

Two-neutron emission in the absorption of stopped pions on lithium isotopes

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The $(\pi^-, 2n)$ reaction on ${}^6\text{Li}$ and ${}^7\text{Li}$ nuclei has been studied in a kinematically complete experiment. Distributions of excitation energy of residual nuclei, of recoil momentum, and of angle spanned by relative and c.m. momenta of emitted neutrons have been extracted. The reaction mechanism has been investigated through a comparison with theoretical predictions.

NUCLEAR REACTIONS $(\pi^-, 2n)$ on ${}^6\text{Li}$ and ${}^7\text{Li}$, $E=0$ measured rate (En_1, En_2, ω) ; excitation spectra for residual nuclei deduced, recoil momentum distributions and correlations of relative and c.m. momenta of emitted neutrons extracted.

I. INTRODUCTION

The absorption of stopped π^- followed by an emission of two neutrons has been experimentally studied in detail on ${}^9\text{Be}$, ${}^{10}\text{B}$, and ${}^{12}\text{C}$,¹ and on ${}^{14}\text{N}$.² The results have shown a dominance of quasifree mechanism for the transitions to the lower excited states of the residual nuclei. The data, however, cannot be directly compared with a theory since no calculation takes into account simultaneously a proper description of the pion absorption dynamics and realistic wave functions for the absorbing and the residual nucleus. Still, a comparison with other reactions like (p, pd) or with fractional parentage coefficients (cfp) calculated with a realistic interaction allows, to a certain extent, the analysis of the transitions to lower excited states in which only surface (p -shell) nucleons take part. This situation, however, makes the analysis of the events corresponding to higher excitations difficult. The possible interpretations of these events are (1) direct mechanism involving s -shell nucleons, and (2) nondirect mechanism involving more than two p -shell nucleons. Even a nucleus as light as ${}^9\text{Be}$ has five p -shell nucleons, which makes studying these effects separately difficult.

The structure of the lithium isotopes, especially ${}^6\text{Li}$, is far better studied than other $1p$ -shell nuclei, and their wave functions are reliable. They also contain only a few p -shell nucleons; one n - p combination in ${}^6\text{Li}$ and two in ${}^7\text{Li}$. In the $(\pi^-, 2n)$ reaction, transitions to the levels higher

than ground state in the case of ${}^6\text{Li}$, and transitions to the levels higher than the first excited state in ${}^7\text{Li}$, certainly involve s -shell nucleons. Also, the small number of outer shell nucleons reduces the complexity caused by the distortion effects that accompany the s -nucleon absorption.

Another interesting aspect of the lithium isotopes is their clustering property. These nuclei are known to show d - α and t - α clustering behavior. One can study the π^- absorption on t or α cluster by using these nuclei as a target instead of the free ${}^3\text{H}$ or ${}^4\text{He}$ target. Because of the fact that after the emission of two neutrons the residue of the affected cluster is bound to the other cluster, the absorption by an n - p pair in different quantum states leads to different states of the residual nucleus. Therefore, by using information on the properties of excited states, the relative population of residual excited states can provide information about the quantum state of the absorbing n - p pair. It is much more difficult, and requires polarization measurements, to obtain experimentally the same kind of information by using free ${}^3\text{H}$ or ${}^4\text{He}$ targets.

II. THEORETICAL CONSIDERATION

Figure 1 shows the kinematical variables used in this paper.

In the quasifree description of the $(\pi^-, 2n)$ reaction, we assume that the pion is absorbed by a neutron-proton pair in the target. In the initial state, the angular momentum of the pair's center

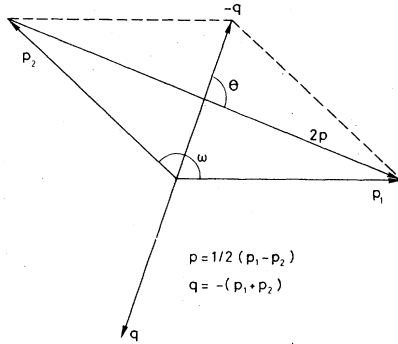


FIG. 1. Kinematical variables used in this paper.

of mass and of each nucleon with respect to the target's center of mass are L , l_1 , and l_2 , respectively. The total angular momentum Λ is written as $\Lambda = l_1 + l_2 = L + l$, where l denotes the relative angular momentum of the nucleons. The relationship between the quantum numbers L , l , and the principal quantum numbers N and n , associated with the c.m. motion and the relative motion of the two nucleons, and the dependence of the differential rate on q , the recoil momentum (q distribution), is already discussed in Ref. 1.

The importance of the rate dependence on the angle θ (θ distribution) has been pointed out by Koltun.³ He treated this problem very generally, showing that the θ distribution can be expressed as a sum of Legendre functions. The θ distribution has been measured on ^9Be , ^{10}B , and ^{12}C targets for different final states.¹ They are very often almost isotropic. It can be shown that under certain conditions, the assumption of a direct quasifree mechanism implies isotropic θ distributions for a π -nucleon interaction operator expressed as

$$\Theta = \nabla_{\pi} - a \nabla_N. \quad (1)$$

In the Galileian invariant interaction,

$$a = \mu/M,$$

where M and μ are the mass of nucleon and pion respectively and in the static approximation

$$a = 0.$$

Neglecting the final-state interactions, the nuclear part of the matrix element for the pion absorption is written as

$$\langle e^{i\vec{p} \cdot \vec{R} + i\vec{q} \cdot \vec{R}} | \Theta | \sum \psi_{NL}(\mathbf{R}) Y_{LM}(\hat{\mathbf{R}}) \psi_{nl}(\mathbf{r}) Y_{lm}(\hat{\mathbf{r}}) \rangle, \quad (2)$$

where $\psi(\mathbf{R})Y(\hat{\mathbf{R}})$ and $\psi(\mathbf{r})Y(\hat{\mathbf{r}})$ are the initial state wave functions describing the c.m. and relative motion of the two nucleons, respectively. In the

expansion of plane waves for the c.m. and relative motion in the final state, the spherical harmonics for the angles of p and q are functions of the angle between p and q , that is, θ . The term ∇_{π} and ∇_N in the operator Θ correspond to the pion absorption from the P and S orbits.

If pions are restricted to being absorbed from the P orbit, the gradient operator does not play any role in the nuclear part of the matrix element. The quantization axis is chosen to be the direction of either p or q . The angular part of the amplitude is expressed as

$$\sum a_L Y_{LM}(\hat{q}) \text{ or } \sum b_l Y_{lm}(\hat{p}). \quad (3)$$

And hence the distribution is

$$\sum_M \left| \sum_L a_L Y_{LM}(\hat{q}) \right|^2 \text{ or } \sum_m \left| \sum_l b_l Y_{lm}(\hat{p}) \right|^2. \quad (4)$$

The θ distributions are isotropic as long as the initial state of the two nucleons is well described by the wave functions with a definite single value of either L or l , since

$$\sum |Y_{LM}(\hat{q})|^2 = \sum |Y_{lm}(\hat{p})|^2 = 1. \quad (5)$$

If the absorption occurs from the S orbit, the choice of the quantization axis to be the direction of q gives the angular part of p proportional to

$$\sum b'_l Y_{l+1, m'}(\hat{p}) + \sum b''_l Y_{l-1, m''}(\hat{p}) \quad (6)$$

if ∇_N operates on the relative motion of the two nucleons. The θ distribution becomes isotropic only in the case of $l=0$. When the quantization axis is chosen to be the direction of p , the angular part of q is

$$\sum a_L Y_{LM}(\hat{q}), \quad (7)$$

which gives an isotropic θ distribution if the state is well described by a single value of L . Therefore, when the gradient operator ∇_N in (1) acts on the relative motion of the two nucleons, it is convenient to choose the direction of p as a quantization axis. The dependence of the amplitude on the angle between p and q is given by the spherical harmonics for q ,

$$\sum a_L Y_{LM}(\hat{q}) \quad (8)$$

in the matrix element (2). Thus the θ distribution is isotropic for the pion absorption by two nucleons whose states are well described by a definite single value of L .

When the gradient operator ∇_N acts on the c.m. motion of the two nucleons, the direction of q is

chosen to be the quantization axis, and the dependence on the angle between \hat{p} and q is given by

$$\sum b_l Y_{lm}(\hat{p}) \quad (9)$$

in the matrix element (2). The θ distribution is isotropic for absorption from the P and S orbits as long as the initial state of the two nucleons is well described by a single value of l . The gradient operator acting on the c.m. motion of the two nucleons leads to the angular momentum change $\Delta L = 1$ between the initial and final states. The nuclear Fermi motion, however, does not provide enough momentum to cause such a change when the pion momentum is small compared to q , which is the case for the absorption from the atomic bound state in light nuclei. Thus absorption due to the c.m. motion of the two nucleons is not likely to occur.

In conclusion, the θ -distribution should be isotropic if $l=0$ or if the initial nuclear state is single-valued in L . This condition is satisfied in almost all cases, however, since the strongly interacting nucleon pair absorbing the pion is generally in relative s state. Even if this is not the case, the fact that our θ distributions consist of events having limited q values (see Sec. III) drops the contribution of higher L 's leaving only the smallest L , even if the initial state consists of several different L 's.

The fact that the measured θ distributions are often almost isotropic supports therefore the dominance of the direct quasifree mechanism.

III. EXPERIMENTAL PROCEDURE

Negative pions of 70 MeV from the CERN Synchrocyclotron (SC) low-energy pion channel were stopped in enriched ${}^6\text{Li}$ and natural lithium targets of $\sim 3 \text{ g/cm}^2$.

The details of the experimental setup as well as the data handling are described in Ref. 1. A neutron flight path of 5.8 m has been chosen for both neutron counters. This long flight path allowed us to measure the excitation energy of the residual nuclei with a resolution of 4.5 MeV FWHM for the ground states, and with better resolution for higher excited levels.

The target telescope consisted of counters CI, CII before a Teflon degrader, counter CIII, a hodoscope and counter CIV before the target, and CV, a large counter behind the target. The events were triggered by (I.II.III. hodoscope. IV.V) coincidence signals. All the counters were plastic scintillators. The thin counter CIV, 0.5 mm thick, served to reject events from pions stopping in the hodoscope. Nevertheless, a carbon contamination

from CIV and CV cannot be completely excluded and thus had to be considered in the data analysis. Also, events from ${}^7\text{Li}$, the residue of the enriched ${}^6\text{Li}$ target, and events from ${}^6\text{Li}$ contained in the natural lithium target are recognized as small contaminations in the ${}^6\text{Li}$ and ${}^7\text{Li}$ data, respectively.

The data have been corrected for geometrical acceptance in our ω range between 154° and 180° by taking into account the shape of the counters. Within the experimental limitations ($E_{\text{kin}} > 15 \text{ MeV}$, $\omega > 154^\circ$) the data are free from geometrical bias and can be directly compared with the theory. The recoil momentum (q -) distributions are obtained by dividing the corrected rate by the three-body phase-space factor. For the θ distributions, q has been restricted to values for which there is no reduction in phase space caused by our restricted ω range. In all figures, the errors given are statistical.

IV. RESULTS AND DISCUSSION

${}^6\text{Li}$

Figure 2(a) shows the measured excitation spectrum of the residual nucleus ${}^4\text{He}$. Two well-separated peaks, a narrow one corresponding to the ground state, and a much wider one between $E_x = 20$ and 40 MeV, are clearly seen. Calligaris *et al.*⁴ already reported this gross structure. For the first time, however, the broader peak provides indications of fine structure.

The experimentally known excited levels of ${}^4\text{He}$ are listed in Table I together with their spin, parity, and isospin. All of them are particle unstable and therefore have a large width except for the 20.1 MeV level. A detailed comparison of the observed structure and the known levels is rather difficult within the experimental energy resolution. Nevertheless, the following statements can be made:

- (i) The $0^+(T=0)$ state at 20.1 MeV does not seem to be strongly populated.
- (ii) Although a possible ${}^{12}\text{C}$ contamination makes the determination difficult, the population of the 0^- and 2^- states (both $T=0$) at 21.1 and 22.1 MeV is, at most, rather small.
- (iii) The positive parity state at 25.5 MeV ($T=0$) seems to be strongly populated.
- (iv) At least one negative parity $T=1$ state between 26.4 and 30.5 MeV is rather strongly populated.
- (v) Higher excited states (known or unknown) up to 40 MeV are also populated.

A comparison between the excitation energy spectrum in Fig. 2(a) and the one in Fig. 2(b) containing only events with large recoil momenta

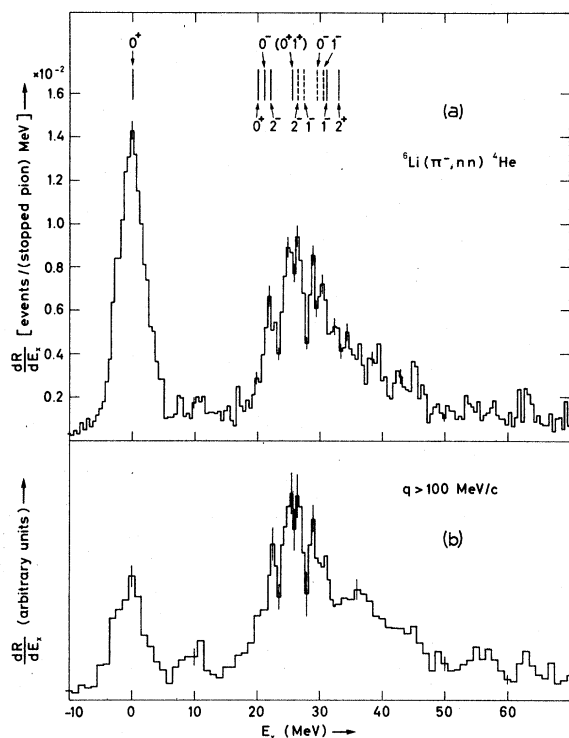


FIG. 2. Excitation energy spectra of ${}^4\text{He}$. (a) All data (positions and quantum numbers of the known levels are also indicated). (b) Events with large recoil momenta.

reveals that the ground state transition is much more concentrated at smaller recoil momenta than are the transitions to excited states. (The small peak at ~ 9 MeV is due to the residual ${}^7\text{Li}$.) The shape of the excitation spectrum in the region $E_x = 20 \sim 35$ MeV is quite similar in both parts of Fig. 2. This means that the transitions to the excited states have similar recoil momentum dependence.

TABLE I. Experimentally known excited states of ${}^4\text{He}$ nucleus (from Ref. 5).

E_x	J^π	T
20.1 MeV	0^+	0
21.1	0^-	0
22.1	2^-	0
25.5	$(0^+ 1^+)$	0
26.4	2^-	1
27.4	1^-	1
29.5	0^-	1
30.5	1^-	1
31.0	1^-	0
33.0	2^+	0

A. Ground state transition

In a cluster model description, the ground state transition corresponds to the absorption of the π^- by a 3S_1 deuteron cluster (p -shell nucleons) bound to a ${}^4\text{He}$ cluster (s -shell nucleons). The intercluster motion is $2s$ state. The recoil momentum distribution (q distribution) for the ground state transition is shown in Fig. 3. It confirms an $L=0$ transition having its maximum at $q=0$ MeV/ c . The very small width (HWHM ~ 45 MeV/ c) is due to the small separation energy of the two clusters. According to Sakamoto *et al.*,⁶ a strong cancellation occurs in the π^- absorption rate at small radii due to the node in the $2s$ state intercluster wave function, and this effect also reduces the width of the q distribution. Because of such a cancellation, a simple calculation by Sakamoto *et al.* using a square well potential for the intercluster motion gives a good fit to the measured q distribution as shown in Fig. 4. The harmonic oscillator wave function, having poor asymptotic behavior at large radii, gives too broad a distribution. It should be noted that the q distribution in Fig. 4 is not directly comparable with the q distributions obtained from (x,xd) quasifree knock-out reactions on the same target. In the case of the $(\pi^-, 2n)$ reaction, the deuteron cluster also

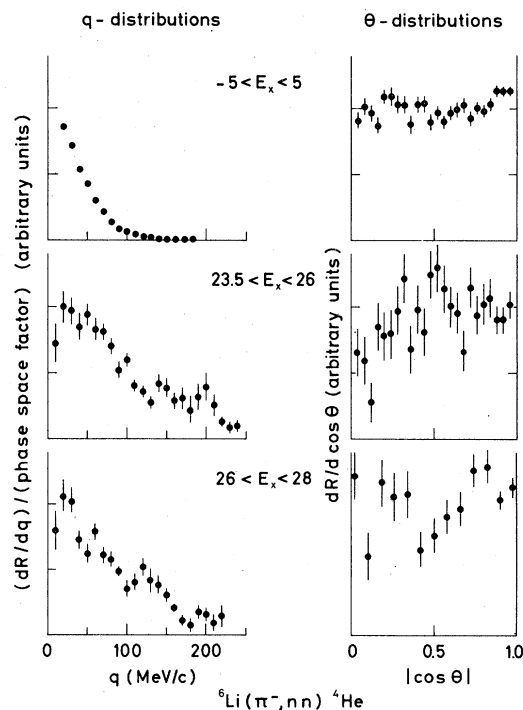


FIG. 3. q and θ distributions for different regions in excitation energy of ${}^4\text{He}$.

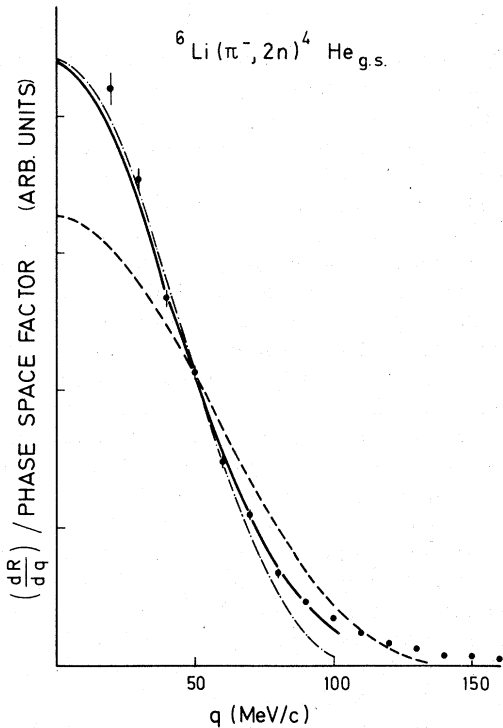


FIG. 4. Measured q distribution for the transition to the ground state of ${}^4\text{He}$. The solid line is a theoretical curve from Ref. 6 (2s motion in a square well potential). The dashed and dot-dashed curves are calculated for 2s motion in a harmonic oscillator potential. See also text.

breaks up. This affects the q distribution since q and the relative momentum of the two nucleons in the deuteron cluster p are correlated because of energy conservation. The above mentioned square well function giving a good fit to the present data gives 32 MeV/c HWHM of the q distribution for (x, xd) reactions, which is the absolute value squared of the Fourier transform. This agrees well with existing experimental data^{7,8} in which the distortion effect is small.

The θ distribution for this transition, also shown in Fig. 3 along with the transitions to excited levels, will be discussed later.

The measured ω distributions integrated over excitation energy for the ground state and for excited states are shown in Figs. 5(a), 5(b), and 5(c) respectively. The ground state transition, exhibiting a strong peaking towards 180° , indicates the dominance of the quasifree reaction mechanism.

The ω distribution involves a combined effect of q and θ distributions. Many authors have calculated ω distributions. Most of them used a harmonic oscillator function for the intercluster

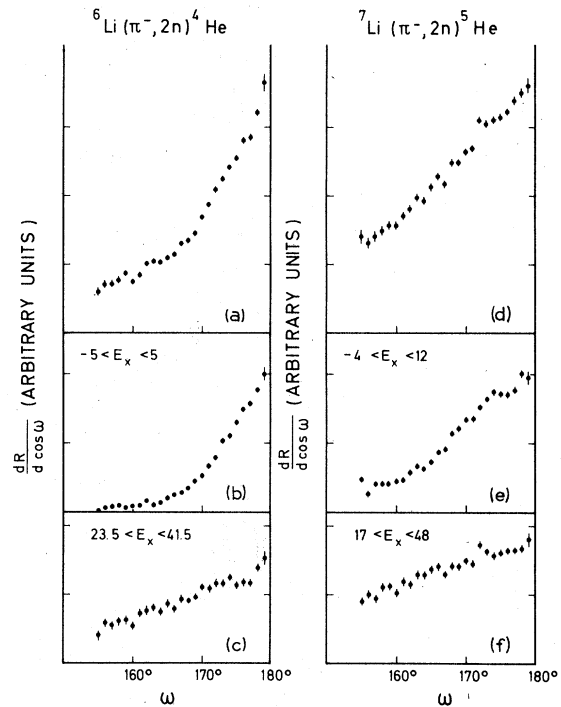


FIG. 5. ω distribution integrated over all excitation energies (a) and (d), and for different regions in excitation energy (b), (c), (e), and (f) of ${}^4\text{He}$ and ${}^5\text{He}$, respectively.

motion which, we have seen, gives a bad fit to the q distribution. It is therefore not surprising that none of the existing calculations give a good fit to the data. In Fig. 6, our data are compared with theoretical predictions which did not use shell model wave functions. One is from Jain and Banerjee,⁹ who use the Wood-Saxon potential for the intercluster motion. They include the distortion effect, but the width of the calculated ω distribution is too large. The ω distribution for the ground state transition is better fitted by Alberi and Taffara.¹⁰ They use a very simple exponential type $\alpha - d$ relative wave function, and they do not include the distortion effect. The ground state θ distribution shows isotropy (see Fig. 3). This means that the q and ω distribution are directly correlated. Finally, Kopaleishvili and Machaveli¹¹ calculated only the ω distribution integrated over the whole E_x range by using an $\alpha - d$ model and the shell model. In both cases the fit is not satisfactory; their calculation using a harmonic oscillator function gives a ω distribution that is far too wide.

The data for the ground state transition are displayed in Figs. 7(a) and 7(b) in terms of the

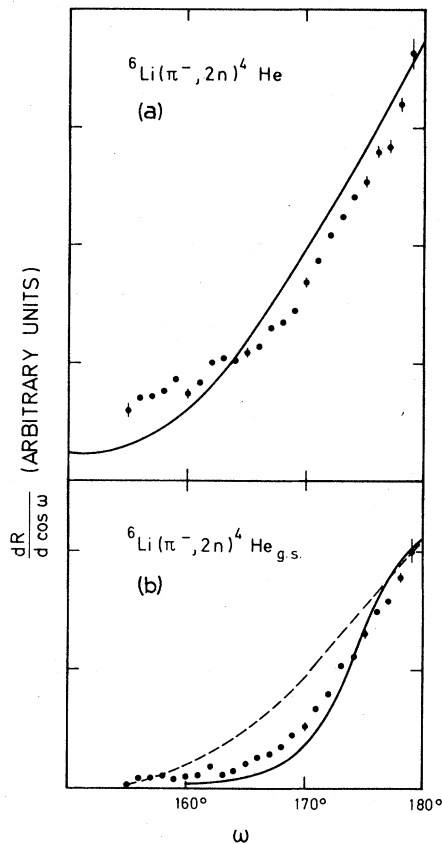


FIG. 6. ω distributions for the residual nucleus ${}^4\text{He}$. (a) All events; the solid line is a theoretical curve from Ref. 11. (b) Events from the transition to the ground state; the solid curve is from Ref. 10 and the dashed one from Ref. 9.

E_n and p distributions. Reflecting the very narrow q distribution, E_n and p distributions both show a narrow peak. The E_n distribution is centered at half of the Q value for the reaction, and the peak is symmetrical because the two emitted particles are identical. The value of p is restricted to a very limited range, which is expected because of energy conservation and because of the small value of q .

In summarizing the ground state transition, it can be said that all distributions indicate clearly the dominance of the direct quasifree reaction mechanism. Even relatively simple theoretical calculations seem to give a qualitative agreement with the measured q distribution.

B. Transitions to the excited states

In the quasifree picture, these transitions correspond to a removal of either two nucleons from the s -shell α cluster (s^{-2}), or one from the s - and

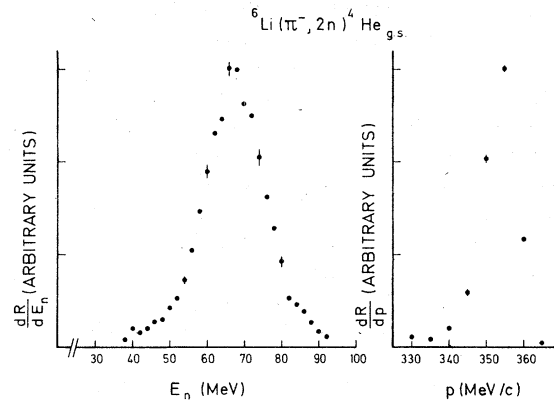


FIG. 7. E_n and p distribution for the transition to the ground state of ${}^4\text{He}$.

the other from the p -shell deuteron cluster ($s^{-1}p^{-1}$). As the relative momentum of the two emitted nucleons must be large, the main contribution to the absorption comes from the short-distance part of the two-nucleon relative wave function in the initial state. With the separation energy of the two clusters being very small, the intercluster wave function is widely spread in space. For this reason, the $s^{-1}p^{-1}$ absorption might be suppressed. In fact Golovanova and Zelenskaya¹² predict a ratio of 1:0.2:1.5 for p^{-2} (ground state) : $s^{-1}p^{-1}$: s^{-2} absorption.

The 0^- and 2^- levels at 21.1 and 22.1 MeV are known to have a s^3p^1 configuration. The population of these levels in the $(\pi^-, 2n)$ reaction corresponds to removing an n - p pair in $\Lambda = 1$, $T = 0$ state. Both levels are populated in the ${}^6\text{Li}(p, {}^3\text{He}){}^4\text{He}$ reaction at 43.7 MeV¹³ which indicates that the cfp is not small. Therefore, the weak population of these levels in the $(\pi^-, 2n)$ reaction seems to support the above argument and the prediction of Golovanova and Zelenskaya.

The 20.1 MeV 0^+ state is only weakly populated in both $(p, {}^3\text{He})$ and $(\pi^-, 2n)$ reactions. This probably means that there is very little 0^+ (20.1 MeV) component in the ${}^6\text{Li}$ ground state, which agrees with the predominant $(1s^{-1})(2s)$ configuration proposed for this level (see Ref. 5).

The 25.5 MeV ($0^+, 1^+$) $T = 0$ state is 1.7 MeV above the $d + d$ threshold. Haase *et al.*¹⁴ have clearly observed this level in the ${}^6\text{Li}(d, \alpha d){}^2\text{H}$ reaction and weakly observed it in both ${}^6\text{Li}(\alpha, \alpha t){}^1\text{H}$ and ${}^6\text{Li}(\alpha, \alpha {}^3\text{He})n$ reactions. They interpret this level as a state having a d - d structure. In such a case, the strong transition probability to this level in the present reaction can be easily understood because it corresponds to an s^{-2} absorption. The measured q distribution clearly indicates

$L=0$, which is consistent with the above interpretation. The width of the distribution is about 100 MeV/c. The s^{-2} might be suppressed in heavier $1p$ -shell nuclei due to either the distortion effect or to any possible surface absorption effect of π^- . Only two p -shell nucleons are found in ${}^6\text{Li}$, thus these effects are probably weaker.

In the energy range of 21 to 28 MeV, Burman and Nordberg¹⁵ interpreted their data from the analogous $(\pi^-, 2p)$ reaction as preferential excitation of $T=1$ negative parity states. At that time, however, no positive parity level in ${}^4\text{He}$ between 21 and 28 MeV was known. At present, only negative parity $T=1$ states are known between 26.4 and 30.5 MeV. On this basis, one might conclude that at least one negative parity $T=1$ state is rather strongly populated. This statement, however, contradicts the argument against a $s^{-1}p^{-1}$ transition, since in the quasifree mechanism only $s^{-1}p^{-1}$ absorption can lead to a negative parity state. There is also an additional difficulty with a quasifree $s^{-1}p^{-1}$ absorption mechanism.

It was seen that to remove one p - and one s -shell nucleon to populate 21.1 or 22.1 MeV negative parity states one needs about 25 MeV, the separation energy corresponding to these states. To remove two s -shell nucleons to populate the 25.5 MeV level, one needs 29 MeV. The excitation energy of the observed negative parity $T=1$ state is about 29 MeV, which corresponds to a total separation energy of 33 MeV. From the simple shell model point of view, this is too large for an sp pair. Furthermore, the q distributions of this E_x region shown in Figs. 3 and 8 are very similar to the one for the 25.5 MeV level region, indicating no admixture of an $L=1$ component, which would be expected for the $s^{-1}p^{-1}$ absorption.

A possible alternative interpretation is as follows. The π^- is absorbed by the two nucleons in p shell. Then one of the neutrons emitted with an average energy of 67 MeV interacts with the core in the ground state and excites it. If this interpretation is correct, the population of the excited levels should be similar to the one observed in the ${}^4\text{He}(n, n'){}^4\text{He}^*$ reaction around 67 MeV. The reaction ${}^4\text{He}(p, p'){}^4\text{He}^*$ has been studied at 55 MeV by Hayakawa *et al.*¹⁶ and at 100 MeV by Goldstein *et al.*¹⁷ In the former measurement, where the experimental resolution is better and is about 1 MeV, many levels were observed between 20 and 35 MeV. The angular distribution $\sigma^*(\theta_{lab})$ is peaked at 30 to 50 degrees. The interacting neutron loses its kinetic energy in exciting the core (α) and also changes its direction. According to this picture, the originally narrow q distribution (the pion was absorbed by the two p -shell nucleons) will be significantly widened by

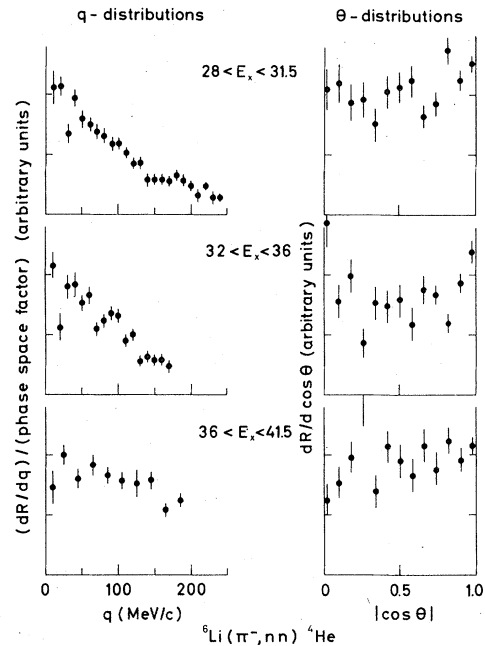


FIG. 8. q and θ distributions for different regions in excitation energy of ${}^4\text{He}$.

this effect. It is difficult to judge the significance of this mechanism, however, from the measured q distributions shown in Figs. 3 and 8. The energy distributions of the emitted neutrons corresponding to different E_x regions are shown in Fig. 9. If the excitation of the core is entirely due to the secondary interaction of one of the emitted neutrons, the other neutron should leave the system with a kinetic energy of about 67 MeV. In fact, all the E_n -distributions in Fig. 9 exhibit a shoulder at 70 MeV and then drop quickly. We do not consider this to be enough evidence for the significance of this mechanism, however.

The θ distributions for the excited state transitions are shown in Figs. 3 and 8. Generally, they exhibit isotropy. From the discussion in Sec. I, this fact agrees with the quasifree mechanism being dominant for the excited state transitions, too.

The p distributions for these transitions are shown in Fig. 9. As is the case with the ground state transition, the value of p varies little. Therefore, the information about the correlation effect might be derived from the absolute rate, but not so much from the p distribution.

To compare the present data with calculations, one needs information on the relative population of different atomic orbits from which the pion is absorbed. Bassalleck *et al.*¹ have observed, however, that given the present experimental uncer-

tainties, the relative population of final states in $1p$ -shell nuclei is quite similar for the same q range in the $(\pi^+, 2p)$ reaction at low energies and in the $(\pi^-, 2n)$ reaction. If charge independence holds, the main difference between these two reactions is that in the former case, π^+ is in a scattering state, and in the latter, π^- is bound. In heavier $1p$ -shell nuclei, π^- is believed to be absorbed mostly from the $2P$ orbit, whereas in the case of π^+ , the relative contribution of S/P is almost equal to the ratio S wave/ P wave in the plane wave. For ${}^6\text{Li}$, the present excitation spectrum is very similar to the one obtained by Favier *et al.*¹⁸ and by Arthur *et al.*¹⁹ for π^+ at 70 MeV. Together with the observations made with heavier targets, this suggests that the relative population of the levels is independent of the orbit from which the π^- is absorbed. (Of course it is true only when the transition is not forbidden by angular momentum conservation.) In fact, it can be shown that if one assumes a quasifree mechanism and π -nucleon interaction as discussed in Sec. II, the radial part of the matrix element for the absorption from the S orbit is identical to that for the P -orbit ab-

sorption except for a factor p (see Appendix). This means that the absorption from the S orbit gives rise to excitation spectra similar to those obtained from the P -orbit absorption, apart from the spin-isospin selection rule, which can be different for the P - and S -pion absorptions. This also explains the fact that the excitation spectra of the residual nucleus obtained from the absorption of stopped pions are similar to those for low energy pions in flight.

Finally, Fig. 5(c) shows the distribution of the opening angle ω for the region of high excitation energies. It is still peaked at 180° , but it is much wider than the ground state distribution. As the θ distributions are generally isotropic, a wider ω distribution is directly related to the wider q -distributions.

${}^7\text{Li}$

Figure 10 shows the measured excitation spectra without and with limitation on the recoil momentum q . Like ${}^6\text{Li}$, the spectrum consists of two groups of events, one corresponding to removing p -shell nucleons only and the other involving the removal

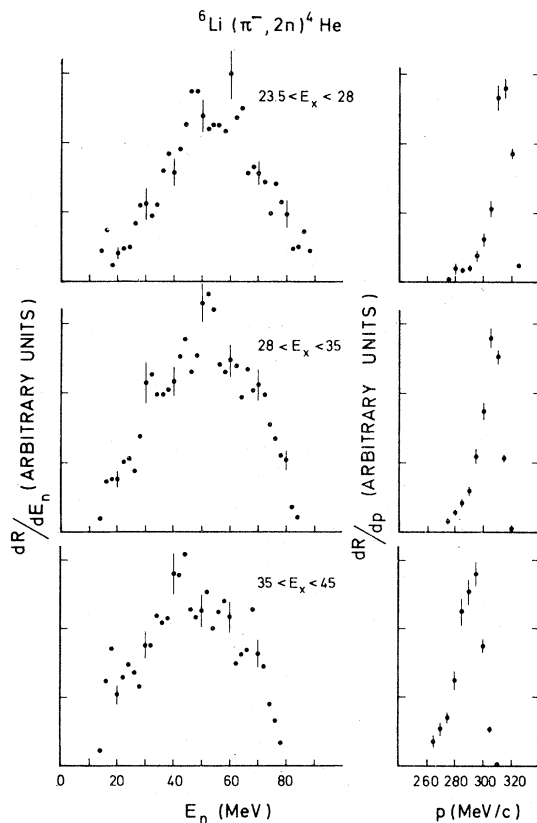


FIG. 9. E_n and p distributions for different regions in excitation energy of ${}^4\text{He}$.

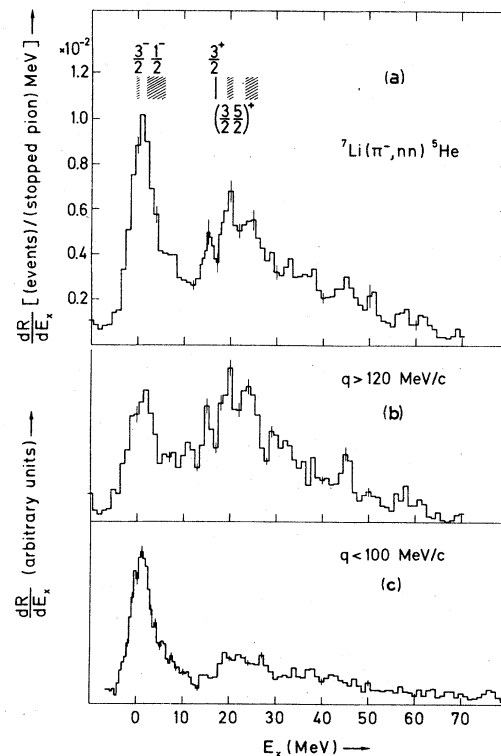


FIG. 10. Excitation energy spectra of ${}^5\text{He}$. (a) All data (positions, widths and quantum numbers of the known levels are also indicated). (b) and (c) events involving restrictions on recoil momentum.

of s -shell nucleons. The same gross structure was already observed in the analogous $(\pi^+, 2p)$ reaction^{18, 19} but not in the existing data^{20, 4} for the present reaction.

Removing an n - p pair from the $1p$ shell leads to ${}^5\text{He}$ in the ground state ($\frac{3}{2}^-$) and the first excited state ($\frac{1}{2}^-$). They are both populated in the present data. For the higher excited states, only three levels are experimentally established.²¹ A possible ${}^{12}\text{C}$ contamination would be peaked at $E_x \sim 15$ MeV. This makes the precise evaluation of the transition to the $\frac{3}{2}^+$ level at 16.76 MeV difficult. Since this level is narrow, however, it is certainly not strongly populated. At the position of the known levels, 19.9 MeV and 25 MeV, we observe two maxima. Also, a rather large number of events leads to excited states higher than 30 MeV, but no separated peaks are seen.

A comparison of Figs. 10(b) and 10(c) shows that the transitions to the ground and first excited state of ${}^5\text{He}$ are connected with smaller q values than the transitions to higher states. This is the same behavior as in ${}^6\text{Li}$, though it is less pronounced. The structure at high excitations in Fig. 10 is similar in all three spectra, indicating similar q dependence for all the high excited states.

A. Ground and first excited state transitions

The success of cluster model calculations²² as well as the experimental results on (p, pt) ²³ and $(\alpha, 2\alpha)$ ²⁴ quasifree scattering and on the $(p, 2d)$ reaction²⁵ indicate that the ground state of ${}^7\text{Li}$ is well described by an α - t system with relative angular momentum $\mathcal{L} = 1$. The triton spin $\frac{1}{2}$ is parallel to \mathcal{L} to form $J^\pi = \frac{3}{2}^-$.

In this model, one n - p pair with antiparallel and one with parallel spin are found in the triton cluster. Removing the pair in the antiparallel spin state leaves a neutron in the p shell with spin parallel to \mathcal{L} , thus forming the ground state ${}^5\text{He}(\frac{3}{2}^-)$. The population of this level is proportional to

$$R_t + fR_s,$$

where R_t and R_s denote spin triplet ($T = 0$) and singlet ($T = 1$) absorption rates and f the fraction of the π^- absorbed from atomic S orbit. The absorption of a π^- from P orbit by a nucleon pair in singlet ($T = 1$) state is almost forbidden as the slowly moving pion brings almost no angular momentum to the nucleon pair.³ This is also experimentally supported by the fact that $T = 0$ absorption is dominant in heavier $1p$ -shell nuclei where the pion is mainly absorbed from the $2P$ atomic or-

bit.^{4, 2}

On the other hand, removing the n - p pair in the parallel spin state leaves the neutron with spin antiparallel to \mathcal{L} , thus giving ${}^5\text{He}$ in the first excited state ($\frac{1}{2}^-$). The population is proportional to

$$R_t.$$

Therefore, from the ratio of the population of the ground state to that of the first excited state expressed as

$$r = 1 + f \frac{R_s}{R_t},$$

one can calculate the ratio R_t/R_s if the fraction f is known. If the spatial part of the triplet and singlet pair in the triton cluster are assumed to be similar, this ratio can be related to the relative strength of the $T = 0$ and $T = 1$ part of the absorption operator. On the other hand, if theoretical considerations indicate that the ratio of the operator strength is unity, then the ratio R_t/R_s supplies information about the difference of the spatial part of nucleon pairs in triplet and in singlet state.

Historically, in order to obtain the same kind of information, many authors have worked with the ratio of the rates for the two reactions:

$$W(\pi^-, 2n)/W(\pi^-, np).$$

The experimentally obtained ratio varies, however, from 3 to 10 depending on the author.²⁶ Several calculations have been performed to explain the data, including final state interactions, differentiating the short range part of the pair in $T = 0$ and $T = 1$ state, or relative s -wave or p -wave absorption, etc.²⁷ This quantity is very difficult to obtain experimentally because the efficiency of the detection system, including the multiple scattering effect of the protons in the target, can easily influence it. Moreover, the final state is not very well determined in the experimental condition. The measurement of the relative population of the ground and first excited state of ${}^5\text{He}$ is free from these effects. Also, the final state interaction has minimal effect since in both cases two neutrons are emitted and the energy distribution of them is not very different. In addition, the nucleon pairs in the triton cluster can be considered to be almost in pure s state.

As the q distributions corresponding to these transitions are not very different, we deduced the ratio r with a least χ^2 fit from the spectrum with small q events. There the tail with events of high excitation energy is small. The value of r thus obtained is $\frac{4}{3}$. For ${}^7\text{Li}$, f is estimated to be 0.4,²⁸ giving

$$R_t/R_s = 1.2,$$

which is close to unity.

Some ambiguity comes from the uncertainty of f . A measurement in coincidence with $2P$ - $1S$ pionic X-ray ($f=1$) would give a more precise value.

It should be noted that the transitions to both ground and first excited state imply the admixture of $\Lambda=0$ and $\Lambda=2$. The pure shell model predicts the ratio to be 1:1. According to the calculation by Balashov *et al.*,²⁹ the ratio is 0.55:0.45, also not far from 1:1. The $l=0$ component should be dominant in the α - t cluster model, which means the q distributions should contain both $L=0$ and $L=2$ components. Because of the kinematical conditions, high momentum components and therefore high L components are suppressed in the distributions. Although the measured q distributions shown in fig. 11 are dominated by $L=0$, a small sign of $L=2$ component can be seen in the data as a small shoulder at about 150 MeV/c. The same overlapping of $L=0$ and $L=2$ component in the recoil momentum distribution has been observed in the analogous (π^+ , $2p$) reaction by Favier *et al.*¹⁸

The θ distribution for the transitions to ground and first excited state are shown in Fig. 11. They could be slightly inclined and also a little bit structured, but still $P_0(\cos\theta)$ component is dominant. The ω distribution for these transitions shown in Fig. 5(d) is therefore broader than the one for the ${}^6\text{Li}$ ground state transition, reflecting

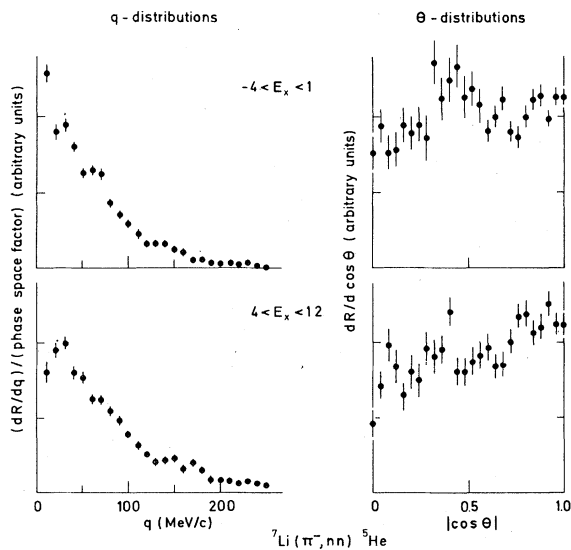


FIG. 11. q and θ distributions for different regions in excitation energy of ${}^5\text{He}$.

the broader q distributions. The E_n and p distributions are shown in fig. 12.

B. Transitions to the higher excited states

The narrow level of ${}^5\text{He}$ at 16.76 MeV ($\frac{3}{2}^+$) is known to have a structure of ${}^4S_{3/2}$.²¹ This level is weakly but clearly populated in the reaction ${}^7\text{Li}(p, {}^3\text{He})$ at 43.7 MeV, and the angular distribution indicates the dominance of $L=1$.³⁰ This means that the level is populated by removing a neutron from $1p$ and a proton from $1s$ shell and that they are in a relative $l=0$, $S=1$, $T=0$ state. As already mentioned, a possible ${}^{12}\text{C}$ contamination makes a precise determination of the transition to this level difficult. But its relatively weak population indicates a small $s^{-1}p^{-1}$ absorption rate, as was already discussed in the ${}^6\text{Li}$ part, which is again in agreement with a prediction of very small $s^{-1}p^{-1}$ absorption by Golovanova and Zelenskaya.¹²

A problem arises, however, when the large

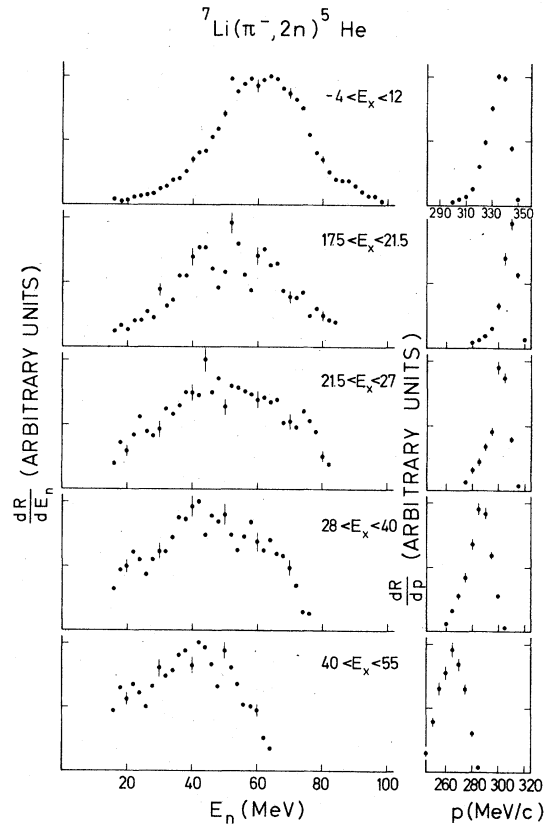


FIG. 12. E_n and p distributions for different regions in excitation energy of ${}^5\text{He}$.

transition rate to the 19.9 MeV level is considered. This level has a positive parity,²¹ and thus the transition to this level implies an $s^{-1}p^{-1}$ absorption since the ground state ${}^7\text{Li}$ has a negative parity. Two interpretations are possible. One is the argument discussed in the ${}^6\text{Li}$ part for the $T=1$ transition, namely an absorption of π^- by two p -shell nucleons followed by a core excitation caused by one of the neutrons emitted. Again, E_n distributions are shown in Fig. 12, but as the distribution for the ground and first excited state transition is very broad, it is impossible to examine this hypothesis.

Examining the data on the elastic d - ${}^3\text{He}$ scattering at 3 to 12 MeV, Kilian *et al.*³¹ have argued that there is a $\frac{3}{2}^-$ level with a width of 2 MeV at 19.6 MeV, which overlaps with the positive parity level at 19.9 MeV. According to Schröder *et al.*,³² this state has a structure of ${}^4\text{He}^*(0^+) - n$, ${}^4\text{He}^*(0^+)$ being the 20.1 MeV 0^+ excited state of ${}^4\text{He}$. If this level really exists, its population is the other possible explanation. Kilian *et al.* suggest $(1s)^2(1p)^3$ configuration for this state, which is one $1p$ nucleon coupled to ${}^4\text{He}^*(0^+)$ having $(1s)^2(1p)^2$ configuration. The interpretation is attractive since this energy region corresponds to the separation energy of two $1s$ -shell nucleons. The q distribution of the transition to this state, shown in Fig. 13, exhibits a monotonical decrease with increasing q , and seems to indicate $L=0$, thus supporting the above possibility. The narrower width of the level may fit the present excitation spectrum better. One difficulty is that the 20.1 MeV 0^+ state of ${}^4\text{He}$ should be easily populated through the $(\pi^-, 2n)$ reaction on ${}^6\text{Li}$, if it has such a configuration. This is not the case, as we have already seen.

Apart from a large width, nothing is known so far about the level at 25 MeV where the present data show a fairly strong enhancement. We show the q and θ distribution corresponding to this region in Fig. 13. As was mentioned before, rather large rates have been recorded for the E_x region higher than 25 MeV. The q and θ distributions for different E_x regions are also shown in the figure. The q distributions become broader with increasing E_x , but still they seem to have their maximum at $q=0$. The θ distributions are more or less isotropic, although they may contain more indications of structure than ${}^6\text{Li}$.

The analogous $(\pi^+, 2p)$ reaction has been measured by Favier *et al.* at 70 MeV.¹⁸ Again the excitation spectrum is rather similar to ours. In the case of π^+ , the relative population of the ground and first excited state can be different from ours since the relative contribution of the S -wave pion absorption, where the singlet ($T=1$) absorption

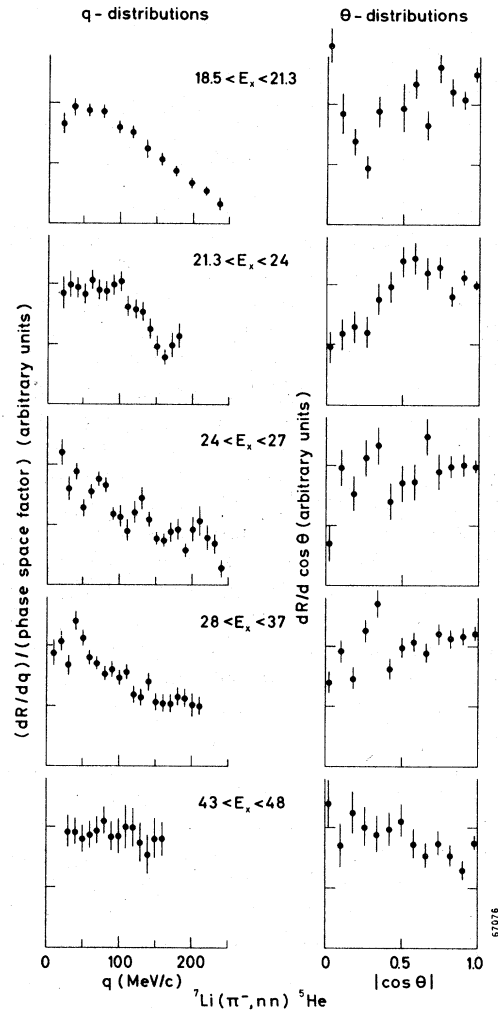


FIG. 13. q and θ distributions for different regions in excitation energy of ${}^5\text{He}$.

is forbidden, may not be the same. Also, the rate seems to be higher in the high E_x region relative to the ground state, but this is probably due to the difference of the kinematics.

V. CONCLUSIONS

In both ${}^6\text{Li}$ and ${}^7\text{Li}$ targets, two well-separated large peaks, one corresponding to the removal of only p -shell nucleons and the other involving s nucleons, are observed.

In ${}^6\text{Li}$, the measured q distribution for the ground state transition is well reproduced by a simple calculation using a square-well potential for the intercluster motion, although the shell model wave function fails. This fact, as well as the measured isotropic θ distribution, supports the dom-

inance of the quasifree direct mechanism for this transition.

In this paper, the relationship between the width of the q distribution and the separation energy of the removed nucleon pair has often been mentioned. In Fig. 14, the width (HWHM) of measured q distributions as a function of the separation energy for the most prominent $\Lambda=0$ transitions of the lithium targets together with other $1p$ -shell nuclei already treated in previous publications are plotted. The straight line is only to guide the eye but the general trend is clear. The case of ^{14}N seems to be exceptional. It may indicate a $1S$ motion of the c.m. of the pair, whereas $2S$ is usually observed for $\Lambda=0$ transitions at low excitation energies.

The plausible assumption of direct mechanism and the cluster model description of the ground state of ^7Li allows us to calculate the relative strength of triplet and singlet absorption from the relative population of ground and first excited states of ^5He . An experimentally known atomic S -orbit absorption fraction of 0.4 results in an almost equal strength of triplet and singlet matrix element.

The residual states corresponding to a direct removal of a sp pair, namely the 20.1–22.1 MeV levels in ^4He and the 16.8 MeV level in ^5He , do not seem to be strongly populated.

The strong population of the 25.5 MeV 0^+ level in ^4He can be understood if a s^{-2} direct absorption mechanism is assumed. The measured q distribution supports this interpretation.

If the known level scheme for ^4He and ^5He is assumed to be complete in the energy range of 20–30 MeV, at least one unnatural parity state is rather strongly populated in both nuclei: in ^4He , a $T=1$ state between 26.4 and 30.5 MeV, and in ^5He , a positive parity state at about 20 MeV. With the quasifree $s^{-1}p^{-1}$ absorption mechanism

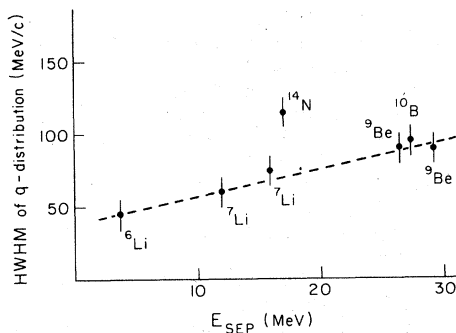


FIG. 14. Width of the q distributions of the most prominent $\Lambda=0$ transitions as a function of the pair separation energy.

seeming rather unlikely, a p^{-2} absorption followed by an excitation of the core due to the final state interaction is proposed as explanation. The measured neutron kinetic energy distribution for ^4He does not contradict such an interpretation. In the case of ^5He , it is also possible that the peak at about 20 MeV does not correspond to the $(\frac{3}{2}, \frac{5}{2})^+$ level, but to a $\frac{3}{2}^-$ level at 19.9 MeV reported by Kilian *et al.* The measured q distribution fits the latter interpretation better.

In both ^6Li and ^7Li , large numbers of events lead to very highly excited levels. Little is known about these states, but a broad level at $E_x \sim 24$ MeV in ^5He seems to be strongly populated.

The measured θ distributions are in most cases almost isotropic and are in agreement with a quasifree mechanism in both targets, although they more often contain some structure in ^7Li .

Finally, we note that only in lithium isotopes does clear evidence for absorption on inner shell nucleons exist in the excitation spectra of residual nuclei.

APPENDIX

The radial part of the matrix element (2) is

$$\int j_L(qR)\psi_{NL}(R)R^2 dR \int j_l(pr)\psi_{nl}(r)r^2 dr \quad (\text{A1})$$

for the absorption of P -wave pions. Because of the gradient operator the radial parts of the matrix element are

$$\int j_L(qR)\psi_{NL}(R)R^2 dR \times \begin{cases} \int j_{l+1}(pr) \left(\frac{d}{dr} - \frac{l}{r} \right) \psi_{nl}(r)r^2 dr \\ \int j_{l-1}(pr) \left(\frac{d}{dr} + \frac{l+1}{r} \right) \psi_{nl}(r)r^2 dr \end{cases} \quad (\text{A2})$$

for the absorption of S -wave pions occurring on the relative state. Operating d/dr directly to $\psi_{nl}(r) = r^l f(r)$, where $f(0) = \text{const.}$ and $f(\infty) = 0$,

$$\begin{aligned} & \int j_{l+1}(pr) \left(\frac{d}{dr} - \frac{l}{r} \right) \psi_{nl}(r)r^2 dr \\ &= \int j_{l+1}(pr)r^l \frac{d}{dr} f(r)r^2 dr, \end{aligned}$$

which becomes by integration by parts,

$$\begin{aligned}
&= - \int \frac{d}{dr} \{j_{l+1}(pr)r^{l+2}\} f(r) dr \\
&= -p \int j_l(pr) f(r) r^{l+2} dr \\
&= -p \int j_l(pr) \psi_{nl}(r) r^2 dr, \quad (A3)
\end{aligned}$$

where

$$\frac{d}{dz} \{z^{l+2} j_{l+1}(z)\} = z^{l+2} j_l(z) \quad (A4)$$

is used. On the other hand,

$$\begin{aligned}
&\int j_{l-1}(pr) \left(\frac{d}{dr} + \frac{l+1}{r} \right) \psi_{nl}(r) r^2 dr \\
&= (2l+1) \int j_l(pr) r^{l+1} f(r) dr \\
&+ \int j_{l-1}(pr) r^{l+2} \frac{d}{dr} f(r) dr, \quad (A5)
\end{aligned}$$

where the last term becomes

$$\begin{aligned}
&\int j_{l-1}(pr) r^{l+2} \frac{d}{dr} f(r) dr \\
&= - \int \frac{d}{dr} \{j_{l-1}(pr) r^{l+2}\} f(r) dr \\
&= -(2l+1) \int j_{l-1}(pr) r^{l+1} f(r) dr \\
&+ p \int j_l(pr) r^{l+2} f(r) dr. \quad (A6)
\end{aligned}$$

Here

$$\frac{d}{dz} j_{l-1}(z) = \frac{l-1}{z} j_{l-1}(z) - j_l(z) \quad (A7)$$

is used. Thus

$$\begin{aligned}
&\int j_{l-1}(pr) \left(\frac{d}{dr} + \frac{l+1}{r} \right) \psi_{nl}(r) r^2 dr \\
&= p \int j_l(pr) \psi_{nl}(r) r^2 dr. \quad (A8)
\end{aligned}$$

The quantities (A3) and (A8) are, except for a factor (\cdot) p , identical to the corresponding part of (A1).

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