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Nuclear Levels in Li^6

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With the aid of the photographic detection method, reactions with emergence of several particles were studied, which arise as a result of interaction of fast deuterons (with energies up to 13.8 mev) with nuclei of Li^6 and Li^7. The following reactions were detected: Li^6 $(d; 2d)$ He^4, Li^6 $(d; d', p, n)$ He^4 and Li^7 $(d; t, d')$ He^4, which lead to the formation of excited Li^6 nuclei. The following levels of the Li^6 nucleus were found (with $T = 0$): $E_1^* = 2.2$ mev, $E_2^* \approx 4.5$ mev and $E_3^* \approx 7.5$ mev.

FROM the point of view of the shell model, $(1s)^4 (1p)^2$ is the probable configuration of the ground state of Li^6. This configuration corresponds to the assumption that the four nucleons in the $(1s)$ state form a system similar to the α-particle, in whose field the other two nucleons occupy places in the p-shell. Since there is every reason to think that the excitation of the α-particle does not appear before energies ~ 15 mev[1,2], it follows that the first levels of the Li^6 nucleus must correspond to different states of the two nucleons in the field of the α-particle. Therefore, an experimental investigation of the properties of the Li^6 nucleus is of considerable interest, since it makes it possible to draw a number of conclusions concerning the character of the neutron-proton interaction as well as concerning their interaction with the group of four nucleons in the $(1s)$ state.

1. In the present investigation, the interaction of fast deuterons with the nuclei of Li^6 and Li^7 was studied. The registration of the reaction which took place was made by means of the photographic method; lithium was introduced into the emulsion layer of the plate, which was then irradiated with deuterons in such a way that their tracks were completely within the emulsion. Under such conditions, because of the continuous decrease of the energy of the deuterons as they were slowed down, the disintegrations of the lithium nuclei could be caused by deuterons of different energies.

We used plates of type E-1 (Ilford) with layer thickness of 100μ. Emulsion of type E-1 was chosen because, under proper conditions of developing, it makes it possible to obtain tracks of singly charged particles, α-particles, and other, heavier nuclei, which differ markedly in their external appearance (grain dimensions and density). These properties of the E-1 emulsion greatly facilitate the identification of tracks in analyzing the stars belonging to various reactions.

The introduction of lithium in the emulsion layer was accomplished by saturation in a solution of lithium acetate; the concentration of lithium atoms was then determined, as well as the uniformity of its distribution in depth and area of the emulsion layer.

The plates saturated with lithium were irradiated in a cyclotron with deuterons of 13.8 ±.2 mev energy. The maximum density of deuteron tracks with which, in the majority of cases, it was still possible to determine with certainty the point of entry into the emulsion of the deuteron causing the reaction in question, was 5×10^5 deuterons per sq. cm of plate surface. It should be noted that the handling of plates with such density of tracks was only possible with the aid of a special stereomicroscope.

General inspection of the irradiated and developed plates for the purpose of finding stars belonging to different reactions, was carried out with a magnification of 450×.

We have investigated plates saturated with an acetate of the natural mixture of lithium isotopes, as well as plates which contained lithium enriched with the isotope Li^6. On equal areas of plates of both kinds were found approximately equal numbers of various stars consisting of two, three and four rays (not counting numerous cases of d-p scattering). Among them were a number of stars consisting (besides the deuteron track causing the disintegration) of one track of an α-particle and two tracks of singly-charged particles.

Energetically possible reactions with $Q \geq -5$ mev, which could give stars of this type, are the following:

TABLE 1

Type of reaction	Q (mev)
$Li^6(d, t, p)He^4$	+ 2.5
$Li^6(d, 2d)He^4$	— 1.5
$Li^6(d, d', p, n)He^4$	— 3.7
$Li^6(d, p, p)He^6$	— 5.0
$Li^7(d, d', t)He^4$	— 2.5
$Li^7(d, t, p, n)He^4$	— 4.7

Identification of the stars was made on the basis of the laws of conservation of energy and momentum. The necessary measurements of track lengths, angles between them and projection of tracks on a vertical axis* were made with MBI-8 microscopes.

In identifying each star, it was assumed successively that it belongs to one of the reactions listed above. Then, from the measured lengths of the tracks, the kinetic energies ϵ_i and momenta $\mathbf{p}_i$ of the emerging particles** were determined, and on the basis of the equalities $\epsilon_d + Q = \Sigma\epsilon_i$ and $\mathbf{p}_d = \Sigma\mathbf{p}_i$ it was determined to what reaction the star in question belonged***. Figure 1 gives graphically the results of this analysis in the case of the star pictured in Figure 2. Here vertical lines represent the values of the differences $|(\epsilon_d + Q) - \Sigma\epsilon_i|$ (continuous lines) and the values of the differences $|\mathbf{p}_d - \Sigma\mathbf{p}_i|$ (dotted lines) for reactions of the various types indicated on the axis of abscissas.

The conditions $|(\epsilon_d + Q) - \Sigma\epsilon_i| = 0$ and $|\mathbf{p}_d - \Sigma\mathbf{p}_i| = 0$ were fulfilled for the reactions studied within limits of error which were, on the average, ±0.25 mev for total energy and ± 0.5 momentum units form momentum*.

This method of identification is sufficiently reliable, since the difference in Q-values for the reactions in question is substantially greater than the error in the determination of total energy.

*The coefficient of shrinkage was 2.5 for all of the plates examined.

**For unit of momentum the momentum of a nucleon with energy of 0.5 mev was taken.

***For those reactions as a result of which, besides the α-particle, two different singly-charged particles appeared, for instance a proton and a triton, each of the tracks in turn was assumed to be the track of one of these particles.

*Maximum possible errors in the determination of the total energy and momentum were calculated separately for each star.

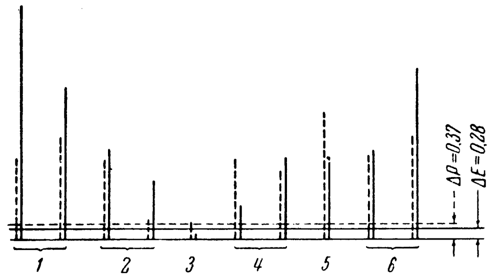


FIG. 1. Values of the differences: Continuous lines $\Sigma\epsilon_i - (\epsilon_d + Q)$ and dotted lines $P_d - \Sigma P_i$ found on the supposition that the star pictured in Fig. 2 belongs to the various possible reactions. For 1 -- $Li^6(d, t, p)He^4$ the sign of the difference is minus; for the other reactions: 2 -- $Li^7(d, d', t)He^4$, 3 -- $Li^6(d, 2d)He^4$, 4 -- $Li^6(d, d', p, n)He^4$, 5 -- $Li^6(d, 2p)He^6$, 6 -- $Li^7(d, t, p, n)He^4$, the sign of the difference is plus.

2. As a result of the processing of the plates described above, it was found that the overwhelming majority of three-ray stars consisting of two tracks of single charge particles and one α-particle track, belong to the following reactions:

$$Li^6(d; 2d)He^4, \quad Li^6(d; d', p, n)He^4,$$

$$Li^7(d; t, d')He^4.$$

1) *Reaction* $Li^6(d, 2d)He^4$. This reaction was the most numerous among the reactions mentioned; as far as is known to us, this reaction has not been previously observed. This was probably due to the use of other methods of registration in the corresponding experiments.

Figure 2 shows a microphotograph of a star pertaining to this reaction.

If one regards the deuteron and the α-particle in the Li^6 nucleus as more or less independent formations, it may be assumed that such a reaction consists in the pulling out by the incident deuterons of a deuteron comparatively weakly bound to the α particle in the Li^6 nucleus. Obviously, in this case the kinetic energy sums of the α-particles and the deuterons (determined in the corresponding center-of-mass system), must have a continuous distribution in the entire interval of possible values.

On the other hand, it may be assumed that the reaction under consideration takes place in two

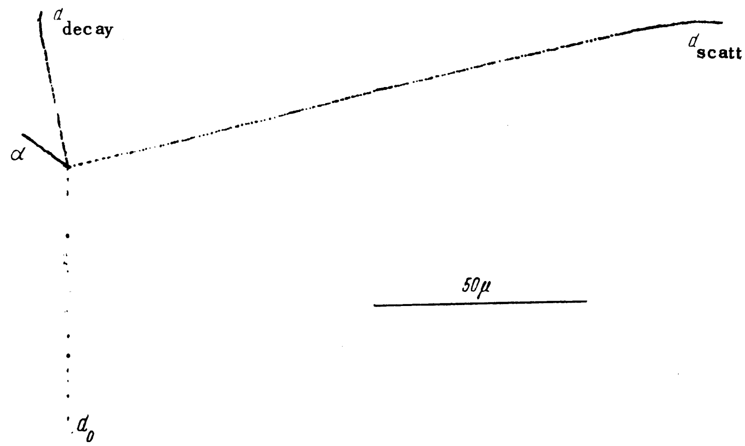


FIG. 2. Microphotograph of a star belonging to the reaction $Li^6(d, 2d)He^4$.

stages; the incident deuteron, undergoing inelastic scattering, excites the Li^6 nucleus to a definite level from which it then decays into a deuteron and an α-particle. In this case the sum of the kinetic energies of the α-particle and the deuteron (in the center-of-mass system of the Li^6 nucleus), plus the binding energy must equal the excitation energy of the level in question.

This hypothesis may be checked by the construction of the corresponding vector diagrams, from which it is possible, first, to find the momentum received by the Li^6 nucleus in the center-of-mass system of Li^6 and the incident deuteron, and, second, to determine the momenta (energies) of the α-particle and the second deuteron in the center-of-mass system of the excited Li^6 nucleus. The energy of the level is in this case determined by

$$E^* = \varepsilon_d + \varepsilon_\alpha + |Q|.$$

The energy of the Li^6 level may also be found by means of the following relation:

$$E^* = {}^2/_3[E - 2E' + \sqrt{EE'}\cos\vartheta], \qquad (1)$$

where E is the energy of the incident deuteron, E' is the energy of the scattered deuteron and ϑ is the scattering angle (all in the laboratory coordinate system).

It is necessary to note, however, that in both cases the analysis of the stars is made more difficult by the circumstance that it is not known in advance which of the two deuterons present in the star is the inelastically scattered one and which is the one which appears as a result of decay of Li^6. Hence, during the processing it was necessary to assume successively each one of the deuterons to be scattered and the other appearing as a result of decay; hence, obtaining two values of E^* for each star. It should be noted that reduction with Eq. (1) is rather cumbersome because the determination of the true value of angle ϑ is complicated.

The graphical method turned out to be simpler. For each star two vector diagrams were constructed (with the above assumptions concerning the two deuterons), with the aid of which two values of the sum $\epsilon_\alpha + \epsilon_d$ (in the center-of-mass system of the excited Li^6 nucleus) were obtained.

On of these sums, $E_1 = \epsilon_{d_{scatt}} + \epsilon_\alpha$, obtained in the case when the scattered deuteron is taken for the one resulting from decay, is obviously not connected with the positions of the levels of the Li^6 nucleus. Since the energy $\epsilon_{d_{scatt}}$ may assume any values lying in the allowed limits, the sum E_1 will have a continuous distribution.

The second sum is $E_2 = \epsilon_{d_2} + \epsilon_\alpha$. If the process mentioned above takes place, in which the incident deuteron pulls out the deuteron d_2 from the Li^6 nucleus, the energies ϵ_{d_2} and ϵ_α will also have any values in the allowed intervals. In this case the sum E_2, like the sum E_1, will have a continuous distribution, If, however, excitation of the Li^6 nucleus to definite levels takes place, with subsequent disintegration into α-particle and deuteron, the sum $E_2 = \epsilon_d + \epsilon_\alpha$ must have discrete values equal to $E^* - |Q|$ where E^* is the excitation energy corresponding to the level in question. Therefore, in order to determine whether the disintegration of the excited Li^6 nucleus from the various levels is taking place, it is necessary to ascertain whether in the sequence of pairs of sums E_1 and E_2 there are groups of neighboring values belongi ng to definite levels.

Upon analysis of the vector diagrams it was found that one of such paired sums in the majority of cases is markedly different from the other. Among the smaller sums there were many values near to 0.7 mev which, in a sum with reaction energy $|Q| = 1.5$ mev gives a value equal to 2.2 mev which coincides exactly with the known energy of the first excited state of the Li^6 nucleus[3]. Figure 3 shows the distribution of the quantity $E^* = \epsilon_d + \epsilon_\alpha + |Q|$ for (*d*; 2*d*)-stars constructed using the most frequently occurring values of the sums. The graphs shows a distinct maximum at the energy $E^* = 2.2$ mev.

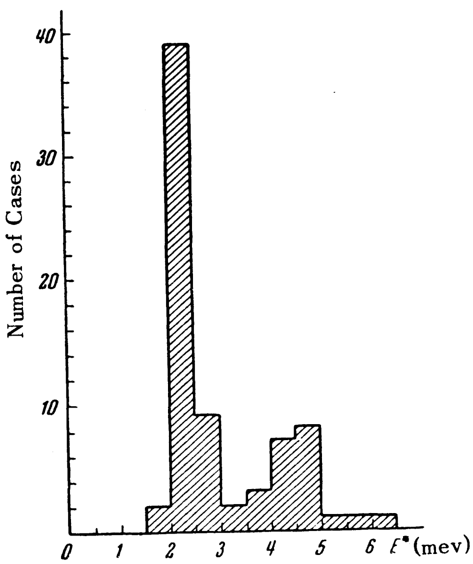


FIG. 3. Distribution of the quantity $E^* = \epsilon_d + \epsilon_\alpha + |Q|$.

It may, therefore, be regarded as established that the decay of the excited nucleus of Li^6 during the reaction (*d*, 2*d*) takes place in the majority of cases from the level at 2.2 mev. This level, as was to be expected, has isotopic spin zero, since the decay products in this case are an α-particle and a deuteron (which have isotopic spins zero).

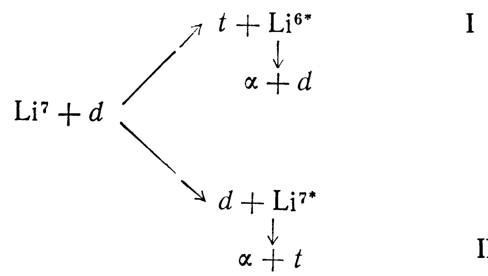
Besides the group of stars corresponding to the level at 2.2 mev, there is a certain number of stars for which the quantity E^* lies within the limits ~3.5 to ~5 mev. It was not possible to determine, because of their small number, the origin of these stars with sufficient definiteness. They could, for instance, correspond to the process, mentioned above, in which a deuteron is pulled out from the lithium nucleus or to the decay of the excited Li^6 nucleus from higher levels. The character of the histogram shown in Fig. 4 speaks in favor of the last supposition, since a sufficiently definite maximum at $E^* \approx 4.5$ mev is observed which confirms the available indications of the existence of a level of Li^6 at ~4.5 mev[4]. This level as well as the level at 2.2 mev should have isotopic spin $T = 0$.

We have not found any (*d*, 2*d*) stars corresponding to higher le vels of the Li^6 nucleus.

2) *Reactions* $Li^6(d, d', p, n)He^4$ and $Li^7(d; t, d')He^4$. Besides stars belonging to the reaction $Li^6(d; 2d)He^4$, we found stars corresponding to reactions $Li^6(d; d', p, n)He^4$ and $Li^7(d;t, d')He^4$

The value of Q for the reaction $Li^6(d;d', p,n)He^4$ is −3.7 mev; hence the decay of the excited Li^6 nucleus formed during the inelastic scattering of a deuteron cannot take place in this case from the level at 2.2 mev. The next level which can be excited by an inelastically scattered deuteron is the level at ~4.5 mev. However, all of the stars observed by us which belong to the reaction $Li^6(d; d', p, n)He^4$ correspond to a previously unobserved level whose energy turned out to be 7.6 ± .3 mev. We have not found any stars corresponding to the level at 4.5 mev.

Figure 4 shows a microphotograph of a star corresponding to the reaction $Li^7(d; t, d')He^4$ which can, apparently take place in two ways*:



*We have also found a small number of stars corresponding to the reaction $Li^7(d; t, p, n)He^4$.

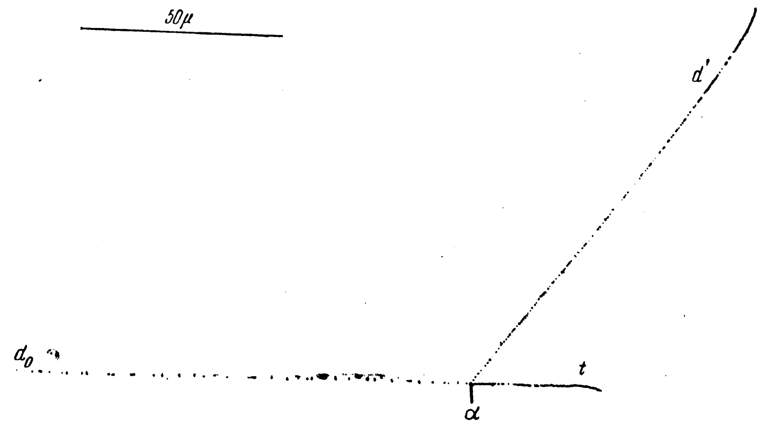


FIG. 4. Microphotograph of a star belonging to the reaction $Li^7(d, t, d')He^4$.

The reaction

$$Li^7 + d \rightarrow t + Li^{6*} \rightarrow \alpha + d$$

allows, obviously, to determine the position of certain levels of the Li^6 nucleus.

As a result of the analysis of stars belonging to this reaction, we have found levels at 2.2 and ~4.5 mev, as well as the level, mentioned above, at ~7.5 mev[*], which was found in studying the reaction $Li^6(d; d', p, n)He^4$. The appearance of levels at 2.2 and ~4.5 mev, belonging to the Li^6 nucleus, is confirmation of the fact that the reaction $Li^7(d; t, d')He^4$ may take place in the manner indicated.

Besides the stars for which the values of E^* are 2.2 ~ 4.5 and 7.5 mev, we found a comparatively small number of stars which cannot be attributed to any of the known levels of the Li^6 nucleus. One may assume that these stars correspond to unknown levels of the Li^6 nucleus or to the second course of the $Li^7(d; t, d')He^4$ reaction. However, the small number of such stars made it impossible to make any definite conclusions in this regard.

In the literature there are indications of the existence of a level of the Li^6 nucleus with isotopic spin $T = 0$ at ~5.4 mev[4]. However, the data obtained by us concerning the reactions $Li^6(d; 2d)He^4$, $Li^6(d; d', p, n)He^4$ and $Li^7(d; d, t')He^4$, do not confirm so far the existence of this level.

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[*] An indication of the existence of this level (private communication) appeared recently in the review of Ajzenberg and Lauritsen, e.g., see Rev. Mod. Phys. 27, 77 (1955).

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