Lifetime of the 563-keV level of ^{24}Na

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(Received 25 February 1975)

The lifetime of the 563-keV level of ^{24}Na has been measured by means of the recoil-distance method. In the geometry used, the "stopped" and "shifted" peaks lie above and below the K edge of bismuth. The use of a bismuth absorber of suitable thickness essentially eliminated the stopped peak from the spectrum, leading to an exponential function for the transmitted intensity as a function of the recoil distance. The mean life was measured as $\tau_m = 62 \pm 8$ ps.

[NUCLEAR REACTIONS ^{26}Mg(d, $\alpha\gamma$), $E = 4.5$ MeV, measured $\alpha\gamma$ coin, $T_{1/2}$ recoil distance; deduced $B(\Lambda)$.]

I. INTRODUCTION

In the course of an experimental investigation of low lying levels of ^{24}Na underway in this laboratory,[1-3] several experiments have been performed to determine the lifetime of the 563-keV second excited state of this nucleus. The low γ-ray energy of the main deexcitation mode (91 keV) and the expected order of magnitude of the lifetime make a measurement using the mechanical recoil-distance method[4] possible, in principle. This was attempted in a preliminary experiment using the ^{23}Na($d, p\gamma$)^{24}Na reaction in which the intensity of the 91-keV γ rays at $\theta_\gamma = 90°$ in coincidence with protons around 180° was measured as a function of flight distance. This was accomplished by blocking the view of the γ-ray detector on a variable part of the flight path by means of a movable absorber of 1-mm-thick tantalum. An upper limit of 80 ps was found, indicating a large [>0.5-W.u. (Weisskopf units)] $M1$ strength for the 563 → 472 keV ($2^+ \rightarrow 1^+$) transition.

As the drastic increase of recoil velocity desired for the lifetime determination could not be achieved with our accelerator, it was decided to use the Doppler shift recoil-distance method. The resolution of the γ-ray detector was artificially improved by exploiting the K-absorption edge of Bi, which happens to lie within 500 eV of the γ-ray energy involved. Details of this method are given in Sec. II B.

II. EXPERIMENTAL

A. Plunger apparatus

The range of the motion of the electrostatic plunger apparatus[5] in this laboratory was extended with a mechanical arrangement (Fig. 1). In this arrangement the target foil and attracting electrode are displaced with respect to the stopper foil by means of a ring on which three wedges are mounted. The ring is turned over a range of about 40° by a micrometer, giving a total displacement of about 1 mm. At short distances, $D < 250$ μm, the capacity, and thus the distance, between the stopper foil and the target foil is kept constant by applying a feedback correction to the voltage of the electrode.

The calibration procedure, in which the relation between the capacity of the foils and their distance is determined, was performed before and after the lifetime measurement. A Michelson interferometer arrangement with a He-Ne laser is used for the calibration (Fig. 2). The laser beam hitting the foil is 5 mm wide, so the image of an elliptical region of the target foil with a smallest dimension of 5 mm is projected on a screen. The target spot lies well within this region. The distance is changed slowly from one capacity setting to another by introducing a large time constant in the stabilizer and the number of fringes that pass by when going from one setting to the next is counted. Each fringe corresponds to a change $d = \frac{1}{4}\lambda/\cos\theta$ in the distance between the foils. For the laser light we used $\lambda = 0.6328$ μm, and $\theta = 44.8° \pm 0.2°$, giving $d = 0.2226 \pm 0.0008$ μm.

The target foil was 0.5-μm nickel on 0.5-μm copper. On the downstream side of this foil 120-μg/cm^2 Mg, enriched to 99.4% in ^{26}Mg, was vacuum deposited. The oxygen content of the target was, during the lifetime measurement, 11 at.% —or less—of the magnesium. This was determined in a separate Rutherford scattering experiment with 4-MeV α particles, performed after the lifetime measurement. The stopper foil was made of 0.8-μm gold and 0.6-μm nickel. Nickel was

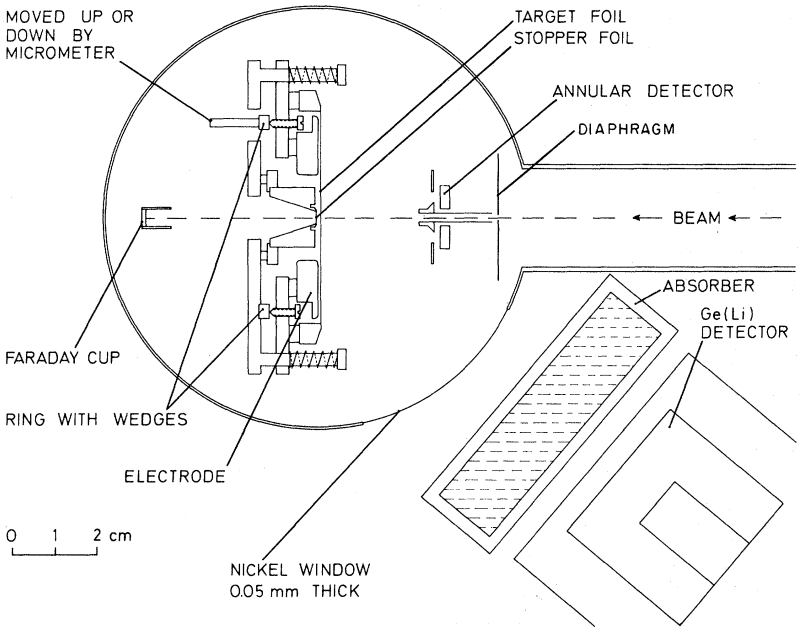

FIG. 1. Setup of the recoil-distance lifetime measurement.

used because of its excellent mechanical properties and the copper and gold are applied to conduct heat away from the beam spot. Both foils were produced in this laboratory and stretched as described in Ref. 5. The aluminum ring upon which the target foil is cemented, was heated to 50°C to increase the mechanical tension of the foil.[5]

During the lifetime measurement, the pattern of parallel fringes, projected on the screen by the interferometer, did not change. This proves that the target foil remained taut during the measurement. In a separate experiment, the target foil was removed, and the stopper foil became visible to the interferometer. Up to a beam intensity of 500 nA of 4-MeV α particles, the pattern of fringes remained stable, but for higher intensity it became unstable, indicating that the foil became slack due to thermal expansion caused by beam heating. The dissipation of the beam during the lifetime measurement was much less, so we may conclude that the target foil was also taut during the measurement.

B. Bismuth absorber

The 563-keV level of ^{24}Na decays for $(97.5 \pm 0.5)\%$ to the 472-keV first excited state[3] with a γ-ray energy of 90.99 ± 0.03 keV.[6] The maximum Doppler shift of γ rays produced with the reaction ^{26}Mg-$(d, \alpha)^{24}$Na at the deuteron energy of 4.4 MeV used in this experiment (see Sec. IIC) is 1.2 keV. Therefore, the stopped and shifted peaks that are produced in a recoil-distance measurement are not resolved with the Ge(Li) detector at our disposal. We decided therefore to use the fact that the absorption of low-energy photons takes place predominantly by the photoelectric effect of the K-shell electrons. At a photon energy below the binding energy of the K-shell electrons, the absorption drops by an order of magnitude.

The binding energy of the K-shell electrons of bismuth is 90.526 keV.[7] So if we place the γ-ray

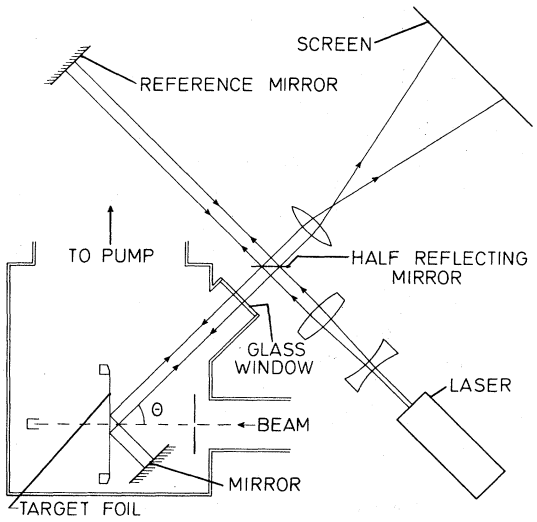

FIG. 2. Michelson interferometer arrangement for calibration and on-line control of the flatness of the target foil.

detector at a backward angle and put a bismuth absorber between the target and the detector, the stopped peak is absorbed to a large extent by the bismuth, whereas the shifted photons, with an energy below the K-electron binding energy, are only slightly absorbed and are detected. A homogeneous layer of bismuth was made, using a glass cuvette with a concentrated solution of bismuth nitrate in 50% nitric acid. The resulting thickness of bismuth was 0.44 ± 0.01 g/cm^2. Measurements of the transmission of photons through the absorber as a function of energy are reported in Sec. II D.

C. Lifetime measurement

With the Groningen 5-MV Van de Graaff accelerator,[8] the ^{26}Mg target was bombarded with a 22-nA beam of 4.474-MeV deuterons. The setup of the experiment is drawn to scale in Fig. 1. The ^{24}Na nuclei are produced by the reaction ^{26}Mg$(d, \alpha)^{24}$Na. The yield of the 563-keV second excited state has a pronounced maximum at $E_d = 4.40$ MeV. The deuteron energy had to be increased by 74 keV in order to compensate for the energy loss in the target foil.

The α particles were detected in a 50-μm-thick annular silicon detector collimated to the angular interval 167° to 172.5°. The detector was cooled by a Peltier element. Due to straggling in the target foil, the α-particle peaks from the first and second excited states were not resolved.

γ rays were detected in coincidence with these α particles in a 30-cm^3 Ge(Li) detector positioned at 140° with respect to the beam. The coincident γ-ray spectrum as well as the single α-particle spectrum were measured at 11 different positions of the target foil; the position was changed every hour.

Periodically, the absorber was removed in order to measure the yield of the stopped and shifted peaks together. The total amount of time during which coincident spectra were collected with the Ge(Li) detector at 140° was 110 h. Coincident γ-ray spectra in the region of 65 to 170 keV, measured at three different positions of the target foil, are shown in Fig. 3.

At the end of the measurement, after the calibration of the plunger apparatus, the target foil was removed, and the stopper foil was bombarded with 4.400-MeV deuterons. From the particle spectrum we could conclude that target material was absent.

D. Determination of the absorption curve

In order to be able to analyze the measured yield of the 91-keV γ-ray line as a function of the distance between the target foil and the stopper foil, the absorption of the bismuth absorber had to be determined for γ-ray energies corresponding to γ emission of recoils in flight, as well as for γ emission by stopped recoils.

In order to verify the difference in energy of the 91-keV γ rays and the absorption edge, five separate coincidence measurements, using the ^{23}Na$(d, p\gamma)^{24}$Na reaction were performed. The protons were detected at 60° or 80° with respect to the beam, and the γ rays were detected at 180° with respect to the direction of the associated nuclei. The NaBr target used in this experiment was thin enough to allow the residual nuclei to recoil into vacuum. By varying the beam energy between 2 and 5 MeV, and the position of the particle counter, the Doppler shift of the 91-keV γ rays took on five different values between 270 and 630 eV. In each coincidence measurement, the transmission of the absorber is measured by comparing the yield of the photopeak with and without the absorber. We find the absorption edge at a Doppler shift of 0.45 $\pm$ 0.02 keV, in excellent agreement with the difference of energy between the Bi absorption edge and the 91-keV transition as quoted in the literature[6,7] (0.46 ± 0.03 keV).

The transmission of the absorber above the absorption edge was measured using the same γ

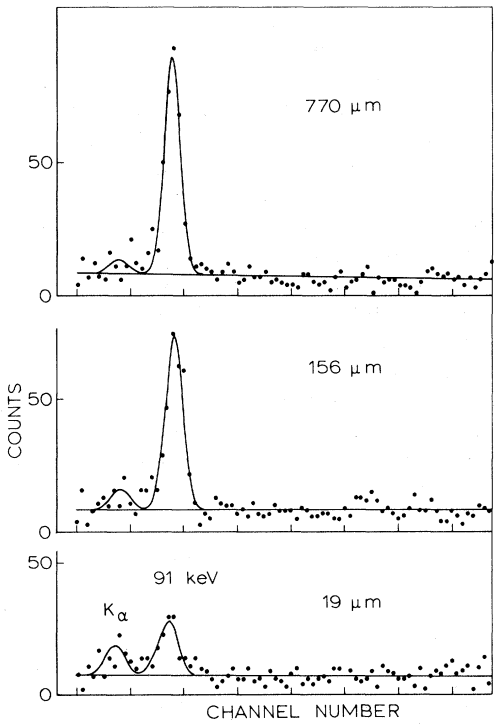

FIG. 3. Coincident γ-ray spectra as a function of distance. The drawn curves are the result of five Gaussian fits on a linear background.

rays, but now produced from a target with a thick backing. The transmission below the absorption edge was measured with a ^{109}Cd source emitting 88.03-keV γ rays, and also with the $K\alpha$ and $K\beta$ characteristic x rays from a separate piece of bismuth, irradiated by γ rays from a ^{57}Co source. From these results, the transmission curve as a function of energy, $T(E)$, in the region of interest was determined [Fig. 4(a)].

III. ANALYSIS AND RESULT

The coincident γ-ray spectra obtained in the lifetime measurement were analyzed with a simultaneous least-squares fit to five Gaussians on a linear background. These peaks are: the $K\alpha_1$, $K\alpha_2$, $K\beta_{1,3}$, and $K\beta_2$ x-ray peaks of bismuth with energies 74.81, 77.11, 87.17, and 89.19 keV[9] and the 91-keV γ ray. The centroid of the latter varied from 90.96 keV for the smallest recoil distance to 90.17 keV for the largest distance. The centroid was calculated to sufficient accuracy from the lifetime obtained in a preliminary analysis. The difference between the centroids of the peaks was kept constant in the fitting procedure; the ensemble as a whole was allowed to find its optimal position in the spectrum. It was unnecessary to use more than one peak-width parameter for the different peaks. For large distances it was treated as a free parameter but for short distances, the full width at half-maximum was kept at a constant value. The ratios of the areas of the x-ray peaks were kept constant in the fit. These ratios were determined in a separate measurement in which the absorber was irradiated by the γ rays from a ^{137}Cs source. In Fig. 3, coincident γ-ray spectra with the five-Gaussian fits are given for three different distances. In Fig. 5, the yield of the 91-keV γ ray is given as a function of the distance between the target foil and the stopper foil. The data are normalized to the yield of the $\alpha_{1,2}$ peak in the single-particle spectrum.

In order to extract the lifetime from Fig. 5, we calculate first the velocity-vector distribution of the recoiling ^{24}Na nuclei. A Monte Carlo procedure is performed[5]; the scattering of recoils in a thin layer of target material is assumed to lead to a Gaussian distribution in each of two perpendicular angular deflections. Using this assumption the distribution of scattering angles can be expressed in terms of the mean value of the cosine of the scattering angle, for small angles. We used, as a reasonable approximation, the mean value as given by Blaugrund.[10] Tabulated range energy relations of Northcliffe and Schilling[11] are used. The small oxygen content of the target was neglected in these calculations.

The experimental yield as a function of distance, $N(D)$, together with the yield measured without absorber, I_{exp}, are fitted to the function

$$N(D) = I \int_0^\infty T(E) f(E, D, \tau) dE ,$$

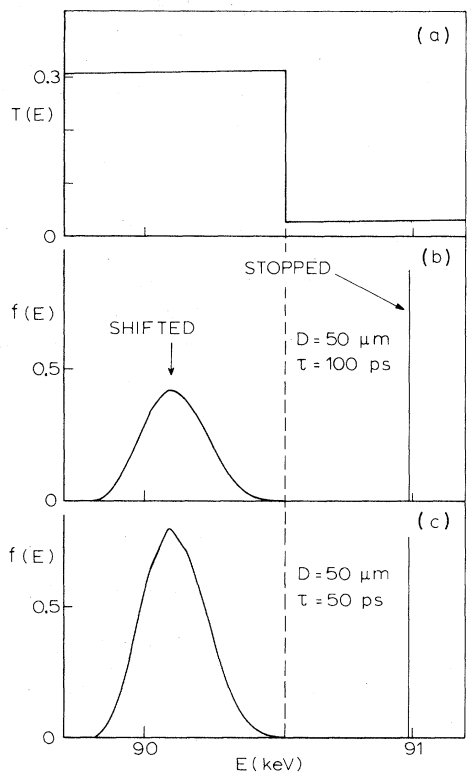

FIG. 4. (a) The transmission of the absorber with bismuth nitrate as a function of energy. (b) and (c): Calculated normalized shapes of the γ-ray spectrum for different values of the lifetime τ and the recoil distance D.

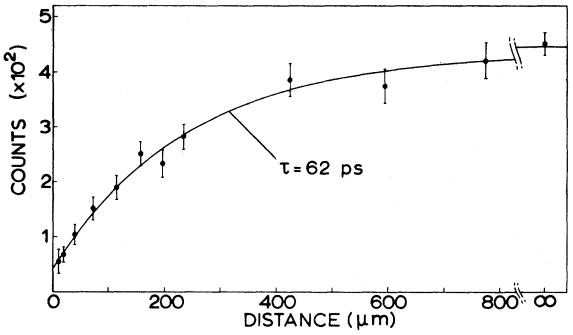

FIG. 5. Yield of the 91-keV γ ray as a function of distance. The point at infinity is the yield measured without absorber times the transmission at the energy of the shifted peak.

in which I is the yield without absorber, $T(E)$ the transmission of the absorber, and $f(E,D,\tau)$ the normalized shape of the γ-ray spectrum, calculated from the recoil-vector distribution, the lifetime, and the stopper distance[5] (see Fig. 4). In the simple case that $T(E)=T$ for E below the absorption edge (corresponding to decay in flight) and $T(E)=0$ for E above the absorption edge (corresponding to decay of stopped recoils), and neglecting the recoil-vector distribution, the theoretical expression for the yield simplifies to

$$N(D)=IT[1-\exp(-D/v\tau)]$$

in which v is the recoil velocity.

The fraction of the shifted peak with energy above the absorption edge is less than 0.1%.

In the fitting procedure

$$Q^2=\sum_i \frac{[N(D_i)-N_{\exp}(D_i)]^2}{\sigma^2[N_{\exp}(D_i)]}+\frac{(I-I_{\exp})^2}{\sigma^2(I_{\exp})}$$

is minimized with respect to the parameters τ, I, and the real distance at the origin of the relative distance scale D_0.

In the calculation of $N(D)$ the following effects were taken into account:

(1) The variation of the efficiency of the Ge(Li) detector as a function of energy. This was measured using Compton scattered γ rays from ^{57}Co, varying the scattering angle, and comparing the yield with the result of the Klein-Nishina formula.

(2) The relativistic decrease of the solid angle of the Ge(Li) detector as it is seen by the moving nuclei.

(3) The changing position of the target with respect to the detector.

(4) The anisotropy of the γ rays. This has been measured earlier in this laboratory, yielding $A_2/A_0=-0.29\pm0.02$ and $A_4/A_0=0.00\pm0.03$ for the Legendre-polynomial coefficients.

In order to study the effect of vacuum deorientation of the nuclei, coincident γ-ray spectra were taken under the conditions described in Sec. IIC, with the Ge(Li) detector at 0° with respect to the beam, without the absorber. At 0° the sensitivity to a possible attenuation of the angular correlation is at its maximum. The spectra were measured at three values of the recoil distance: 13, 233, and 770 μm. No significant attenuation of the γ-ray anisotropy was found when the recoil distance was increased.

The result of the fitting procedure is:

$$\tau=62\pm8 \text{ ps},$$

$$D_0=10\pm7 \ \mu\text{m},$$

$$I=1448\pm55.$$

The error of τ, due to uncertainties of the transmission parameters, is much smaller than 8 ps.

IV. CONCLUDING REMARKS

The mean lifetime of the 563-keV 2^+ second excited state of ^{24}Na is 62 ± 8 ps. The decay to the 1^+ first excited state has a pure $M1$ character, since even a 1% admixture of $E2$ radiation would imply an $E2$ strength of 3000 W.u. The $M1$ strength of this decay is 0.65 ± 0.08 W.u.

The 2.5% branch to the 4^+ ground state has an $E2$ strength of 1.4 ± 0.3 W.u.

The authors express their appreciation to Tj. H. de Boer for the use of the optical equipment, E. N. H. Kuperus for making the cuvette, J. L. W. Petersen for the manufacture of the silicon detector, and L. Venema for the production of the foils and target.

[1]A. S. Keverling Buisman, Ph. B. Smith, P. J. M. Smulders, and H. Gruppelaar, Nucl. Phys. A176, 161 (1971).
[2]P. J. M. Smulders, Nucl. Phys. A210, 579 (1973).
[3]A. S. Keverling Buisman and P. J. M. Smulders, Nucl. Phys. A228, 205 (1974).
[4]J. Thirion and V. L. Telegdi, Phys. Rev. 92, 1253 (1953).
[5]E. H. du Marchie van Voorthuysen and Ph. B. Smith, Nucl. Instrum. (to be published).
[6]P. M. Endt and C. van der Leun, Nucl. Phys. A214, 1 (1973).
[7]J. A. Bearden and A. F. Burr, Rev. Mod. Phys. 39, 125 (1967).
[8]D. O. Boerma and Ph. B. Smith, Nucl. Instrum. 86, 221 (1970).
[9]E. Storm and H. J. Israel, Nucl. Data A7, 565 (1970).
[10]A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).
[11]L. C. Northcliffe and R. F. Schilling, Nucl. Data A7, 233 (1970).