimate for $\langle\cos\theta_{\mathrm{c.m.}}\rangle$. A representation of the slowing down process[20] is $-M_1 dv_z/dt = K_n(v_z/v_0)^{-1}+K_e(v_z/v_0)$, where $v_0=c/137$, and $M_1$ and $v_z$ are the mass and velocity in the $z$ direction of the ion being stopped. From the work of Ormrod, MacDonald, and Duckworth[21] it is apparent that the Lindhard-Scharff[22] estimate of $K_e$ for Na[23] ions stopping in any material should be decreased by $(18\pm10)\%$. We estimated $K_n$ by the method used by Warburton, Olness, and Poletti.[20] Accordingly, we use for Na[23] ions stopping in metallic sodium ($\rho=0.97$ g/cm$^3$) $K_e=(2.38\pm0.24)$ keV cm$^2$/$\mu$g and $K_n=0.34$ keV cm$^2$/$\mu$g, while for stopping in NaI($\rho=3.67$ g/cm$^3$), we employ $K_e=(1.02\pm 0.10)$ keV cm$^2$/$\mu$g, and $K_n=0.19$ keV cm$^2$/$\mu$g. The characteristic electronic stopping times $\alpha(=M_1v_0/K_e\rho)$ for the two materials are therefore 2.31 and 1.23 psec, respectively. As in the previous work,[19] we checked the $F(\tau)$ curves calculated using the above assumptions with those calculated by the method due to Blaugrund[23] in which the nuclear scattering is specifically taken into account.

Figures 3 and 4 are partial spectra illustrating the Doppler shifts observed for most of the $\gamma$ rays listed in Table I. A comparison among the three full-energy peaks shown in Fig. 3 shows that the Doppler shift of the 2.39-MeV $\gamma$ ray is attenuated from the expected full kinematic shift: The attenuation displayed in the figure corresponds to $F(\tau)=0.48\pm0.08$ for a bombarding energy of 3.75 MeV and a metallic Na stopper. The energy shifts of the 2.078- and 2.640-MeV $\gamma$ rays displayed in Fig. 3 correspond to values

TABLE II. Energy levels in Na[23]. (Energies in keV.)

| Present work | Previous[a] | Adopted |
|---|---|---|
| 440.15±0.4 | 439.2±0.8 | 439.8±0.4 |
| 2077.6±1.1 | 2078±4 | 2077.7±1.1 |
| 2390.2±0.9 | 2393±5 | 2390.6±0.9 |
| 2639.5±1.4 | 2641±6 | 2639.8±1.4 |
| 2704.8±1.0 | 2705±5 | 2704.8±1.0 |
| 2981.1±1.5 | 2985±6 | 2982.1±1.5 |
| 3678.1±1.7 | 3679±5 | 3678.4±1.7 |
| | 3850±5 | 3850±5 |
| 3911.7±2.1 | 3915±5 | 3912.5±2.1 |

[a] Reference 18.

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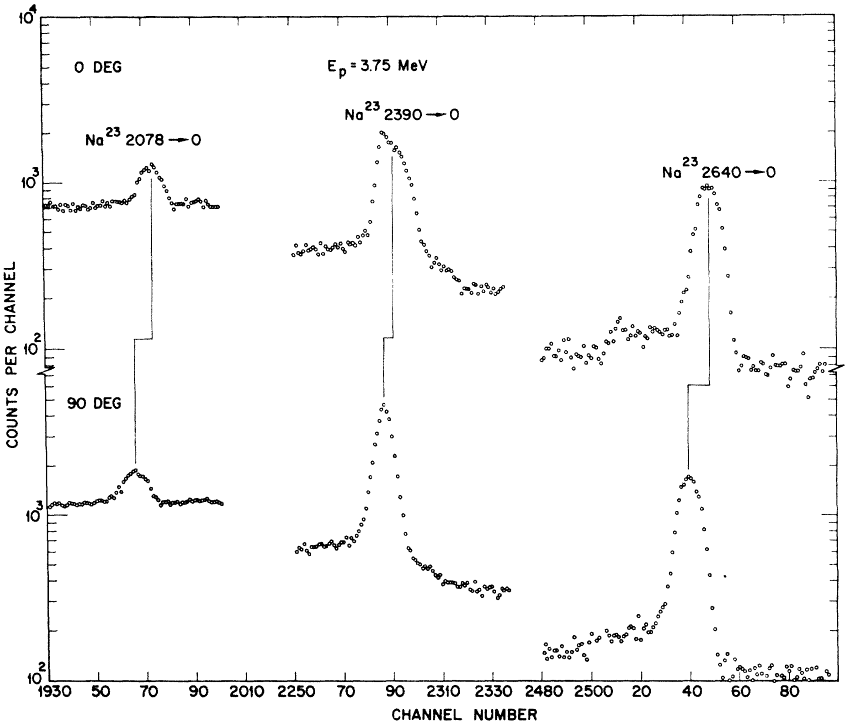


FIG. 3. Partial $\gamma$-ray spectra obtained from the bombardment of a thick metallic Na target with protons of 3.75 MeV. The 2.078- and 2.640-MeV $\gamma$ rays (arising from the ground-state decay of the corresponding levels) have measured Doppler shifts essentially equal to the expected full kinematic shift. However, for the 2.390-MeV $\gamma$ ray arising from the ground-state transition of the 2.390-MeV level the Doppler shift is attenuated. The resulting $F(\tau)$ when averaged with that obtained for $Na^{23}$ ions stopping in NaI implies $\tau_m = 0.95\pm0.20$ psec for the 2.39-MeV level.

of $F(\tau)=0.92\pm0.11$ and $0.85\pm0.09$, respectively. In Fig. 4, we display the Doppler shifts of four $\gamma$ rays. We see that the 2.64- and 2.26-MeV $\gamma$ rays from the 2.64- and 2.70-MeV levels have shifts attenuated from the expected full kinematic shift corresponding to $F(\tau)=0.72\pm0.08$ and $0.76\pm0.09$, respectively, for a bombarding energy of 5.25 MeV and a fused NaI stopper. The average energy shift of the 2.39- and 2.54-MeV $\gamma$ rays from the 2.39- and 2.98-MeV levels corresponds to $F(\tau)=0.30\pm0.05$ and $1.03\pm0.10$, respectively, for the same conditions. Averaged results obtained from the analysis of the spectra displayed in Figs. 3 and 4 and other similar spectra lead to the lifetimes quoted in Table III. A comparison with other measurements is made and an average of the present and other work is taken to arrive at the adopted values which are shown in column 4. For the levels at 2.39, 2.64, and 2.70 MeV there is fair agreement between the results of the present work and those quoted in Ref. b of Table III, or in Rasmussen.[11]

TABLE III. Lifetimes of excited states of $Na^{23}$.

| Level (MeV) | This work | Lifetime (psec) Other | Adopted |
|---|---|---|---|
| 0.44 | | 1.60±0.08[a] | 1.60±0.08 |
| 2.08 | <0.23 | 0.22±0.03[b] | <0.23 |
| 2.39 | 0.95±0.20 | 1.55±0.09[b] | 1.25±0.20 |
| 2.64 | 0.20±0.08 | 0.36±0.06[b] | 0.15±0.03 |
| | | 0.13±0.03[c] | |
| 2.70 | 0.20±0.10 | 0.10±0.02[b] | 0.15±0.08 |
| 2.98 | <0.07 | 4.7±0.07 fs[c] | 4.7±0.7 fs |
| 3.68 | <0.17 | 0.04±0.04[b] | <0.12 |
| 3.85 | ... | 0.17±0.04[b] | 0.17±0.08 |
| 3.91 | <0.10 | 0.06±0.03[b] | <0.12 |

[a] Reference 18.
[b] J. L. Durell *et al.*, Phys. Letters **29B**, 100 (1969), where, for the purpose of computing adopted lifetimes, we have increased the errors quoted so that they are roughly equal to those of the present work. The reason for this is that in both experiments the factor determining the accuracy of the measurement for short lifetimes is the uncertainty in the recoil velocity distribution of the recoiling Na ions. This uncertainty was essentially the same in both cases.
[c] References 10 and 11.

## IV. DISCUSSION

Pelte[5] has pointed out that in order to account for the decay properties of the 2.39-MeV level in terms of the Nilsson unified model[1] it is necessary to antisymmetrize correctly the wave functions taking account of isotopic spin. As Pelte[5] has shown, this correct treatment allows us to understand the marked inhibition of the magnetic dipole 2.39→0 transition. On the other hand, the decay of the 2.64-MeV level can be correctly treated using just the simple single-particle Nilsson[1] calculations. We can understand the reasons for this difference in the following way: If isotopic spin is a good quantum number, then the 2.39-MeV level in $Na^{23}$ which is the lowest member of the $K^\pi=\frac{1}{2}^+$ band based on Nilsson orbit No. 9 is a linear combination of two wave functions. The first

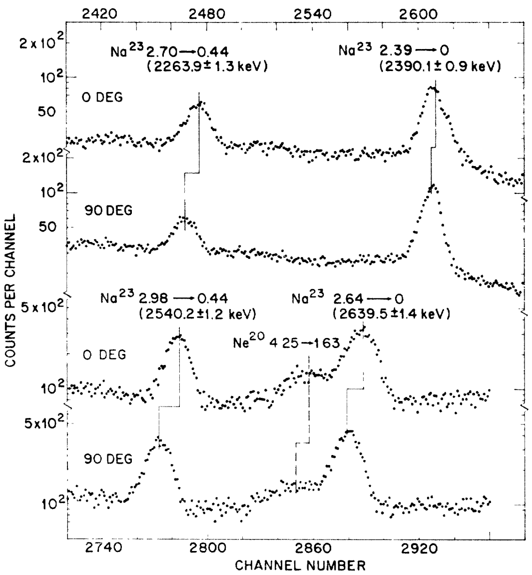


FIG. 4. Partial $\gamma$-ray spectra obtained from the bombardment of a thick NaI target with 5.25-MeV protons. The four $\gamma$-ray full energy peaks shown correspond to decays of the 2.39-, 2.64-, 2.70-, and 2.98-MeV levels of $Na^{23}$. For the 2.39-MeV $\gamma$ ray the Doppler shift is markedly attenuated, while as expected no significant attenuation is observed for the 2.54-MeV $\gamma$ ray because of the short lifetime of the 2.98-MeV level. The 2.264- and 2.640-MeV $\gamma$ rays from the 2.70- and 2.64-MeV levels exhibit small but significant attenuations of the Doppler shift: $F(\tau) = 0.76\pm0.09$ and $0.72\pm0.08$, respectively.

must represent two neutrons in orbit No. 7 plus a proton in orbit No. 9 while the second represents a neutron plus a proton in orbit No. 7 together with a neutron in orbit No. 9. The $M1$ (or $E2$) transition from the 2.39-MeV level to the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ members of the ground-state band can arise if either the neutron or the proton in orbit No. 9 jumps into orbit No. 7. Destructive interference between these two components could then explain the long lifetime and the branching ratio of the 2.39-MeV level.

On the other hand, the 2.64-MeV level arises from a proton hole in orbit No. 4, and of course we can consider the ground-state band to be based on a proton hole in orbit No. 7. An $E1$ transition can, therefore, take place between these two states simply by the jumping of a proton. Another way of looking at the problem is to say that to be treated correctly the decay of the 2.39-MeV level must be considered as a 3-particle (or 2-hole, 1-particle) problem while the decay of the 2.64-MeV level can be considered correctly within a one-particle model, which requires no antisymmetrization. We will now consider the decay of the 2.64-MeV level in more detail.

From Nilsson's paper [Eq. (35) of Ref. 1] we have

$$B(E1, JK\to J'K')$$
$$=e^2(12/23)^2(\hbar/M\omega_0)(3/4\pi)(JK1\Lambda\,|\,J'K')^2G_{E1}^2, \quad (1)$$

where from Poletti and Start,[3] $\hbar\omega_0=12.3$ MeV, $e$ is the electronic charge, $M$ the proton mass, and $G_{E1}$ is given in terms of the Nilsson[1] normalized expansion coefficients $a_{l\Lambda}$ by

$$G_{E1}=(\sqrt{\tfrac{5}{3}})[(1/\sqrt{2})a_{21}'a_{10}+a_{22}'a_{11}]. \quad (2)$$

For $\eta=4$, this yields $G_{E1}=-0.0955$. The radiative width is given by

$$\Gamma(E1)=(16\pi/9)(E_\gamma/\hbar c)^3B(E1), \quad (3)$$

where $E_\gamma$ is the energy of the $\gamma$-ray transition. Similarly,

$$B(M2)=(e\hbar/2Mc)^2(\hbar/M\omega_0)(1/16\pi)A(J_f)^2G_{M2}^2, \quad (4)$$

where $A(J_f)=(1-2b_{M2})$ or $(2+b_{M2})$, respectively, for $J_f=\frac{3}{2}$ and $\frac{5}{2}$ and

$$G_{M2}=(2/\sqrt{3})(g_l-3g_s/4)$$
$$\times(2a_{22}'a_{11}-\sqrt{2}a_{21}'a_{10})-\sqrt{3}g_sa_{21}'a_{11}, \quad (5)$$

while

$$b_{M2}=\{(\sqrt{6})g_sa_{21}'a_{10}+4g_l(a_{21}'a_{11}+\sqrt{2}a_{22}'a_{10})/\sqrt{3}\}G_{M2}^{-1}. \quad (6)$$

The radiative width is given by

$$\Gamma(M2)=(4\pi/75)(E_\gamma/\hbar c)^5B(M2). \quad (7)$$

From these relations we obtain the following estimates for the partial widths:

$$\Gamma(E1,\ 2.64\to0)=38.5\text{ meV},$$
$$\Gamma(M2,\ 2.64\to0)=6.7\times10^{-3}\text{ meV},$$

and

$$\Gamma(M2,\ 2.64\to0.44)=2.03\times10^{-2}\text{ meV}.$$

Experimentally, we know only the total width for the ground-state decay: $\Gamma_{\rm expt}(\text{tot } 2.64\to0)=4.7$ meV. Superficially, then, the agreement between experiment and the Nilsson-model calculation is not good; however, it must be remembered that a single-particle estimate[24] of the $E1$ width of the 2.64-MeV level for decay to the ground state is $\Gamma_W=1.01\times10^4$ meV, hence the calculation has succeeded in explaining a large part of the observed inhibition.

Dubois[4] has suggested that the level at 3.68 MeV is the $\frac{3}{2}^-$ member of the $\frac{1}{2}^-$ band based on the 2.64-MeV level. In this case, it is interesting to calculate its expected decay modes using the Nilsson model.[1] The $M1$ decay to the 2.64-MeV level is easily calculated from Eq. (37c) of Ref. 1, while the two possible $E1$ decays are calculated from Eq. (1) above. We ignore the possible interband $M2$ decays which were shown to be negligible above. In this way, we obtain

$$\Gamma(M1,\ 3.68\to2.64)=\ 3.14\text{ meV},$$
$$\Gamma(E1,\ 3.68\to0.44)=42.72\text{ meV},$$

and

$$\Gamma(E1,\ 3.68\to0)=41.8\text{ meV}.$$

[24] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, p. 862 ff.

This, obviously, does not reproduce the experimentally observed decay branching of the 3.68-MeV level. (Only an upper limit for this lifetime is known.) A more realistic estimate of the expected lifetime of the 3.68-MeV level could perhaps be obtained by using the experimentally determined $E1$ width of the 2.64-MeV level to estimate the expected $E1$ widths of the 3.68-MeV level by taking account of the different Wigner coefficients in Eq. (1). This results in

$$\Gamma(E1,\ 3.68\to 0) = 3.62\ \text{meV},$$

$$\Gamma(E1,\ 3.68\to 0.44) = 3.70\ \text{meV},$$

and, as before,

$$\Gamma(M1,\ 3.68\to 2.64) = 3.14\ \text{meV}.$$

The corresponding percentage branchings are 35, 35, and 30%, respectively, compared to the experimentally observed branchings of 2, 77, and 19% (there is also a 2% branch to the 2.39-MeV level), while the predicted lifetime for the 3.68-MeV level is $6.2\times10^{-14}$ sec. Experimentally only an upper limit $\tau_m < 17\times10^{-14}$ sec is known.


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# Directional Correlation of Gamma Rays in $^{72}$Ge*

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The $\gamma$ rays of $^{72}$ Ge following the $\beta$ decay of 14.1-h $^{72}$Ga have been studied using a 20-cm$^3$ Ge(Li) detector in coincidence with a $2\times2$-in. NaI(Tl) crystal. Directional-correlation measurements have been carried out on the cascades involving 630-, 894-, 1231-, 2202-, 2491-, and 2508-keV $\gamma$ rays with the 834-keV ground-state transition from the first excited 2+ state. 1-3 directional-correlation measurements (with the intermediate $\gamma$ ray unobserved) have been made between $\gamma$ rays of energy 601, 786, 1000, 1051, 1215, 1597, and 1861 keV and the 834-keV transition. Spin assignments of 2 for the 1464- and the 3036-keV levels have been confirmed. The 630- and 2202-keV transitions are nearly pure $E2$ and $E1$, respectively. The level at 2065 keV has been assigned a spin of 3. The 601-keV transition has a maximum $M1$ admixture of 10%. Assuming that the 2515-keV level is a 3− state, the following spin and mixing assignments can be made. The level at 1728 keV is found to have a spin of 4, which requires 0.4–1.3% octupole mixture in the 894-keV transition. The levels at 3325 and 3342 keV have been assigned spins of 3 and 2, respectively. The 786-, 1597-, 2491-, and 2508-keV transitions are all nearly pure $E1$.

## I. INTRODUCTION

THE nuclear level structure of $^{72}$Ge was first studied in detail by Kraushaar, Brun, and Meyerhof.[1,2] They examined the levels in $^{72}$Ge from both the $\beta^-$ decay of $^{72}$Ga and the $\beta^+$ and electron-capture decay of $^{72}$As. Their decay scheme was based on conversion-electron and $\beta$ spectra, $\gamma$-ray spectra using scintillation detectors, and $\beta$-$\gamma$ and $\gamma$-$\gamma$ coincidence measurements. Except for the first excited state, their spin and parity assignments were based on log$ft$ values.

The first direct measurement of the spins of several of the excited states was made by Arns and Wiedenbeck.[3] Some other spin assignments have been made from proton inelastic-scattering experiments.[4–6] Recently, the $\gamma$-ray relative intensities have been measured with high-resolution Ge(Li) detectors.[7–9] The decay scheme proposed by Camp[9] has been checked by Ge(Li)-Ge(Li) coincidence measurements.[10] These measurements have confirmed major features of the level structure originally proposed by Kraushaar *et al.*, and,

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