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Excited Level in Li^7 from the $Li^6(d, p)Li^7$ and $Be^9(d, \alpha)Li^7$ Reactions

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An annular magnet has been used to determine the difference in energy of the particles from the $Be^9(d, \alpha)Li^7$ and $Li^6(d, p)Li^7$ reactions. These energies have been measured through a direct comparison with the alpha-particles from polonium, and they serve to determine the energy of the level in Li^7 excited in these processes. The values obtained are 482±3 kev for the $Be^9(d, \alpha)$ reaction and 483±6 kev for the $Li^6(d, p)$ reaction.

I. INTRODUCTION

SIX nuclear interactions are known that lead to the formation of a Li^7 nucleus in a low lying, excited state.[1] This occurs in the case of bombardment of Li^6 by deuterons, the bombardment of Be^9 by deuterons, the bombardment of B^{10} by neutrons, the K-electron capture of Be^7, and the noncapture excitation of Li^7 by protons and alpha-particles. Gamma-rays have been observed to result from each of these processes, and the most recent results place their energy in the neighborhood of 480 kev, although values ranging from 400 to 500 kev have been reported. Except in the case of the Be decay and the noncapture excitation by alpha-particles, two groups of charged particles have been observed to result from each of these reactions; and here also the reported energy of the excited Li^7 nucleus, as determined from measurements on the difference in energy between the particle groups, differs in many cases by amounts exceeding the experimental error assigned to the measurements.

This discrepancy is particularly striking in the case of the $Li^6(d, p)Li^7$ and $Be^9(d, \alpha)Li^7$ reactions. Here, both the incident and emergent particles are charged, and it might be expected that the measurements would be free of the uncertainties that often accompany the determination of gamma-ray and neutron energies. The first reaction was studied by Rumbaugh, Roberts, and Hafstad,[2] who found two groups of protons, the energy separation of which corresponded to an excited state in Li^7 of 455±15 kev. The second reaction was investigated by Graves,[3] who measured the energy difference of the two groups of alpha-particles. This determination led to a value of 494±16 kev for the energy of the excited state. In each of these experiments, the energies of the particle groups were measured in terms of the range-energy relationship for protons and alpha-particles. Graves, in discussing the possibility of reconciling this discrepancy, has concluded that this is not possible without serious revision of the accepted range-energy curve and has suggested that two closely spaced levels of Li^7 may be involved in these various reactions.

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[1] These reactions have been summarized by W. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 191 (1948).

[2] L. H. Rumbaugh, R. B. Roberts, and L. R. Hafstad, Phys. Rev. **54**, 657 (1938).

[3] E. R. Graves, Phys. Rev. **57**, 855 (1940).

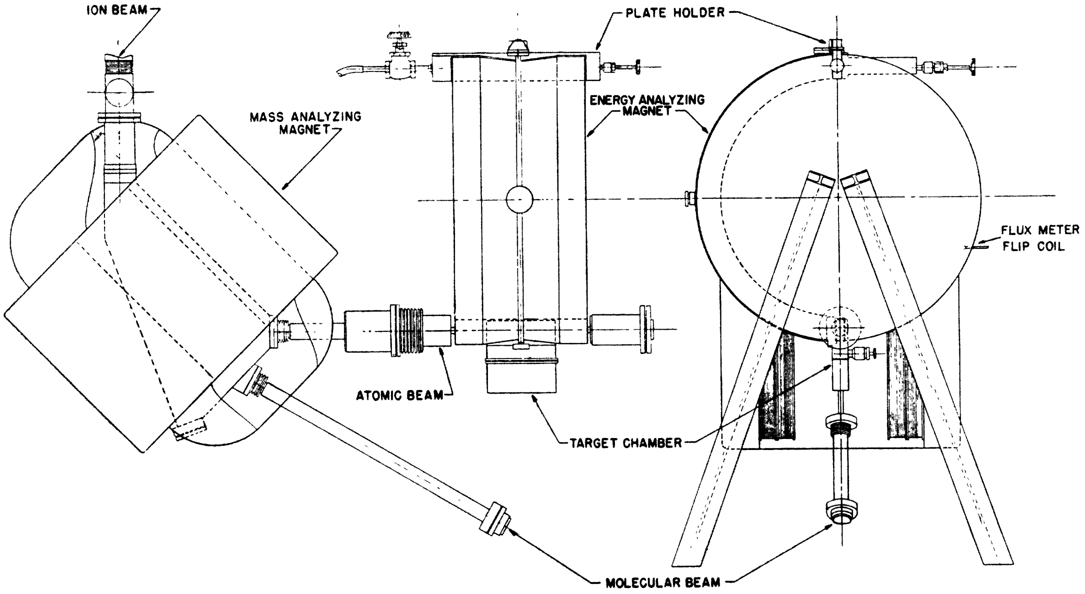

FIG. 1. Schematic diagram of apparatus.

The High Voltage Laboratory of the Institute has recently completed the construction and preliminary testing of a large annular magnet designed especially for the investigation of nuclear energy levels.[4] This magnet is particularly suitable for investigating the energies of protons and alpha-particles in the range of those encountered in the reactions just described. We have used this equipment to study, under as nearly identical conditions as possible, these two modes of the formation of Li^7.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

Certain essential features of the experimental arrangement are shown schematically in Fig. 1. The ion beam from an electrostatic accelerator is first analyzed into its various mass components by a 90-degree deflecting magnet. The diatomic beam that results from this analysis is brought to a focus in the plane of a pair of insulated slit jaws, the currents to which provide a controlling signal for a voltage stabilizer of the corona-spray type. These currents, together with the visual indication obtained from a quartz plate placed behind the slit jaws, also provide a continuous indication of the position of the atomic beam which is brought out in a horizontal extension of the vacuum system at right angles to the direction of the incident beam from the accelerator. This component is brought to a focus on a target located between the poles of a large annular magnet. This magnet is made of Armco iron castings with accurately ground faces and follows closely the essential dimensions of the one designed by Cockcroft[5] and used by Rutherford and his collaborators[6] for the precise determination of the energy of the alpha-particles from natural radioactive substances. It produces a uniform field over an annular region having a mean diameter of 70 centimeters and an annular width of 5 centimeters, the gap between the pole faces being 14 millimeters. The targets are contained in a chamber placed in a 1-inch wide slot cut through the annular region. A slit is placed at the entrance to this chamber to determine the position and define the energy of the beam striking the target. The targets, together with alpha-particle sources for calibrating the magnet, are mounted around the perimeter of a wheel, so that various targets and reactions may be studied without the necessity of opening the vacuum system.

At the far end of the diameter that includes

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[4] Buechner, Van de Graaff, Strait, Stergiopoulos, and Sperduto, Bull. Am. Phys. Soc. **23**, No. 3, 30 (1948).

[5] J. D. Cockcroft, J. Sci. Inst. **10**, 71 (1933).

[6] Rutherford, Wynn-Williams, Lewis, and Boden, Proc. Roy. Soc. **A139**, 617 (1933).

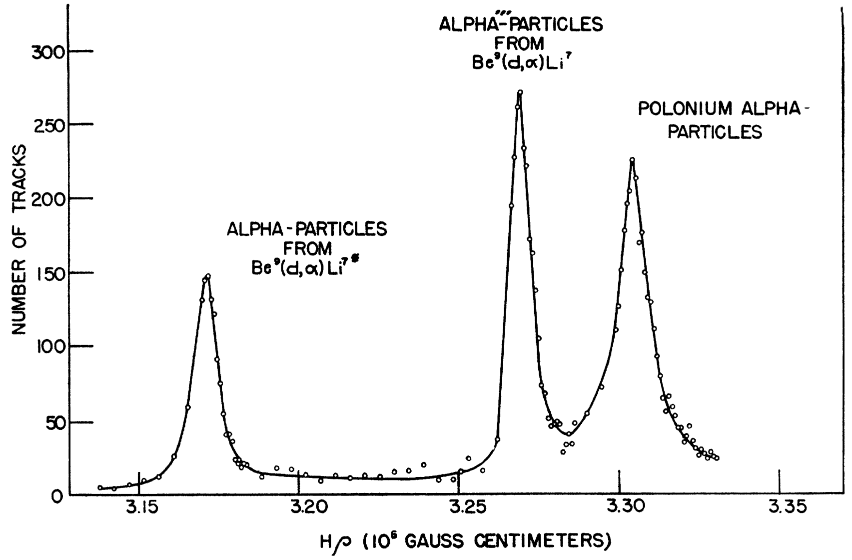

FIG. 2. Alpha-particle groups from $Be^9(d\alpha)Li^7$, together with group from polonium used for determination of analyzing field strength.

the target, a 1-inch wide slot is cut in the magnet to accept a vacuum enclosure, in which a number of 1-inch by 2-inch nuclear-track photographic plates (Eastman NTA plates have been employed in these experiments) are placed. A thin-walled vacuum chamber is placed in the annular region between the pole faces and connects this plateholder with the target chamber. The arrangements within the plateholder are such that each plate in turn may be placed at the exit end of this connecting vacuum chamber, the long axis of the plate lying along the diameter which includes the target. The geometry is such that those charged particles emitted from the target in a direction at right angles to the incident beam pass through the annular field and are brought to a focus on the surface of the plate. The plate is inclined so that the incident particles make an angle of 30 degrees with the emulsion. A fine indexing mark is placed permanently upon each plate when it is in position for exposure, an optical system with slits being employed for this purpose. The distance between these defining slits and the position of the beam on the target is measured with a precision cathetometer, so that measurements on the plates of the distance between the tracks and the index can be accurately translated into radius of curvature in the magnetic field. These measurements are carried out on a mechanical stage of a dark-field binocular microscope.

As the apparatus is normally employed, each plate is exposed at a different magnetic field strength, the incident bombarding voltage being held constant. Thus, each plate covers a certain interval in the energy spectrum of the particles resulting from the reaction, the width of the interval for a particular plate depending upon the field strength at which it was exposed. The field strengths are measured with a sensitive null device that consists essentially of two flip coils coupled together mechanically. One coil is placed in the field of the annular magnet, while the other is mounted within the field of a Helmholtz coil located some distance away. These coils are caused to oscillate in synchronism through 180 degrees about diameters placed at right angles to their respective magnetic fields and are connected in series so that the e.m.f.'s generated are opposite in polarity. A sensitive galvanometer is connected in the circuit through a reversing switch driven by the same mechanical system, the polarity of the galvanometer being reversed at the instant the coils reach the limit of their oscillating motion. Thus, the field strength of the gap is measured in terms of the current through the Helmholtz coil which is necessary to give zero deflection on the galvanometer. The sensitivity of the device is such that, as used at present, full-scale deflection on the galvanometer corresponds to a change in the magnetic field strength of about one part in 1000.

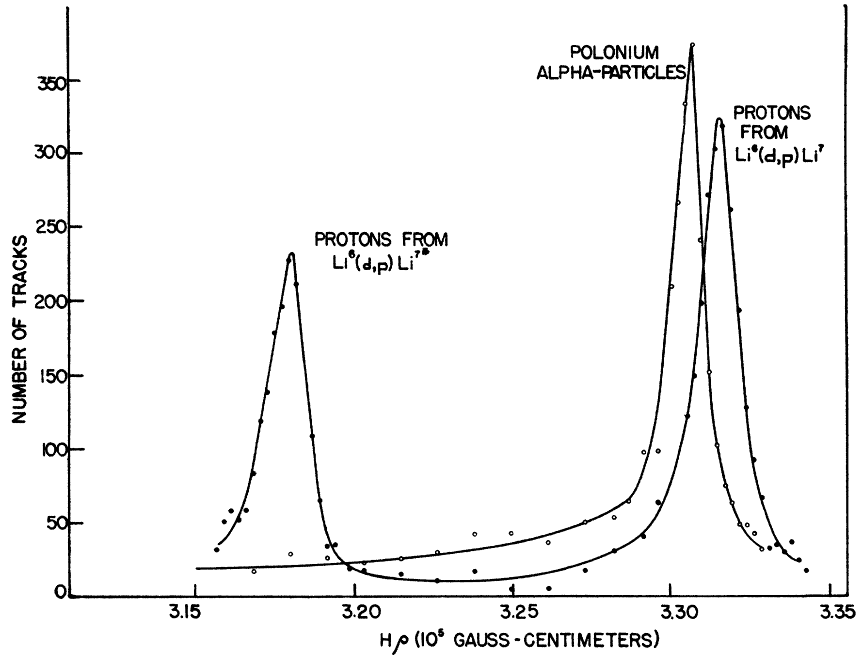

FIG. 3. Proton groups from $Li^6(dp)Li^7$, together with alpha-particles from polonium.

This flux meter is calibrated in terms of the magnetic field strength required to produce a measured deflection of the alpha-particles from polonium, the alpha-particle source being placed in the position normally occupied by the target. With the flux meter calibrated in this way, the annular magnet provides a very convenient and precise method for the determination of the energy of the bombarding proton or deuteron beam. For this purpose, the incident beam is directed onto a thin gold-foil target, and the magnet is used to measure the energy of the elastically scattered particles. This determination can thus be made with an accuracy comparable to that of the determination of the energy of natural alpha-particle groups.

For the purposes of the present experiment, however, neither the flux-meter calibration nor the incident bombarding energy need be determined with any precision, the only requirement being that the analyzing field strength and the bombarding energy be kept constant during a particular run. This results from the fact that for bombarding voltages of the order of 1.3 Mev the particles from both the $Li^6(d, p)$ and the $Be^9(d, \alpha)$ processes are emitted with energies nearly equal to 5.30 Mev, the energy of alpha-particles from polonium. Also, in each case the difference in energy between the particle groups is such that both can be simultaneously recorded on the same plate. Thus, by an appropriate selection of the bombarding voltage and the analyzing field strength, it is possible to obtain on a single plate either the proton groups from the lithium reaction or the alpha-particle groups from the beryllium reaction, together with a calibrating group of polonium alpha-particles for the determination of the magnetic field strength. Since both groups of particles are measured from a single plate, the magnetic field strength for which is accurately known, their energy separations may be determined with high precision without the necessity of assuming linearity of the flux meter or of the determination of the incident bombarding voltage. These energy differences, when corrected for the masses of the interacting particles, give directly the difference in energy between the excited level and the ground state of Li^7. Furthermore, since the data on each group are taken simultaneously and since the measurements are made in terms of differences, various possible complications, such as the effects of surface contaminants, tend to cancel out so as not to affect appreciably the final results.

III. RESULTS AND DISCUSSION

In Fig. 2 we have plotted the distribution of particle tracks along a plate exposed during the bombardment with deuterons of a thin (5 kv) target of beryllium evaporated on a silver backing. The deuteron energy in this case was 1.38 Mev, and the two alpha-groups from the $\mathrm{Be}^9(d, \alpha)$ reaction are clearly resolved. The abscissae are the $H\rho$ values calculated for the individual points, the field strength being determined from the position of the alpha-particles from a polonium source which, subsequent to the bombardment and with the field strength maintained constant, was inserted into the position normally occupied by the target. This calibrating peak is also plotted in the figure. In addition to these alpha-particles, a sharp group of protons was also found on this plate. These result from the $\mathrm{Be}^9(d, p)\mathrm{Be}^{10}$ reaction and are not plotted in the figure.

The energy of each group is taken to be that corresponding to a point on the high energy side of the peak at a height which is one-third the maximum in each case. Numerous experiments have indicated that this point is essentially independent of such variables as target thickness and total exposure, and the selection of this point is in agreement with the results of Rutherford and his collaborators with a similar magnet.[6] Actually, since in these particular measurements the important quantity is a difference in energy between the groups, it is relatively unimportant which point on the peak is selected, and the difference between the value obtained when the top of the peak is employed instead of a point at one-third the maximum is less than the experimental error in the individual determinations.

The difference in energies between the two alpha-particle groups is found to be 307 kev. Using Bethe's 1947 table of masses,[7] we thus obtain 482 ± 3 kev as the energy of the excited state of Li^7 involved in this reaction. The stated experimental error has been arrived at from a consideration of the various experimental factors involved. These include the uncertainty in the determination of the locations of the peaks, the non-uniformities of the magnetic field at the target and the photographic plates, the homogeneity and constancy of the magnetic field, the geometry of the apparatus, and the finite width of the entrance slits. It should be pointed out that, since this is a difference measurement, many of the possible sources of error affect each group in a similar way and thus tend, to a large extent, to cancel out. In these experiments, the first of these factors is by far the most important and limits the determination at the energies of the individual peaks to closer than ±1.5 kev. This leads to ±3 kev as the probable error in the determination of the energy of the level.

These results are in excellent agreement with those of Lauritsen, Fowler, Lauritsen, and Rasmussen,[8] who measured the energy of the gamma-rays resulting from this reaction. Using photoelectrons in a magnetic-lens spectrometer, these authors arrived at a value of 480 ± 10 kev for this energy level. The result also agrees within the experimental error with that of Graves, to which reference has already been made.

In a similar way, the difference in energy between the proton groups resulting from the $\mathrm{Li}^6(d, p)\mathrm{Li}^7$ reaction has been determined. Through the courtesy of Dr. E. L. Hudspeth, we were supplied with a thin Li^6 target which was separated in the Rumbaugh spectrograph at the Bartol Research Foundation by W. J. Scott. Bombardment of this target with deuterons gives the results shown in Fig. 3. Here, the difference in energy between the two proton groups is 422 kev, from which we obtain a value of 483 ± 6 kev for the energy of the Li^7 level excited in this reaction. The exposures for the observation of this reaction were not so high as for the $\mathrm{Be}^9(d, \alpha)$ reaction, and hence the positions of the peaks could not be determined with so high a precision.

This result is not in agreement with that previously quoted, in which proton ranges were employed to measure this energy separation; nor is it in agreement with absorption measurements on the gamma-rays that accompany this reaction.[9] However, the close concordance between this result and that obtained by various methods from the $\mathrm{Be}^9(d, \alpha)$ reaction strongly indicates that only one level of Li^7 is excited in these two

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[7] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).

[8] Lauritsen, Fowler, Lauritsen, and Rasmussen, Phys. Rev. **73**, 636 (1948).

[9] J. H. Williams, W. G. Shepherd, and R. O. Haxby, Phys. Rev. **52**, 390 (1937).

different reactions. This view is strengthened by the agreement of these results with those of Zlotowsky and Williams,[10] Rubin,[11] and Zaffarano, Kern, and Mitchell[12] on the energies of the gamma-rays which result from the capture of orbital electrons by Be^7. These authors obtained values, respectively, of 485±5; 476±10; and 474±4 kev for this excited state of Li^7. Also, Rubin, Snyder, Lauritsen, and Fowler[13] have studied this level though the observation of inelastically scattered protons from Li^7. The result of their determination is 480±2 kev. This is in excellent agreement with preliminary results in this Laboratory on the same process.

Note added in proof: In a recent article, F. N. D. Kurie and M. Ter-Pogossian report a value of 485±5 kev for these gamma-rays [Phys. Rev. **74**, 677 (1948)].

ACKNOWLEDGMENT

We are happy to acknowledge the assistance of the group at the High Voltage Laboratory. We are particularly indebted to Professor R. J. Van de Graaff for his collaboration in the design of the apparatus, and to D. M. Van Patter for development work on the flux meter. This research was assisted by the joint program of the Office of Naval Research and the Atomic Energy Commission.

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[10] I. Zlotowsky and J. H. Williams, Phys. Rev. **62**, 29 (1942).

[11] S. Rubin, Phys. Rev. **69**, 134 (1946).

[12] Zaffarano, Kern, and Mitchell, Phys. Rev. **74**, 105 (1948).

[13] Rubin, Snyder, Lauritsen, and Fowler, Bull. Am. Phys. Soc. **23**, No. 8 (1948).

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Use of Enriched Molybdenum in Cross-Section Measurements of the (p, n): (p, γ) and (d, n): $(d, 2n)$ Reactions

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Molybdenum of natural isotopic composition and molybdenum enriched in isotope 94 were subjected to bombardments with protons and deuterons. After monitoring, and from the saturation intensities and the nature of the decay of the radioactive substances produced, simultaneous equations were set up which yielded the relative values for the reaction cross sections.

For 5-Mev protons, $Mo^{94}(p, \gamma)$: $Mo^{95}(p, n)$: $Mo^{95}(p, \gamma)$: $Mo^{96}(p, n) = 1:260:40:400$. For 10-Mev deuterons, $Mo^{94}(d, n)$: $Mo^{95}(d, 2n)$: $Mo^{95}(d, n)$: $Mo^{96}(d, 2n) = 1:13:17:2.5$. The method is applicable to a wide range of elements.

INTRODUCTION

THE recent availability of enriched isotopes has provided a new approach to the measurement of relative cross sections of nuclei under charged particle bombardment.

The variation of the percent of the isotopic components in the bombarded targets enables one to set up a system of equations, each corresponding to a different activity, with the cross sections as unknowns. If the bombarding beam be properly monitored, these equations can be solved simultaneously to give the relative cross sections, provided that the details of the decay scheme of the resulting radioactive nuclei are known.

The present paper is illustrative of the above method. The relative cross sections for the reactions (p, n) to (p, γ) and (d, n) to $(d, 2n)$ leading to the 20-hour Tc^{95} and the 4.3-day Tc^{96} activities are measured by using natural molybdenum and enriched $Mo^{94}O_3$.**

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** Supplied by the Y-12 plant, Carbide and Carbon Chemicals Corporation, through the Isotopes Division, U.S.A.E.C., Oak Ridge, Tennessee.