THE PHOTONEUTRON CROSS SECTION OF ^{9}Be IN THE INTERMEDIATE ENERGY RANGE

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Summary

The photoneutron cross section of ^{9}Be has been measured in the region from 6·5 to 18 MeV, using filtered bremsstrahlung radiation from an 18 MeV synchrotron. The integrated cross section is in agreement with an earlier experiment, but increased resolution has shown a more complex shape, with sharp maxima at $11\cdot25\pm0\cdot2$ and $13\cdot25\pm0\cdot2$ MeV. The significant features of the cross section are discussed and compared with the level scheme as it is known at present.

I. Introduction

Several studies have been made of the level structure of ^{9}Be, covering mainly the region of excitation up to 7 MeV. A summary of these experiments is given by Ajzenberg and Lauritsen (1955). Experiments on the photodisintegration of ^{9}Be have, with one exception, used monochromatic radiation of energy below 8 MeV. A summary of these experiments is given by Edge (1957).

The level structure of ^{9}Be in the region of excitation 11–17 MeV is so far almost unexplored. This is due to the difficulty of forming ^{9}Be in this region of excitation, either as the compound nucleus or as the final nucleus in reactions induced by charged particles or neutrons. The study of inelastic proton scattering is not conclusive in this energy region, since here the deuterons from the reaction ^{9}Be$(p,d)^8$Be complicate the picture, at least in the study of Benveniste, Finke, and Martinelli (1956). This region of excitation is open for study by γ-induced reactions, and with sufficient resolution, some information on the level structure of ^{9}Be should be obtainable.

The only two competing modes of disintegration of ^{9}Be for excitations below the (γ,p) threshold (16·9 MeV) are

$$^9\text{Be}+\gamma\rightarrow{}^8\text{Be}+n\rightarrow\alpha+\alpha+n, \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$^9\text{Be}+\gamma\rightarrow{}^5\text{He}+\alpha\rightarrow\alpha+n+\alpha. \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

The probability of de-excitation by γ-emission is considered to be so small as to be negligible. Hence, if the total neutron yield from the photodisintegration of ^{9}Be is measured, the cross section obtained from it will be the sum of the cross sections of the reactions (**1**) and (**2**), and is to very good approximation the cross section for photon absorption by the ^{9}Be nucleus. Maxima in this cross section and their relative strengths will thus give information about the excited states of ^{9}Be.

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Nathans and Halpern (1953) measured the γ-induced neutron yield from ^{9}Be from threshold (1·66 MeV) up to 24 MeV in 1 MeV steps, using bremsstrahlung from a 25 MeV betatron. The cross section computed from this yield curve had two broad maxima, one of 1·6 mbarn height at 10 MeV and one 3 mbarn high at 22 MeV.

II. The Experiment

The experiment performed by Nathans and Halpern (1953) has been repeated with the Melbourne 18 MeV synchrotron for the energy interval 4·5–18 MeV, with increase of resolution.

The experimental arrangement used was almost identical with the one described in an earlier paper (Spicer *et al.* 1958). As in the experiment of Nathans and Halpern, a graphite filter was used to " harden " the γ-ray beam before it struck the beryllium target. The thickness of the graphite absorber used was 28 cm. Because of the large decrease in the absorption coefficient of γ-rays in carbon between the energies of 1 and 5 MeV, and its relatively constant value from there up to 20 MeV, the graphite absorber was used to reduce the yield contribution from the cross section between the threshold of the reaction and 4 MeV. This reduction means that any detail in the yield curve at energies higher than 4 MeV is relatively enhanced. Nathans and Halpern (1953) tested this procedure by comparing the cross section for the ^{209}Bi(γ,n) reaction obtained by measuring the yield curve with the absorber in with that obtained from a yield curve measured with no absorber. They found no change in the shape of the cross section curve. Thus, the experimental accuracy in the region 10–18 MeV can be increased by this use of the carbon absorber.

The " filtered " γ-radiation was passed through a transmission ionization chamber, and struck the target which consisted of 100 g of beryllium powder of better than 99·5 per cent. purity contained in a thin-walled polystyrene cylinder. The target was located in the paraffin " house " and the neutron yield was measured with BF_3 counters.

The neutron yield (counts per roentgen) was measured in steps of 0·19 MeV from 5·5 to 18 MeV. Above 10 MeV, at least 40,000 counts per synchrotron energy setting were obtained during several different runs. These runs were taken over a period of some 3 months. Results of individual runs agreed within statistics. A background run was made with the container empty.

The measured doses were corrected for temperature and pressure variations. The counting loss of the detecting system was determined experimentally, and was kept small throughout this experiment. The counting efficiency of the detecting system was checked regularly with a standard Ra-Be source.

III. Analysis of Results

The cross section was derived from the yield curve using the Penfold-Leiss method (Penfold and Leiss 1958). The interposition of the carbon filter necessitated only a slight modification of the original method of analysis. This will now be described briefly.

In the discussion, the following symbols will be used. Reference to these symbols in the actual experimental layout is shown in Figure 1. The γ-ray beam emitted from the synchrotron has a spectral energy distribution $N(E,E_0)$ which is normalized so that $\int_0^{E_0} N(E,E_0)\mathrm{d}E=1$. The dose given at synchrotron energy E_0 is written I photons/cm^2, which gives $I.N(E,E_0)\mathrm{d}E$ photons/cm^2 in the energy interval E to $E+\mathrm{d}E$ at the plane y if no absorber or ionization chamber were interposed.

The γ-ray beam then passes through the carbon filter, the transmission ionization chamber, and the target, in that order. Their effective thicknesses and γ-ray absorption coefficients are X_1, $\mu_1(E)$, X_2, $\mu_2(E)$, X, $\mu_3(E)$ respectively. The target has atomic mass number A and density ρ g cm^{-3}. N is Avogadro's number. The efficiency of the neutron counting system is η, which is determined by measuring the count rate when the calibrated Ra-Be source is placed at the

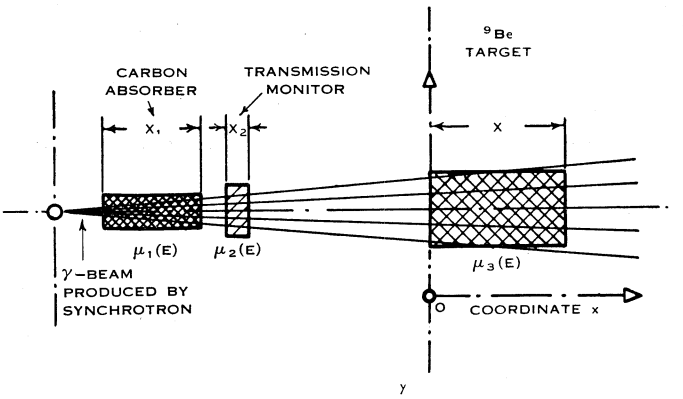

Fig. 1.—Relative positions of the carbon filter, transmission ionization chamber, and long beryllium target. The effective length and absorption coefficient symbols are shown with each object.

centre of the region covered by the beam in the plane y. $G(x)$ is a function of the target coordinates. It allows for the target not being totally immersed in the γ-ray beam, as well as the variation of the γ-ray intensity over the length of the target according to the inverse square law, and for the neutron counting efficiency being a function of x for a small source. $\sigma(E)$ is the cross section for the nuclear absorption of photons by the target. $Y(E_0)$ is the yield as measured (counts/Lucite roentgen). $k.m(E)$ is the registering efficiency of the γ-ray monitor. k is a numerical constant dependent on the intensity units used.

The following relation exists between $Y(E_0)$ and $\sigma(E)$

$$Y(E_0)=\frac{\int_0^{E_0} I.N(E,E_0)\exp\left[-\mu_1(E)X_1-\mu_2(E)X_2\right]\sigma(E)\mathrm{d}E\int_0^X (N\rho/A)\eta\exp\left[-\mu_3 x\right]G(x)\mathrm{d}x}{\int_0^{E_0} I.N(E,E_0)\exp\left[-\mu_1(E)X_1-\mu_2(E)X_2\right]k.m(E)\mathrm{d}E}. \qquad (3)$$

The right-hand integral of the numerator is a function of E only. The integral in the denominator is a function of E_0 only. Thus one defines

$$J(E)=(N\rho/A)\int_0^X \eta \exp\,[-\mu_3(E)x]G(x)\mathrm{d}x, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$kF(E_0)=k\int_0^{E_0} N(E,E_0)\exp\,[-\mu_1X_1-\mu_2X_2]\,.\,m(E)\mathrm{d}E, \quad \ldots\ldots\ldots\ldots \quad (5)$$

and obtains finally for the " reduced yield " $y(E_0)$

$$y(E_0)=kF(E_0)\,.\,Y(E)=\int_0^{E_0} N(E,E_0)\exp\,[-\mu_1X_1-\mu_2X_2]\sigma(E)\,.\,J(E)\mathrm{d}E. \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Since the tables for the evaluation of the cross section are in terms of the intensity spectra $\varphi(E,E_0)$ rather than the number of photons spectra, $N(E,E_0)$, where $\varphi(E,E_0)=E.N(E,E_0)$, we define a " reduced cross section " $s(E)$ by the equation

$$s(E)=\{\sigma(E)J(E)\exp\,[-\mu_1X_1-\mu_2X_2]\}/E. \quad \ldots\ldots\ldots \quad (7)$$

Substituting this expression into (6) gives the integral equation in $s(E)$

$$y(E_0)=\int_0^{E_0} \varphi(E,E_0)s(E)\mathrm{d}E. \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

Equation (8) is identical with the integral equation for which the Penfold-Leiss method gives solutions of $s(E)$ as functions of the $y(E_0)$. The function $\varphi(E,E_0)$ is known from bremsstrahlung theory, and is tabulated by Penfold and Leiss (1958). Thus one can obtain solutions for $s(E)$ and hence for $\sigma(E)$.

IV. Results

The experimental yield curve is shown in Figure 2. The absolute photoneutron cross section $\sigma(E)$, which was evaluated as outlined above, is shown in Figure 3. The photoneutron cross section covers only the region 6·5–18 MeV. The " area of statistical variation ", enclosing $\sigma(E)$, is computed from the statistical error of the measured yield curve points. Due to this factor and the finite resolution of this analysis, the cross section derived may deviate from its centre value within this region in any way provided it remains continuous and does not have a greater number of maxima, minima, and turning points than the centre value curve.

Since the cross section is that for nuclear absorption of photons by beryllium, the peaks in the cross section appear at the energies of excited states of ^{9}Be. Figure 4 shows the cross section curve plotted beside an energy level diagram (from Ajzenberg and Lauritsen 1955). Since Ajzenberg and Lauritsen's review paper, Almqvist, Allen, and Bigham (1955) have reported a previously unobserved level at 9·2 MeV. Except for this 9·2 MeV level, there is at least one independent confirmation of the existence of all known levels.

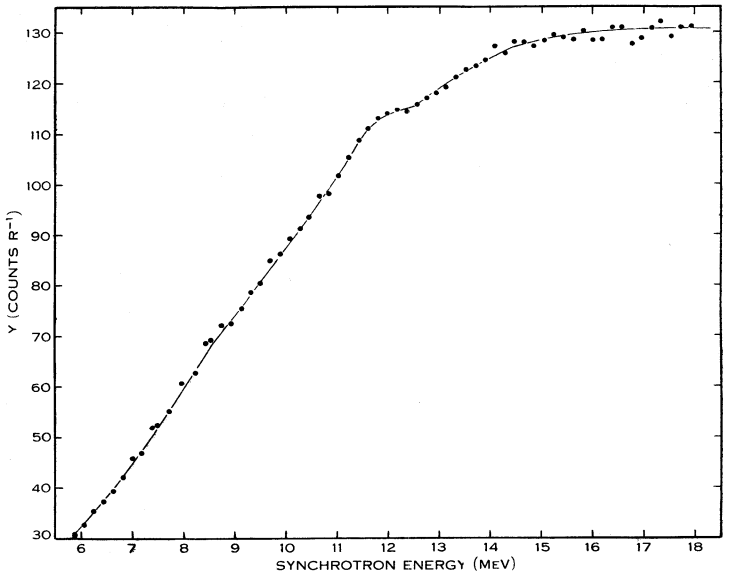

Fig. 2.—The experimental yield curve of photoneutrons from beryllium.

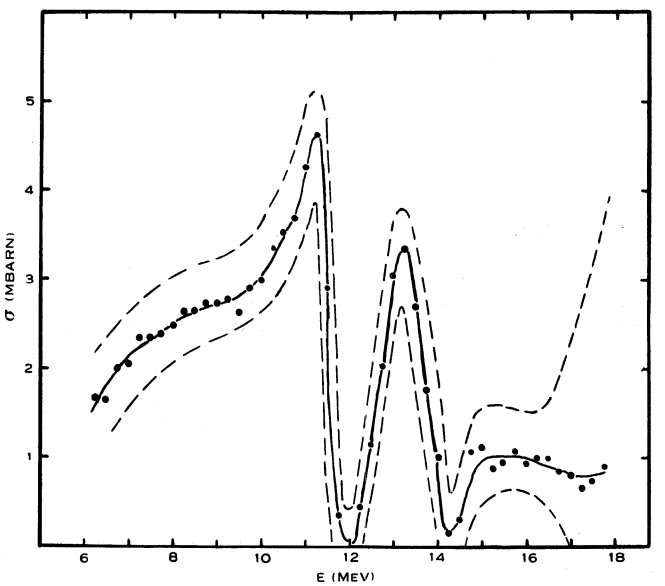

Fig. 3.—The cross section for production of photoneutrons from beryllium. The dashed lines represent the extremes of the area of statistical variation, which is to be interpreted as indicated in the text.

The maximum in the cross section curve at $11 \cdot 25 \pm 0 \cdot 2$ MeV unambiguously confirms the known level at $11 \cdot 3$ MeV. The known levels at $6 \cdot 8$ and $7 \cdot 9$ MeV are presumably responsible for the cross section in the energy region 6–8 MeV. The existence of considerable cross section between 8 and 11 MeV tends to confirm the existence of the $9 \cdot 2$ MeV level.

On the high energy side of the $11 \cdot 25$ MeV peak, the cross section has a maximum at $13 \cdot 25 \pm 0 \cdot 2$ MeV. This cannot be attributed to any known level. The peak has a width approximately the same as the $11 \cdot 25$ MeV level, and so the

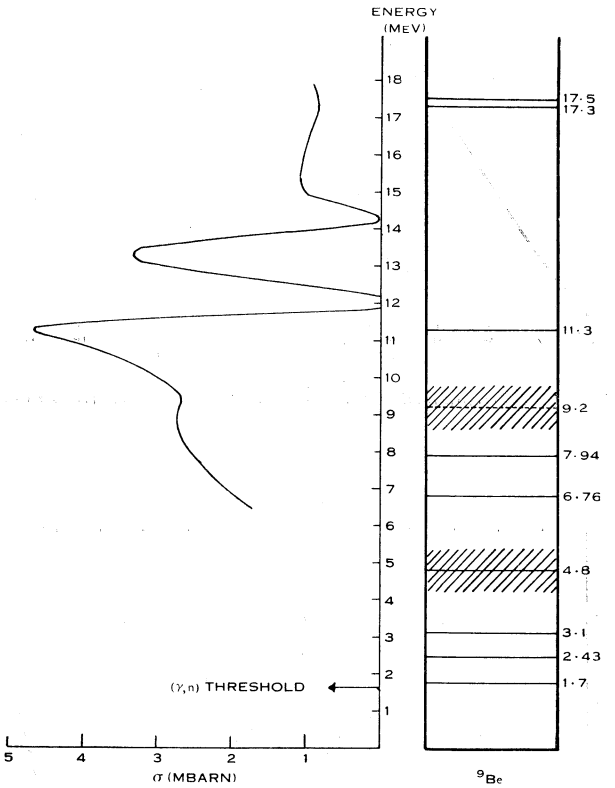

Fig. 4.—The cross section for nuclear absorption of photons in beryllium plotted beside a diagram of previously observed energy levels of ^{9}Be.

existence of one or more energy levels in this region is inferred. There is some support for the existence of an energy level at about 14 MeV in the work on the inelastic scattering of protons from beryllium described by Tyren and Maris (1958).

The integrated cross section for nuclear absorption of photons in ^{9}Be is 22 MeV-mbarn for the energy region from $6 \cdot 5$ to 18 MeV. This is in good agreement with a similar estimate based on the results of Nathans and Halpern (1953). These authors found a peak of height 3 mbarn at 22 MeV in the cross section derived from the yield of photoneutrons. If the $2 \cdot 7$ mbarn found by

Haslam *et al.* (1953) for the peak cross section of the 22 MeV resonance of the ^{9}Be(γ, p) reaction is added to the 3 mbarn noted above, we may give 5·7 mbarn as the height of the 22 MeV giant resonance of ^{9}Be. This giant resonance is considered to be due to electric dipole transitions.

V. Discussion of Results

It is of interest to seek information concerning the spin and parity of the 11·3 and the 13·3 MeV levels from the magnitude of the photon absorption cross section in these two cases. An estimate was made of the integrated cross section for absorption into these two levels, and is expected to be correct in absolute magnitude to within a factor of two. The estimate for the 13·3 MeV level is unambiguous, and involves only the assumption that the peak is due to one single level. In support of this assumption, it is noted that the levels of ^{9}Be at 4·8 and 9·2 MeV have widths exceeding 1 MeV. The shape of the 11·3 MeV level was deduced from the shape of the high energy side of it, since other levels interfere on the low energy side. The results are 4·0 and 3·9 MeV-mbarn respectively for the 11·3 and 13·3 MeV levels.

If the assumption is made that the levels are of Breit-Wigner shape, then

$$\int_{\text{level}} \sigma(E)\mathrm{d}E = \frac{7\cdot 7 S_0 \Gamma_\gamma}{E^2} G_n \text{ MeV-mbarn}, \quad \ldots\ldots\ldots\ldots (9)$$

where E is the energy of the level in MeV,

S_0 is the statistical factor, which equals $(2J+1)/2(2I+1)$; here J is the spin of the excited state and I the spin of the ground state (for ^{9}Be, $S_0=(2J+1)/8$, since $I=3/2$),

Γ_γ is the radiative width of the level in electron-volts,

G_n is the branching ratio for neutron emission, which is unity here if we neglect decay of the excited state by radiation, compared to particle emission.

If a definite multipolarity is assumed for the γ-radiation absorbed by a particular level, then the possible values for the spin of that level are limited. Noting this, the minimum value for the Γ_γ of each of the levels may be calculated, and compared with the value of the rough single particle estimate of this radiative width (the Weisskopf unit (Weisskopf 1951)). This comparison is made in Table 1.

The values of the Weisskopf units were calculated from formulae given by Wilkinson (1956) in a summary of experimental data on radiative widths. In each case, the $E2$ Weisskopf unit is about 200 times smaller than the estimated radiative width. Wilkinson's survey indicates no radiative transition stronger than 14 times that indicated by the Weisskopf unit, and so it is inferred that the transitions to these two levels are not of the electric quadrupole type.

Further support to this idea is obtained from the sum rule for electric quadrupole transitions given by Levinger and Bethe (1950), namely,

$$\int_0^\infty \sigma(E2)\frac{\mathrm{d}E}{E} = \frac{4\pi^2}{137} \cdot \frac{2}{9} \cdot \frac{T.Z}{Mc^2}\langle r^2\rangle_{00},$$

where $\langle r^2 \rangle_{00}$ is the expectation value of the squared displacement of the average nucleon from the centre of mass of the nucleus,

T is the average kinetic energy of the protons in the nucleus.

The insertion of the classical value of $0 \cdot 6R^2$ for $\langle r^2 \rangle_{00}$ leads to too large a value of this quantity (Levinger and Bethe 1950; Levinger and Kent 1954) by a factor of approximately four. Bearing this in mind, we estimate $\int_0^\infty \sigma(E2)\mathrm{d}E/E$ for ^{9}Be to be approximately $0 \cdot 2$ mbarn. Computation of $\int(\sigma/E)\mathrm{d}E$ for the $11 \cdot 3$ MeV level and the $13 \cdot 3$ MeV level gives respectively $0 \cdot 30$ mbarn and $0 \cdot 25$ mbarn. It is scarcely possible that the sum rule would be exhausted by one single level, and so the possibility of electric quadrupole transitions is ruled out.

TABLE 1

COMPARISON OF THEORETICAL AND EXPERIMENTAL INFORMATION ON THE $11 \cdot 3$ AND $13 \cdot 3$ MEV LEVELS OF ^{9}Be

Property	$11 \cdot 3$ MeV Level	$13 \cdot 3$ MeV Level
$\int \sigma(E)\mathrm{d}E$	$4 \cdot 0$ MeV-mbarn	$3 \cdot 9$ MeV-mbarn
$\Gamma_\gamma(E1,M1), J_{\mathrm{max.}}=5/2$	88 ev	119 ev
$\Gamma_\gamma(E2), J_{\mathrm{max.}}=7/2$	66 ev	90 ev
$E1$ Weisskopf unit	686 ev	1120 ev
$M1$ Weisskopf unit..	30 ev	49 ev
$E2$ Weisskopf unit	$0 \cdot 41$ ev	$0 \cdot 74$ ev
Γ_γ/E^3, dipole absorption assumed	$0 \cdot 061$	$0 \cdot 051$

The possibility of distinguishing between $E1$ and $M1$ transitions for these cases has now to be investigated. Wilkinson's survey of radiative widths (1956) indicated that $E1$ transitions have a most probable radiative width of about $0 \cdot 032$ Weisskopf unit, with a spread of about a factor of seven either way. The corresponding quantities for $M1$ transitions are a width of $0 \cdot 15$ Weisskopf units and a spread of a factor of 20 either way. Thus, on this basis, the observed transitions may be either $E1$ or $M1$.

Wilkinson suggests that a transition which shows a value of Γ_γ (eV)/E^3 (MeV) greater than $0 \cdot 02$ has about a 10 : 1 chance of being an $E1$ transition. Since, for the observed cases, Γ_γ/E^3 are $0 \cdot 06$ and $0 \cdot 05$, this suggests that they are electric dipole transitions.

A contrary argument comes from consideration of proton inelastic scattering data on ^{9}Be (Benveniste, Finke, and Martinelli 1956). In this work we consider the analysis of data on the $6 \cdot 8$ and $7 \cdot 9$ MeV levels. This can serve as a rough guide to expectations for the $11 \cdot 3$ and $13 \cdot 3$ MeV levels, since the integrated cross section for photon absorption by a single level is expected to increase approximately with E (Γ_γ varies as E^3, and there is a factor E^2 in the denominator of the expression for $\int \sigma \mathrm{d}E$). Benveniste, Finke, and Martinelli (1956) indicate that the $6 \cdot 8$ and $7 \cdot 9$ MeV levels have opposite parity. This conclusion is correct

in spite of criticisms of their interpretation, which uses values for the nuclear radius of ^{9}Be that are too small (see Summers-Gill 1958). Since the cross section is approximately constant over the energy region 6–8 MeV in the photodisintegration, this indicates that there is not a large difference between the radiative widths for $E1$ and $M1$ transitions at these energies.

Thus we are unable to choose between $E1$ and $M1$ for the mode of absorption of photons into the 11·3 and 13·3 MeV levels. In any case, these two possibilities demand that the spin of the levels be 1/2, 3/2, or 5/2. Since the radiative transition in the region of 6–8 MeV is so strong, these possibilities also apply to the 6·8 and 7·9 MeV levels.

VI. Conclusions

The cross section for photon absorption by the ^{9}Be nucleus has been measured. Peaks in this cross section at 11·3 and 13·3 MeV are associated with levels in the beryllium nucleus at these energies. Consideration of the strength of the radiative transitions leads to the values of the spins of the levels of ^{9}Be at 6·8, 7·9, 11·3, 13·3 MeV coming from the possibilities 1/2, 3/2, 5/2, but no conclusion regarding the parity of these states was possible.

The study of this cross section in steps smaller than 0·25 MeV, as well as the study of the decay products of these levels, should throw further light on their properties.

VII. Acknowledgments

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