The Energy Spectrum of Neutrons from a Po—Be Source

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The energy spectrum of neutrons emitted by a Po—Be source has been determined by the photographic emulsion method. The results agree, on certain assumptions, with the existence of energy levels in the C^{12} nucleus at 2.5, 4.5, and 7.1 Mev. The last two of these are consistently found by other workers, but the existence of the first is sometimes disputed. Possible reasons for the apparent discrepancies in the evidence on this point are discussed.

1. INTRODUCTION

THE energy distribution of the neutrons from a Po—Be source, though studied by various methods by a number of workers, is not known with precision, and a further examination by the photographic emulsion method has been undertaken.

2. EXPERIMENTAL METHOD

Ilford C_2 plates were exposed to neutrons from a pair of Po—Be sources, the plates and sources, 21 cm apart being supported on light wire frameworks in such a way that the nearest scattering material was at a distance of about 150 cm. The sources lay approximately in the plane of the emulsion and on the central axes of the $3''\times 1''$ plates, so that the incident neutron directions made angles of not more than 5° with any line in the plate parallel to the axis. Tracks of protons in the emulsion were measured in the usual way, if their initial directions lay within 13° of the plate axis, as determined by cross-hairs in one eyepiece of the binocular microscope used for observations. The measured lengths were converted to energies by use of the calibration curve for Ilford emulsions of Lattes and Cuer,[1] one point on which was checked by neutrons from a deuterons-on-deuterons source, obtained by use of a 300-kev beam of deuterons from the Ottawa high tension generator. The energy distribution obtained was corrected for the varying proton-neutron collision cross section, using the results of Bailey *et al.*,[2] and for the probability of a track leaving the emulsion, to give the final energy distribution.

This final distribution is shown in Fig. 1. It is derived from a total of nearly 7000 observations, made by three different observers on three separate plates. Of these plates, one was placed alone, the other two sandwiched together, to test whether the proximity of extra glass scattering material had any observable effect on the results. No such effect was detected, the curves derived from the three plates separately differing not more than would be expected from experimental error. The internal consistency of the observations was checked further by plotting separately the distribution obtained by each observer, on all plates together.

All these partial distributions showed the same major features namely: (1) a maximum energy of about 11 Mev, (2) pronounced maxima in the distribution at just over 3 Mev and just under 5 Mev, and a fairly well marked smaller maximum at 7.5 to 8 Mev. The small maximum at 1 Mev occurred in most curves. The experimental accuracy was not sufficient to determine whether the small maxima in Fig. 1 at 5.8 and 9.7 Mev are real or spurious, these maxima showing in some but not all of the partial distributions. These results agree with those of Richards[3] and Demers[3] only with regard to the first point, the existence of an upper limit of about 11 Mev, and in the broad fact of the existence of a maximum intensity somewhere in the range 3 to 5 Mev. The statistical errors of these previous determinations, however, would appear to be considerably greater than those of the present work.

We may therefore regard as established by this work intensity maxima at 3.2, 4.8, 7.7 Mev, and probably one at 1.2 Mev, and an upper limit to the energy of 11 Mev; small maxima at 5.8 and 9.7 Mev are doubtfully suggested.

3. ENERGY LEVELS OF THE C^{12} NUCLEUS

We wish to consider the association of this distribution with the energy levels of the C^{12} nucleus. Hornyak and Lauritsen[4] in a review of many experimental papers,

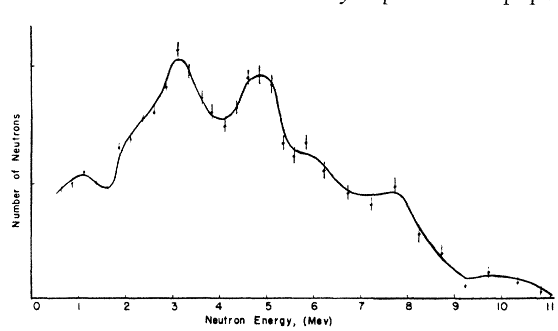

FIG. 1. Energy distribution of neutrons from a Po-Be source, plotted in 0.25 or 0.5 Mev intervals.

[1] C. M. G. Lattes, P. H. Fowler, and P. Cuer, Proc. Phys. Soc. London **59**, 884 (1947).
[2] Bailey, Bennett, Bergstralh, Nuckolls, Richards, and Williams, Phys. Rev. **70**, 583 (1946).
[3] See Anderson, *Neutrons from Alpha-Emitters* (McGraw-Hill Book Company, Inc., New York) Nuclear Science Series, No. 3.
[4] W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 191 (1948).

conclude that the evidence points to the existence of an excited state at 4.3 Mev, another at 7.1±0.4 Mev (as well as higher states), as well as a doubtful level at about 3 Mev. In view of the discussion given below, it is perhaps relevant that all the evidence for this state seems to have been derived from the $Be^9(\alpha,n)C^{12}$ reaction used by us. They give the Q-value for this reaction, ending in the ground state of C^{12}, as 5.75 Mev.

In attempting to correlate our results with these energy levels it is necessary to remember that a reaction of given Q-value will give rise to neutrons of varying energy, owing (a) to the variation in the energy of the incident α-particle and (b) to variation in the direction of emission of the neutron, relative to that of the α-particle. In order to calculate the distribution in energy which one would expect to observe, corresponding to transitions to a single final level in C^{12}, it is necessary to know both the excitation function for this transition, and the distribution in angle of the emitted neutrons.

Considering first this latter point, for α-particles of fixed energy, it is readily seen that a uniform distribution in angle in the center-of-mass system corresponds to a uniform distribution in energy in the laboratory system. For if v_1 be the velocity of center of mass relative to laboratory, v_2 that of neutron relative to the center of mass, and φ the angle between these velocities, then the velocity of the neutron in the laboratory system, V, is given by $V^2=v_1^2+v_2^2+2v_1v_2\cos\varphi$, and its energy E_2 by $E_2=a+b\cos\varphi$. Hence $dE_2=b\sin\varphi d\varphi$. But a uniform distribution in angle gives $dn=k\sin\varphi d\varphi$, hence dn/dE_2 is constant.

The maximum and minimum values of E_2 corresponding to a fixed value of the incident α-energy, E_1, and given Q, are easily calculated from the dyanmics of the collision. They are plotted in Fig. 2 for values of E_1 up to 5.3 Mev, the maximum energy of polonium α-particles, taking Q as 1.25 Mev, corresponding, on Hornyak and Lauritsen's scheme, to transitions to the 4.5 Mev level in C^{12}.

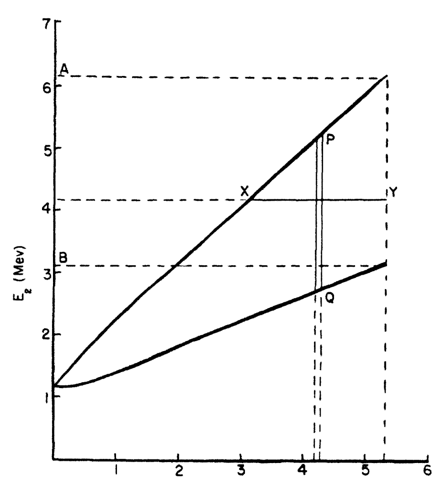

FIG. 2. Maximum and minimum neutron energies (E_2) as functions of α-particle energy (E_1), for transitions to 4.5 Mev level in C^{12}.

To determine accurately the effect of varying α-energies we need the excitation function for this transition. Various workers[5] have measured the excitation functions of neutrons and the associated γ-rays for the $Be^9(\alpha,n)C^{12}$ reaction. They use for the detection of the neutrons various methods, which do not all have the same comparative sensitivity for slow and fast neutrons. Their results correspondingly differ considerably in detail, though showing fair agreement in the general form of the function. The results do not, however, refer specifically to transitions to any given final level. As an approximate basis for calculation, the curve given by Halpern was used.

We may first note one general point concerning the results of this calculation, assuming, as discussed above, that α-particles of fixed energy E_1 liberate neutrons with a uniform distribution of energy. If the number of α-particles having energies in any range dE_1 is proportional to dE_1, if each such particle liberates $f(E_1)$ neutrons, and if these neutrons are spread uniformly over a range of energies (PQ in Fig. 2) of $R(E_1)$, then the number of such neutrons having energies between E_2 and (E_2+dE_2) is proportional to $f(E_1)dE_1\cdot dE_2/R(E_1)$. The total number of neutrons of this energy is therefore proportional to

$$dE_2\int_X^Y f(E_1)dE_1/R(E_1)=F(E_2)dE_2.$$

Since the integrand is always positive, $F(E_2)$ will clearly increase steadily as E_2 decreases from A to B; and unless $f(E_1)$ is exceptionally large for low values of E_1 the maximum of $F(E_2)$ almost certainly occurs at $E_2=B$. Exceptionally, it could occur for a lower value of E_2, but not for a higher one.

It is noticeable that in Fig. 2 the value of E_2 at B is 3.1 Mev. This suggests that the prominent maximum in our curve at that value is derived from transitions to the 4.5 Mev level in C^{12}, the emitted neutrons being distributed uniformly in angle in the center-of-mass system.

$F(E_2)$ has therefore been calculated on this basis by graphical integration, using Halpern's curve for $f(E_1)$, taking Q for transitions to the ground state as 5.75 Mev, and assuming transitions to levels at 0, 2.5, 4.5, and 7.1 Mev. The results are shown in Fig. 3. To show that $F(E_2)$ is not very sensitive to the form of $f(E_1)$ the calculations have also been carried out in two cases assuming $f(E_1)=$ constant, above a threshold at 1 Mev. These results are shown dotted.

Comparing the curves of Fig. 3 with our distribution of Fig. 1, it will be seen that the upper limit of 11 Mev in Fig. 1 agrees with the calculations, and that the

[5] E. Fünfer, Ann. d. Physik (5) **35**, 147 (1939); E. Stuhlinger, Zeits. f. Physik **114**, 185 (1939); A. Szalay and J. Zimonyi, Zeits. f. Physik **115**, 639 (1940); I. Halpern, Phys. Rev. **74**, 1234(A) (1948), or see Anderson.

maxima of the four calculated curves agree with the experimental maxima at 1.2, 3.1, 4.8, 7.7 Mev. Our results, therefore, would seem to agree with the level scheme proposed by Hornyak and Lauritsen, except that the value 2.5 rather than 3.0 fits our results better for their "doubtful" level.

There are, however, difficulties in this interpretation. Evidence for this last level is very conflicting. Various workers (see Bethe and Livingston[6]) with the $Be^9(\alpha,n)C^{12}$ reaction have obtained evidence for it. On the other hand, other reactions involving C^{13} as the intermediate nucleus do not seem to show it. For example Powell,[7] in a photographic emulsion study of the reaction $B^{11}(d,n)C^{12}$ obtained very clear evidence for a 4.5 Mev level in C^{12}, and none at all for any lower one. The $Be^9(\alpha,n)C^{12}$ reaction has also been studied recently by Bradford and Bennett,[8] who used 1.4 Mev α-particles from an accelerator, and photographic emulsion recording at a fixed angle to the beam, thereby eliminating or reducing the causes of our "spread" in neutron energy. They also obtain evidence for a 4.5 Mev level, and no lower ones.

It will be noticed also that, while the maxima of the curves of Fig. 3 agree in position with those of Fig. 1, the experimental maxima are much sharper than the calculated ones. In particular, the pronounced dip in the experimental curve between 3.1 and 4.8 Mev could not be reproduced by combining "calculated" curves in any proportion. Remembering that straggling in the emulsion and varying angles of neutron and proton paths will introduce a broadening into the experimental curves, there seems here to be a definite discrepancy.

We do not feel that we have enough information to account for these apparent discrepancies finally. Certain tentative suggestions may, however, be made. With regard to the 2.5 Mev level, its absence in other experiments might be due to the different excitation of the C^{13} nucleus in those cases. In Powell's experiments, this intermediate nucleus is formed from $B^{11}+d$, in ours from $Be^9+\alpha$. If, as is likely, its life-time is very short, it might remain in fundamentally different states in the two cases such that transitions to the 2.5 Mev level in C^{12}, were forbidden in one case but not in the other. Bradford and Bennett's experiments are more difficult to reconcile with this. But it is noticeable on Halpern's curve that there is a marked resonance for α-energies of about 1.4 Mev. Possibly, therefore, these α-particles enter a fairly clearly marked energy level in C^{13}, from which again transitions to the 2.5 Mev level are forbidden.

The calculated distributions are based on the assumption that neutrons are emitted uniformly in all directions in the center-of-mass system. This appears to be the most plausible assumption. But if, for example, they were emitted predominantly at right angles to the direction of the α-particle, the effect would be to sharpen the maximum of the calculated distribution. It is true that the maximum would also be displaced, perhaps vitiating the whole identification of final levels proposed, but a moderate and symmetrical concentration of directions around the 90° angle might perhaps not displace the maxima greatly.

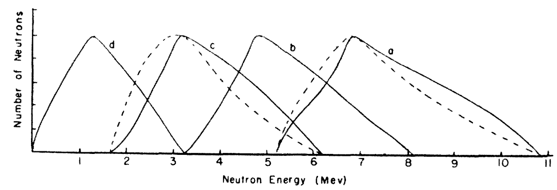

FIG. 3. Calculated neutron distributions for transitions to (a) ground state, (b) 2.5 Mev level, (c) 4.5 Mev level, (d) 7.1 Mev level in C^{12} nucleus.

It is worth noting here that Bradford and Bennett found the ratio of the intensity of their low energy neutron group (transitions to 4.5 Mev level) to that of the high energy group (transitions to ground state) to be 1.3 for observations at 90° and 0.4 in the forward direction. This might be accounted for if the high energy group were uniformly distributed (our high energy group is rather broader than the others) the low one stronger at 90°. Their average ratio also seems to be much lower than in our experiments, where the high energy group is weak, again possibly owing to the different excitations.

It is, of course, clear that the evidence we have is not sufficient to substantiate these suggestions. For example, if the distribution in angle of the emitted neutrons is not uniform, large variations in the calculations can be made by assuming sufficiently asymmetrical angular distributions. If the intensity is assumed to be zero at 90°, and about twice as great in the forward as in the backward direction, it is even possible to obtain, for the single transition to the 4.5 Mev level, a final distribution showing peaks at about 3.1 and 4.8 Mev as observed. The asymmetry necessary is very great, and appears to be in the wrong sense to account for Bradford and Bennett's results, so that this suggestion does not seem to be probable, but it is mentioned to emphasize that without more accurate knowledge the unambiguous interpretation of our results is impossible.

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6 M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 304 (1937).

7 C. F. Powell, Proc. Roy. Soc. **A181**, 344 (1943); F. C. Champion and C. F. Powell, Proc. Roy. Soc. **A183**, 64 (1944).

8 C. E. Bradford and W. E. Bennett, Phys. Rev. **77**, 753(A) (1950).