ANGULAR CORRELATION BETWEEN α–PARTICLES AND γ–RAYS IN THE $Be^9(d,\alpha)Li^{7*}\gamma Li^7$ REACTION

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Summary

The angular correlation of the α-particles and γ-rays in the $Be^9(d,\alpha)Li^{7*}\gamma Li^7$ reaction has been measured. The results show no significant departure from isotropy. The most plausible explanation is that the lowest excited state of Li^7 has spin $\frac{1}{2}$.

I. INTRODUCTION

Attempts to assign a spin value which is above question to the lowest excited state of Li^7 have met with unexpected difficulties.

Early experiments based on the $B^{10}(n,\alpha)Li^{7*}\gamma Li^7,Li^7$ branching ratio indicated a spin of 5/2 (Inglis 1948 ; Feld 1949) which was difficult to interpret theoretically.

Angular correlation measurements between the particle associated with the transition leading to the Li^7 excited state and the γ-radiation emitted as this state decays have been carried out for three nuclear reactions. In general an anisotropic correlation should occur for Li^{7*} spin $> \frac{1}{2}$ but it should be isotropic for spin $= \frac{1}{2}$. For example, the angular correlation between the α-particle and γ-ray from the $B^{10}(n,\alpha)Li^{7*}\gamma Li^7$ reaction has been found by Rose and Wilson (1950) to be spherically symmetric, which is consistent with a Li^{7*} spin value $\frac{1}{2}$. However, the isotropy observed in this experiment can also be explained by a spin value of 5/2 and a possible but unlikely admixture of electric quadrupole and magnetic dipole γ-radiation (Inglis 1951 ; Class and Hanna 1952).

The spin assignment of $I = \frac{1}{2}$ for Li^{7*} is also supported by the measurement of the angular distribution of γ-rays from the inelastic scattering of protons by Li^7 (Littauer 1950), but it has been suggested by Inglis (1951) that the proximity of the bombarding proton energy to a resonance in the compound nucleus, which may have zero total angular momentum, renders this experiment inconclusive.

Newton (1951) has pointed out that the chance cancellation of asymmetry terms which is possible in the $B^{10}(n,\alpha)Li^{7*}\gamma Li^7$ reaction is unlikely to occur for all other reactions leading to the excited state. Four groups measured the p-γ angular correlation in $Li^6(d,p)Li^{7*}\gamma Li^7$ almost simultaneously (Class and Hanna 1951, 1952 ; Newton 1951 ; Burke and Risser 1952 ; Phillips, Heydenburg, and Cowie 1952) ; all reported spherical symmetry within the accuracy of their measurements. Class and Hanna have shown that in this experiment the dipole, quadrupole radiation mixture cannot cause cancellation of asymmetry terms, possible in the $B^{10}(n,\alpha)Li^{7*}\gamma Li^7$ reaction. Unfortunately

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the populations of the magnetic substates of the Li^{7*} nuclei cannot be calculated because of the multiple values of orbital angular momenta of the deuterons and protons involved and because of channel spin degeneracy of the kind discussed by Biedenharn, Arfken, and Rose (1951) for the $B^{11}(p,\gamma,\gamma)C^{12}$ reaction. There is, therefore, the possibility that these populations may be nearly equal and so lead to isotropy.

Because of these doubts it was thought worth obtaining information from a further reaction and therefore a measurement of the α-γ angular correlation associated with $Be^9(d,\alpha)Li^{7*}\gamma Li^7$ has been carried out. Calculations based on the method of Biedenharn, Arfken, and Rose (1951) indicate that, for a Li^7 excited state spin value of 5/2 and plausible angular momenta, the correlation may be expected to be of the order of $0 \cdot 20$ except for a chance cancellation similar to that discussed above.

II. Experimental

The 750 kV. electrostatic generator of the Physics Department, University of Melbourne, was used to supply 400 keV. deuterons.

The deuterons were analysed in a 90° sector magnet and thence passed horizontally through a 3 ft. length of 1 in. diameter tubing to reach the target chamber. The cylindrical target chamber (Fig. 1) was mounted with its axis vertical and coincident with the centre of rotation of the γ-counter, and rigidly attached to the central bearing carrying the γ-counter so that no relative to and fro motion was possible. Approximately $2 \cdot 5$ cm. from the target the beam was defined by a $0 \cdot 32$ cm. diameter aperture. A disk of beryllium $0 \cdot 004$ in. thick was used as target, mounted in a vertical plane on the axis of the chamber in such a manner that the angle between the deuteron beam and the target plane could be varied to check the absorption of γ-rays in the target.

α-Particles from the reaction were detected by a scintillation counter mounted at 152° to the deuteron beam direction in the horizontal plane. Silver-activated zinc sulphide was selected as the phosphor for this counter as it is very insensitive to γ-rays and neutrons. The powder was deposited uniformly on a glass disk by a method previously described (Hirst and Uebergang 1951) and this glass disk was cemented to a glass light pipe which led the scintillations through the target chamber wall to a Mazda 27 M1 photomultiplier tube. To exclude light and avoid counting scattered deuterons the screen was covered by four layers of aluminium leaf, each of 1 mm. air equivalent stopping power. This thickness of aluminium leaf is sufficient to prevent counts from recoil Li^{7+++} nuclei from the reaction.

γ-Rays were detected, after passing through the uniform $\frac{1}{32}$ in. thick wall of the target chamber, by a scintillation counter consisting of a NaI(Tl) crystal and a 5359 EMI photomultiplier. The 1 in. diameter by 1 in. long crystal was immersed in oil in a close-fitting aluminium container which was seated on a rubber " O " ring on the flat photomultiplier end. An oil seal was provided by fitting tight rubber sleeving over the container and photomultiplier.

To improve the energy resolution both the sodium iodide crystal surface and the inner surface of the container were polished. The counter could be moved concentrically about the target to make any angle from 55 to 275° to the α-particle detector.

The solid angle subtended by each counter to the target was approximately 0·14 sterad., that is, approximately 12° half angle.

In addition to the reaction under study the bombardment of beryllium by deuterons gives rise to several competing reactions emitting protons, tritons, and neutrons and associated γ-rays. To these various emissions a small contribution from the bombardment of oxygen and carbon contamination may be

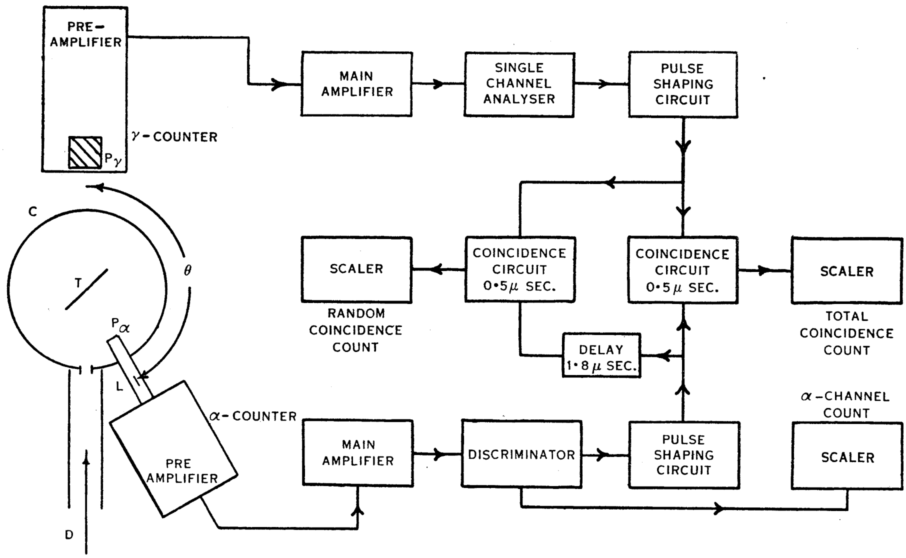

Fig. 1.—Block schematic of counting arrangement. *D*, deuteron beam; *C*, target chamber; P_γ, γ-counter phosphor NaI(Tl); P_α, α-counter phosphor ZnS (Ag); *L*, light pipe; θ, correlation angle.

added (Hornyak *et al.* 1950). Detection by the counters of these emissions can reduce the counting accuracy by causing a high random to true coincidence ratio and by detecting true coincidences from the $Be^9(d,p)Be^{10*}\gamma Be^{10}$ reaction.

A preliminary examination of the γ-radiation in the region of interest was carried out using a fast 10 channel analyser having general characteristics similar to the analyser described by Elmore and Sands (1949).

The analysis, which was made with overlapping runs on 5 V. channel widths, is shown in Figure 2, together with the 364 keV. γ-line from I^{131} which was used for calibration. The γ-peaks at 480 keV. from Li^{7*} and 710 keV. from B^{10*} are clearly resolved from the background. As the γ-radiation associated with the $Be^9(d,p)Be^{10*}\gamma Be^{10}$ protons has an energy of 3·37 MeV., a fast single channel analyser was introduced into the γ-channel and set to the range 40–65 V. (Fig. 2). To prevent loss of true coincidences arising from the 0·2 μsec. resolving time of the analyser, coincidence circuits having 0·5 μsec. resolving time were used. With these resolving times the deuteron beam was limited to approximately $0 \cdot 5\ \mu$A. to maintain a reasonable true to random coincidence ratio.

The electronic circuitry used in conjunction with the counters is shown in block schematic form in Figure 1. Pulses from the particle counter photomultiplier are fed to a preamplifier and thence to a Dynatron type 1008 linear amplifier, the output of which passes to a discriminator. The discriminator output simultaneously operates a scaler and triggers a pulse shaping circuit to produce negative rectangular pulses which operate two coincidence circuits.

The γ-counter output passes to a preamplifier and thence to a fast main amplifier, the output of which is analysed by the single channel pulse amplitude analyser constructed according to the circuit by Roulston (1950). As in the case of the particle counter channel a rectangular pulse is formed to operate the coincidence circuits.

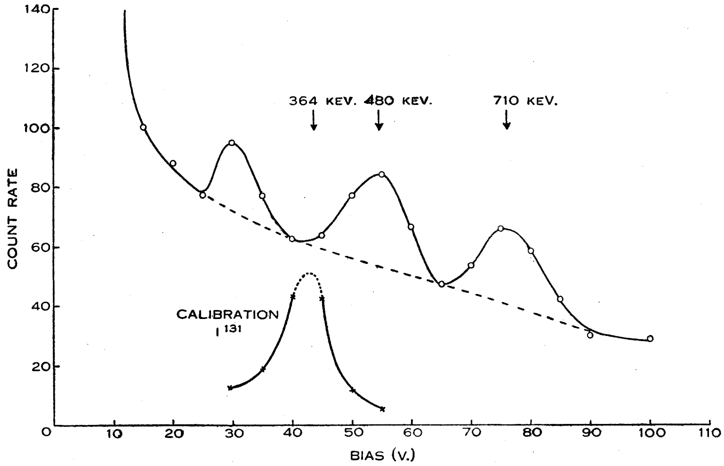

Fig. 2.—Analysis of γ-radiation from deuteron bombardment of Be^9.

To enable an accurate allowance to be made for the random coincidence rate this quantity is measured by one coincidence circuit while another counts true plus random coincidences.

As seen in Figure 1 both particle and γ-channels are connected directly to one coincidence circuit, whilst only the γ-channel is connected directly to a second coincidence circuit, the particle channel pulse reaching the coincidence circuit in this case after travelling through a $1 \cdot 8\ \mu$sec. delay line (approximately four times the coincidence circuit resolving time). In the first case true plus random coincidences will be counted while in the second case no true coincidences can be counted but only random ones.

III. Results and Corrections

With the target plane set at 45° to the α-particle direction, total and random coincidences were counted for several runs. Each run consisted of recording the coincidences counted with the counter set at each of several angles from 60 to 270° against a constant α-particle monitor count.

The target plane was then rotated to make an angle of 105° with the α-counter and several runs again made, each over several angles.

Because the random to total coincidence rate was high, approximately $1:2{\cdot}5$, an accurate knowledge of the ratio of the resolving times of the total and random coincidence circuits was desirable. This was achieved by comparing the resolving time ratio by means of random coincidences from a relatively intense source before and after the measurement at each angle. The stability of the coincidence circuits was found to be very satisfactory, the drift during a 20 minute run being in the order ± 2 per cent.

Using the random count recorded during the measurement of a total count and the mean ratio of the resolving times, a corrected random count was subtracted from the total count, giving the true count at that angle. The true counts for each run were then expressed as a fraction of the mean true count during the run. In this way errors due to variations in the gain of the Dynatron amplifier from one run to another were minimized.

This fractional expression of the true count at each angle was then corrected for eccentricity of the γ-counter with respect to the target, for γ-absorption in the target, and for centre of mass and Doppler effects.

The eccentricity at each angle was determined by measuring directly with a travelling microscope the distance between the γ-counter and the target chamber centre, and the position of the target within the chamber. The maximum correction was $2{\cdot}2 \pm 0{\cdot}1$ per cent.

The corrections for γ-absorption in the target and for change of efficiency of the γ-detector with the energy change due to the Doppler effect were calculated from the absorption coefficients given by Davisson and Evans (1952).

From the known half-life of Li^{7*} (Elliott and Bell 1949) and the range of the Li^{7*} recoil nucleus in beryllium, the velocity at the instant of emission of the γ-ray could be estimated and a centre of mass correction applied using the relation (from Devons and Hine 1949)

$$g(\varphi)=f\left(\varphi-\frac{v}{c}\sin\varphi\right)\left(1-\frac{2v}{c}\cos\varphi\right),$$

where $f(\varphi)$ is the yield measured in laboratory coordinates,
$g(\varphi)$ is the yield in centre of mass coordinates,
v is the recoil nucleus velocity at the instant of emission,
φ is the angle of emission of the γ-ray measured with respect to the direction of the recoil nucleus.

Similarly the Doppler energy change was calculated from

$$\Delta E=E\frac{v}{c}\cos\varphi,$$

where E is the energy of the γ-ray when emitted from a nucleus at rest,
ΔE is the change in energy.

This energy change was converted to a γ-counter efficiency change using the absorption coefficient data mentioned above.

The maximum total of these four corrections was -5 per cent.

The corrected results are plotted against θ in Figure 3. The data represent a total of approximately 13,000 true coincidence counts. With weight factors appropriate to the number of counts at each angle the results were analysed by a least squares method to fit a curve of the form $1+A\cos^2\theta$. The correlation factor A so obtained was $-0\cdot041\pm0\cdot025$.

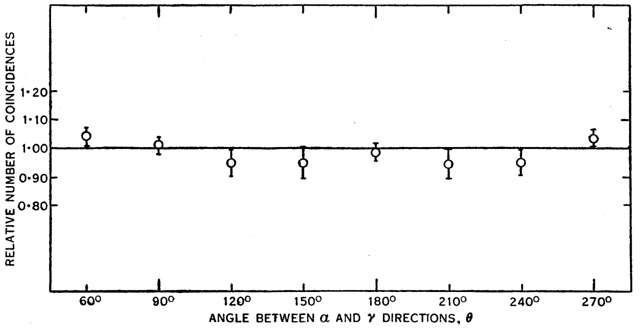

Fig. 3.—α-γ Angular correlation.

IV. Discussion

The results given above show no significant departure from isotropy. While this is consistent with a Li^7 spin of $\frac{1}{2}$, one may consider circumstances which can lead to spherical symmetry if the spin is 5/2.

The anisotropic distribution of the unresolved α-particles from the deuteron bombardment of Be^9 found by Resnick and Hanna (1951) implies that α-particles and deuterons with non-zero orbital angular momentum must contribute significantly to this reaction. The plausible assumption of p wave deuterons allows three feasible values of the spin of the B^{11} compound state, only one of which could produce isotropy by chance cancellation through channel spin degeneracy.

Because of the assumption of Li^{7*} spin of 5/2 and p deuterons, it is likely that the α-particles will have orbital angular momentum $l=1$. The angular correlation for both magnetic dipole and electric quadrupole γ-radiation will then be limited to the form $1+A\cos^2\theta$. Cancellation of asymmetry terms may occur by virtue of an anomalous dipole-quadrupole intensity ratio of about 25 : 1 which may be compared with the theoretical estimate of at least 200 : 1 (Inglis 1951; Lloyd 1951).

It follows that accidental isotropy in this reaction is improbable, which allows only the conclusion that the spin of Li^{7*} is $\frac{1}{2}$ in support of the correlation experiments discussed in the introduction.

V. Acknowledgments

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