Mean Lifetimes of the First Excited States of Li^7 and Na^{23} by Resonance Scattering of Bremsstrahlung

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A 1.4-MeV electron accelerator was used as a source of bremsstrahlung to determine the widths Γ, and, hence, the mean lifetimes τ, of the first excited states of Li^7 and Na^{23}. Self-absorption experiments were performed in both cases. For the 480-keV level in Li^7 the following results were obtained: $\Gamma=(5.28\pm0.27)\times10^{-3}$ eV, corresponding to $\tau=(1.25\pm0.06)\times10^{-13}$ sec. For the 440-keV level in Na^{23} the results obtained were $\Gamma=(3.66\pm0.50)\times10^{-4}$ eV, corresponding to $\tau=(1.80\pm0.28)\times10^{-12}$ sec.

I. INTRODUCTION

ALTHOUGH the possibility of using bremsstrahlung to observe resonant scattering from energy levels was suggested as early as 1946 by Schiff,[1] this method has only recently been applied successfully. Experiments have been reported by Hayward and Fuller,[2] Beckman and Sandström,[3] Booth,[4] Vanhuyse and Vanpraet,[5] and by Seward *et al.*[6] In these experiments the nuclei to be investigated were exposed to continuous x-ray spectra as obtained from electron accelerators, and the scattered radiation analyzed. Since such x-ray beams are continuous in energy up to a specific maximum, all energy levels of the nuclei irradiated below this maximum energy can be excited. Resonance scattering will be observed if the level width is large enough and if the resonance radiation is not lost in the usually large background.

Bremsstrahlung excitation has two main advantages over discrete energy gamma ray excitation. These are (1) that an energy level may be investigated without the problem of finding a γ ray of exactly the correct energy, and (2) that no mechanism for compensating for the energy loss due to recoil of the emitting nucleus need be used. On the other hand, since only a small portion of the incident spectrum is effective in producing the resonant effect, the background in bremsstrahlung experiments is high. Further, if in a particular nucleus two or more energy levels are closely spaced, it may be difficult to distinguish the contribution due to the respective individual levels.

In this paper we report on the measurement of the lifetimes of the first excited states of Li^7 and Na^{23} by the bremsstrahlung method. The first excited state of Li^7 is at 480 keV and its spin is given as 1/2, odd parity. The spin of the ground state is 3/2, odd parity. Na^{23} has a first excited state at 440 keV with spin 5/2, and a ground state with spin 3/2. Both have even parity.

II. THEORETICAL CONSIDERATIONS

According to previous work,[7] the number of gamma rays resonantly scattered by an element dx of scattering material, situated at a depth x cm in a thick target, is given by

$$S(x)dx=\pi^{1/2}N(E_r)\Delta k\left(\sum_{m=0}^{\infty}\frac{(-kx)^m}{m!(m+1)^{1/2}}\right)\exp(-\mu_1 x)dx,$$

where $N(E_r)$ is the number of γ rays per unit energy interval in the region of resonance, Δ is the Doppler width of the level, μ_1 the total electronic absorption coefficient of the scatterer, and

$$k=n(2J_e+1)\Gamma\Delta^2/4(2J_g+1)\pi^{1/2}\Delta.$$

In this expression for k, Γ is the level width, λ is the wavelength of the radiation, n is the number of nuclei per cm^3 of the isotope under study, and J_e and J_g are the spins of the excited and ground states, respectively.

To find the total yield of resonantly scattered quanta, the above expression must be modified to include the effect of absorption of the scattered radiation as it leaves the scatterer, and integrated over the scatterer. This is usually done numerically.

The yield of resonantly scattered radiation can be found by comparing the pulse spectra due to quanta as scattered by a material which produces the resonant effect with those as scattered by a material which gives no resonant effect. The two materials must be matched to give exactly the same electronic scattering. To find the width and hence the mean lifetime of the level which gives rise to the resonant scattering, however, it is necessary to know the flux of incident radiation in the region of resonance. This presents a serious problem. Calculation of the bremsstrahlung intensity from a thick target is a very difficult task. At present no accurate formula exists which enables the spectral distribution to be found. Attempts have been made by other workers to measure the spectrum by using a scintillation counter. It is difficult to see how an accurate result can easily be obtained from these measurements. The pulse spectrum from a scintillation counter for a monoenergetic gamma ray, of energy smaller than 1.02 MeV, consists of a peak, due to the

[1] L. I. Schiff, Phys. Rev. **70**, 761 (1946).
[2] E. Hayward and E. G. Fuller, Phys. Rev. **106**, 991 (1957).
[3] O. Beckman and R. Sandström, Nuclear Phys. **5**, 595 (1958).
[4] E. C. Booth, Nuclear Phys. **19**, 426 (1960).
[5] V. J. Vanhuyse and G. Vanpraet, J. phys. radium **21**, 290 (1960).
[6] F. D. Seward, H. W. Koch, R. E. Shafer, and S. C. Fultz, Bull. Am. Phys. Soc. **5**, 68 (1960).
[7] F. R. Metzger, Phys. Rev. **110**, 123 (1958).

photoeffect in the phosphor, and a distribution with a plateau due to the Compton effect. The relative heights of peak and plateau, as well as the width of the peak, depend on the energy of the radiation and on the size of the crystal. The bremsstrahlung spectrum will, therefore, consist of the superposition of an infinite number of peaks and plateaus of varying height and width. It seems unfeasible to attempt to extract the contribution by radiation of one particular energy to this spectrum.

Fortunately the level width can be found in a self-absorption experiment without knowing the flux of incident radiation in the region of resonance. This technique was developed by Metzger[7] and has been used by a number of workers. If an absorber, thickness d cm, of the same material as the scatterer is introduced in the incident beam, the yield of resonantly scattered radiation from the element dx of scatterer, is obtained by replacing, in the expression for $S(x)dx$, x by $x+d$. The ratio of yield with resonant absorber to yield without resonant absorber is, consequently, independent of $N(E_r)$. In practice, in order to correct for the electronic absorption in the absorber, the yield with the resonant absorber is compared with the yield with a matched nonresonant absorber in the incident beam. This technique was employed in these measurements.

III. EXPERIMENTAL CONSIDERATIONS

The pressurized cascade electron accelerator of the Diamond Research Laboratory in Johannesburg, was used to carry out these measurements. This machine has a maximum output of 3 mA of electrons at 1.4 MeV. The electrons impinge on a thick tungsten target mounted at 45° to the incident beam.

Figure 1 shows the experimental arrangement. The tungsten target of the accelerator was surrounded by a lead cylinder of wall thickness 4 in. and o.d. 20 in. A beam of x rays emerged through a hole of diameter $\frac{1}{2}$ in., in the lead cylinder. The scatterer was placed in this beam, about 20 in. from the tungsten target. The scattered radiation was detected by a scintillation counter consisting of a 3 in.×3 in. NaI crystal and a photomultiplier tube. The counter was heavily shielded with lead of 4-in. thickness. The scattered radiation entered the crystal through a hole of diameter $1\frac{1}{2}$ in. The pulses from the scintillation counter were recorded by a 100-channel pulse height analyzer. The angle of scattering was 130°. This was the largest angle possible for the arrangement. For these experiments the accelerator voltage used was 600 keV. At lower voltages the beam current was too small and at higher energies the peak due to resonant scattering disappeared in the large background, mainly due to Compton scattering. At a scattering angle of 130° the maximum energy of the Compton scattered radiation was about 200 keV. These quanta, therefore, contributed very little to the background in the region where the resonant effect was expected. A thin piece of lead was placed between the scatterer and the detector in order to attenuate mainly the low-energy radiation. Apart from Compton scattering, elastic scattering (Rayleigh and Thompson effects) also add to the background. These contributions are small for the light elements at the energies under consideration.

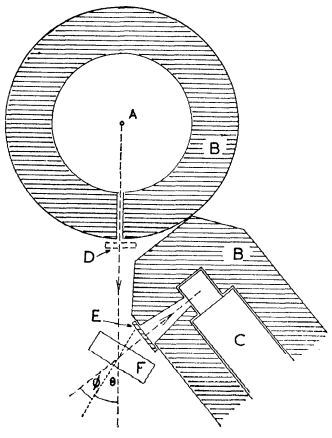

FIG. 1. Outline of the experimental arrangement, where A represents the focal spot of the electron beam, B the lead shielding, C the scintillation counter, D the resonant or nonresonant absorber in the incident beam, E the lead absorber, and F the scatterer.

For the measurements on lithium, a 5.7-cm-thick scatterer was used. It consisted of four blocks of lithium which were sealed in a plastic bag with a small amount of liquid paraffin. The lithium absorber was 1.5 cm thick. As comparison absorber and scatterer carbon slabs were used. For a predetermined total electronic charge striking the accelerator target, measured by means of a current integrator, the yield of radiation for the following combinations of scatterers and absorbers was measured:

(1) Lithium scatterer and carbon absorber;
(2) Lithium scatterer and lithium absorber;
(3) Carbon scatterer and carbon absorber.

The combination of carbon scatterer and lithium absorber was also used but since this gave the same results as the carbon-carbon combination, these measurements were not continued.

In the case of sodium, a scatterer of thickness 5 cm was used. It was also sealed in a plastic bag with liquid paraffin. The absorber was 3.1 cm thick. For comparison purposes aluminum was used. The combinations of scatterers and absorbers were similar in logic to those used in the lithium experiment.

IV. RESULTS

Lithium

The results obtained with the various combinations of scatterers and absorbers are presented in Fig. 2. These results compare very favorably with previous bremsstrahlung work on lithium.[3,4] The strong attenuation of the resonance peak due to the lithium absorber is prominent. From these results, using the theory outlined previously, Γ was found to be 5.28×10^{-3} eV,

corresponding to a mean lifetime

$$\tau = 1.25 \times 10^{-13} \text{ sec.}$$

An error of about 5% must be assigned to this value. Our final result is, therefore,

$$\tau = (1.25 \pm 0.06) \times 10^{-13} \text{ sec.}$$

Several other measurements of the lifetime of the first excited state of Li^7 have been reported. Swann *et al.*,[8] using the $Li^7(p,p')Li^{7*}$ reaction as a source of Doppler-broadened 480-keV gamma radiation, found a lifetime in a self-absorption experiment of

$$\tau = (1.15 \pm 0.14) \times 10^{-13} \text{ sec,}$$

and from a yield measurement of

$$\tau = (1.09 \pm 0.07) \times 10^{-13} \text{ sec.}$$

Beckmann & Sandström[3] found by resonant scattering

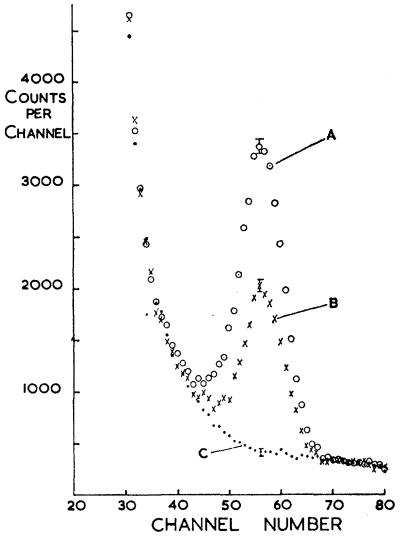

FIG. 2. Results for scattering from lithium. Curve A: lithium scatterer with carbon absorber. Curve B: lithium scatterer with lithium absorber. Curve C: carbon scatterer with lithium absorber.

of thick target bremsstrahlung a value of

$$\tau = (1.1 \pm 0.3) \times 10^{-13} \text{ sec.}$$

They measured the incident spectrum by means of a scintillation counter. Booth,[4] observing resonant scattering of thin target bremsstrahlung, arrived at lifetimes of

$$\tau = (1.4 \pm 0.7) \times 10^{-13} \text{ sec}$$

in a self-absorption experiment and of

$$\tau = (1 \pm 0.5) \times 10^{-13} \text{ sec}$$

for a yield measurement.
On the other hand, Bunbury *et al.*[9] found a value of

$$\tau = (7.7 \pm 0.8) \times 10^{-14} \text{ sec.}$$

[8] C. P. Swann, V. K. Rasmussen and F. R. Metzger, Phys. Rev. **114**, 862 (1959).
[9] D. St P. Bunbury, S. Devons, G. Manning, and J. H. Towle, Proc. Phys. Soc. (London) **A69**, 165 (1956).

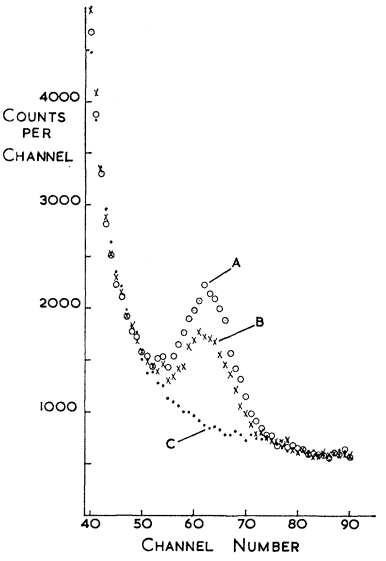

FIG. 3. Results for scattering from sodium. Curve A: sodium scatterer with aluminum absorber. Curve B: sodium scatterer with sodium absorber. Curve C: aluminum scatterer with sodium absorber.

Apart from the latter value, our results are in agreement with other measurements.

The Weisskopf extreme independent particle model predicts a lifetime value of

$$\tau(M1) = 3 \times 10^{-13} \text{ sec.}$$

Sodium

Figure 3 presents the results obtained. In comparison with lithium, measurements had to be taken over much longer periods due to the significantly smaller resonant effect. For the level width Γ a value 3.66×10^{-4} eV was calculated, corresponding to a lifetime of

$$\tau = (1.80 \pm 0.28) \times 10^{-12} \text{ sec.}$$

Rasmussen *et al.*[10] have measured the lifetime of the first excited state of Na^{23}. They used the 440-keV γ radiation from the reaction $Na^{23}(p,p')Na^{23*}$ and found, in a self-absorption experiment

$$\tau = (1.8_{-0.3}{}^{+0.4}) \times 10^{-12} \text{ sec.}$$

Booth *et al.*,[11] using a Ne^{23} radioactive source, report a value of

$$\tau = (1.5 \pm 0.3) \times 10^{-10} \text{ sec.}$$

This result seems to be very high. It is clear that our result is in good agreement with the value found by Rasmussen *et al.*

Recently, another measurement has been reported

[10] V. K. Rasmussen, F. R. Metzger and C. P. Swann, Nuclear Phys. **13**, 95 (1960).
[11] N. E. Booth, G. W. Hutchinson, A. M. Segar, G. G. Shute, and D. H. White, Nuclear Phys. **11**, 341 (1959).

by Ambrozy *et al.*[12] They give a value of

$$\tau = (1.5_{-0.2}{}^{+0.3}) \times 10^{-12} \text{ sec.}$$

Unified model calculations by Paul and Montague[13] have been carried out on Na^{23} and these give a value of

$$\tau(M1) = 4 \times 10^{-13} \text{ sec}$$

for the 440 keV level as a "first trial." The lifetime as calculated by the Weisskopf formula gives the same result.

[12] B. Ambrozy, A. Faudrowicz, A. Jasinski, J. Kownacki, H. Lancman, and J. Ludziejewski, in *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961*, edited by J. B. Berks (Heywood and Company, Ltd., London, 1961), p. 281.

[13] E. B. Paul and J. H. Montague, Nuclear Phys. **8**, 61 (1958).

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Beta Spectrum of Mn^{56}†

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A detailed magnetic spectrometer study of the beta spectrum of Mn^{56} was made with particular emphasis on the shape of the highest energy group. In spite of the high comparative half-life for this 3+ to 2+ allowed transition, no evidence was found for any contribution to the shape factor from higher order terms. The beta spectrum consists of the following groups: 2.838 MeV, 47%, $\log ft = 7.1$; 1.028 MeV, 34%, $\log ft = 5.3$; 0.718 MeV, 18%, $\log ft = 5.5$; 0.30, $\approx 1.\%$, $\log ft = 5.3$.

1. INTRODUCTION

THE shape of the highest energy beta-ray group in the transformation of Mn^{56} is of interest because the relatively high comparative half-life for this transition implies that the influence of the allowed matrix elements is reduced and suggests that the contribution of twice forbidden matrix elements to the decay might become observable.

Earlier investigations have established the general features of the decay scheme.[1–5] The reported half-life is 2.58 h. The ground state of Mn^{56} has been determined to be 3+. The beta decay from this 3+ level to the ground state of Fe^{56} has not been observed. Beta branches to 2+ levels at 845, 2660, 2958, and 3388 keV are present. There is a conspicuous absence of any feeding of the known 4+ level at 2085 keV. The most intense beta group goes to the 845-keV level. Furthermore, the comparative half-life ($\log ft = 7.1$) is rather high for an allowed transition.

In the present investigation, the beta spectrum of Mn^{56} was studied in detail with particular emphasis on the shape of the highest energy group.

2. SPECTROMETER

In this investigation, the 40 cm radius of curvature, shaped magnetic field spectrometer was used.[6] Certain improvements on the original design have been made, and these have been discussed in previous papers.[7–9] In addition, two other changes should be mentioned. First, the main defining baffles were replaced by $\frac{1}{16}$-in.-thick Ta baffles to further minimize any scattering from the baffle edges. Second, a commercial rotating coil gaussmeter[10] was used to measure the magnetic field.

The spectrometer was calibrated by means of the K internal conversion lines of Bi^{207} and Cs^{137} and also by means of the F line of ThB. The standard $H\rho$ values of these are 4657.9, 3381.28, and 1388.44 G-cm, respectively. The effective radius for each line was found to be 40.670, 40.674, and 40.677 cm, respectively. This is a variation of less than one part in 10 000, confirming the excellent linearity of the gaussmeter as claimed by the manufacturer.

An end window proportional counter with a loop anode was used as a detector. The counter window was 0.9-mg/cm² aluminized Mylar. Previous measurements[8] have shown that there is no inherent energy dependence

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[1] A. A. Townsend, Proc. Roy. Soc. (London) **A177**, 357 (1941).
[2] L. G. Elliott and M. Deutsch, Phys. Rev. **69**, 321 (1943).
[3] K. Siegbahn, Arkiv Mat. Astron. Fysik **33A** No. 10 (1946).
[4] P. Kienle and R. E. Segel, Phys. Rev. **114**, 1554 (1959).
[5] W. J. Childs and L. S. Goodman, Bull. Am. Phys. Soc. **3**, 21 (1958); W. J. Childs, L. S. Goodman, and L. J. Kieffer, Phys. Rev. **122**, 891 (1961).
[6] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 257 (1948).
[7] J. H. Hamilton, L. M. Langer, and W. G. Smith, Phys. Rev. **112**, 2010 (1958).
[8] O. E. Johnson, R. G. Johnson, and L. M. Langer, Phys. Rev. **112**, 2004 (1958).
[9] J. H. Hamilton, L. M. Langer, R. L. Robinson, and W. G. Smith, Phys. Rev. **112**, 945 (1958).
[10] Rawson-Lush Rotating Coil 820-Gaussmeter.