

THE $^{14}\text{N}(n, {}^7\text{Li}) {}^8\text{Be}$ REACTION, A POSSIBLE SIX-NUCLEON TRANSFER

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Differential and total cross sections for the $^{14}\text{N}(n, {}^7\text{Li}_{g.s.}) {}^8\text{Be}_{g.s.}$ and $^{14}\text{N}(n, {}^7\text{Li}_2) {}^8\text{Be}_{g.s.}$ reactions have been measured at 14.4 and 18.2 MeV. The angular distributions have been analyzed in the framework of the exact-finite-range DWBA, assuming a direct six-nucleon transfer process.

1. Introduction

During the past years multinucleon transfer reactions have been used both to investigate reaction mechanisms and to extract information about the many nucleon correlations in light nuclei. The presence of many-nucleon clusters reflects itself in collision events. One class of such events are nuclear reactions involving the transfer of a group of nucleons between the projectile and the target nucleus. Most reactions investigated so far, involving the transfer of more than four nucleons, have been induced by heavy ions¹⁾, fewer of them by light charged particles or by neutrons. In particular, the $(d, {}^7\text{Li})$ and $(d, {}^7\text{Be})$ reactions have been analyzed as five-nucleon transfer processes²⁾. Proton-induced reactions involving the transfer of the ${}^6\text{Li}$ cluster have also been studied and the experimental angular distributions analyzed as direct processes with the DWBA expression for the transition amplitude^{3,4)}.

In the present work we investigate the $^{14}\text{N}(n, {}^7\text{Li}_{g.s.}) {}^8\text{Be}_{g.s.}$ and $^{14}\text{N}(n, {}^7\text{Li}_2) {}^8\text{Be}_{g.s.}$ reactions. Total and differential cross sections are measured. Angular distributions of ${}^7\text{Li}$ are analyzed in the framework of the exact-finite-range (EFR) DWBA as pickup processes with the transfer of the ${}^6\text{Li}$ cluster. The transition amplitude⁵⁾ between various possible states is calculated.

2. Experimental procedure and results

The experiment was performed by inducing the breakup of the ^{14}N nucleus with neutrons of 14.4 and 18.2 MeV in nuclear emulsions which were used both as target and detector. The $^{14}\text{N}(n, \alpha\alpha {}^7\text{Li})$ three-body breakup ($Q = -8.82$ MeV) and the $^{14}\text{N}(n, \alpha\alpha t)$ four-body breakup ($Q = -11.29$ MeV) were recorded as three- and four-prong stars, respectively, (the latter only at an incident energy of 18.2 MeV). Details of the analysis of such a kinematically complete experiment performed in the 4π geometry were described elsewhere^{6,7}. As found previously, the correlation spectra show the predominance of sequential processes. The $^{14}\text{N}(n, {}^7\text{Li}) {}^8\text{Be}_{\text{gs}}(2\alpha)$ sequential decay is selected by computing the ${}^8\text{Be}$ excitation energy spectrum from α - α correlations for each three-prong star. Figure 1a shows a representative spectrum thus obtained (at 18.2 MeV). It is

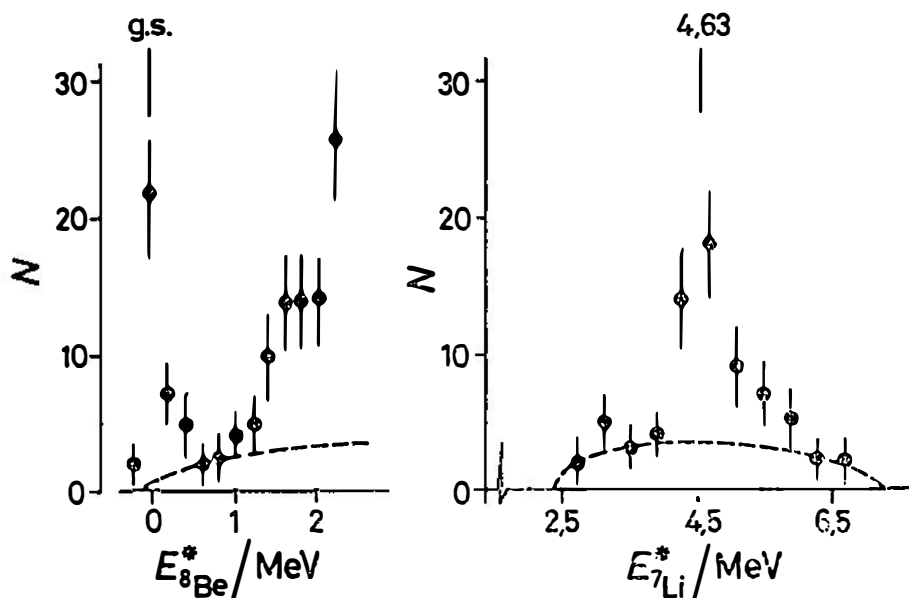


Fig. 1. Correlation spectra measured at 18.2 MeV. (a) α - α correlations for the three-body breakup at 18.2 MeV corresponding to the excitation energy of ${}^8\text{Be}$; (b) α - t correlations for the four-body breakup corresponding to the excitation energy of ${}^7\text{Li}$. The dotted line is the phase-space distribution.

seen from the phase space (dotted line) that more than 93% of the events in the ${}^8\text{Be}_{\text{gs}}$ peak come from the two-body process. However, it was not possible to resolve events decaying via the ${}^7\text{Li}$ ground state and the first excited state at 0.478 MeV. The angular distributions of the ${}^7\text{Li}$ particles emitted in the $^{14}\text{N}(n, {}^7\text{Li}_{\text{gs},1}) {}^8\text{Be}_{\text{gs}}$ reaction are shown in Fig. 2.

The neutron-induced breakup of ^{14}N via the second excited state of ${}^7\text{Li}$ at 4.63 MeV, which occurs above the α - t threshold, yields four particles in the final state. In this case, the events found to decay via the ${}^8\text{Be}_{\text{gs}}$ have to be further

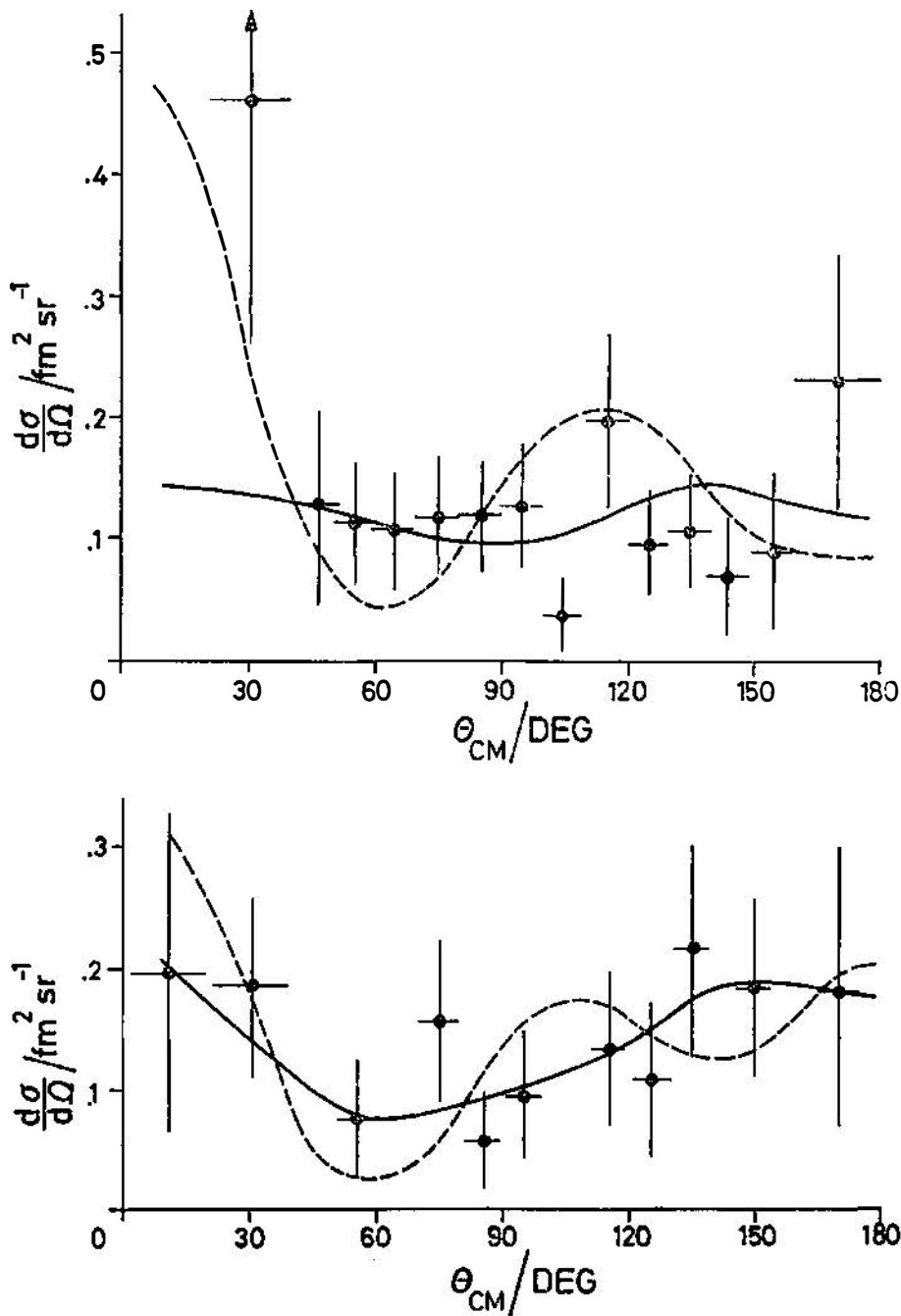


Fig. 2. Angular distributions of ^7Li emitted in the $^{14}\text{N}(n, ^7\text{Li}_{g.s.})^8\text{Be}_{g.s.}$ reaction. Calculated curves correspond to the $3S_1 \rightarrow 1P_2$ ($I_x = 1$) (full line) and $2D_1 \rightarrow 1P_2$ ($I_x = 1$) (broken line) ground-state transitions: (a) at an incident energy of 14.4 MeV, (b) at an incident energy of 18.2 MeV.

analyzed by examining their α - t correlation spectrum. Thus the ^7Li excitation energy was computed for each event from the data measured on the triton and on that α -particle which does not form the ^8Be ground-state peak. The 4.63 MeV peak thus obtained, rising above the phase-space distribution (Fig. 1b), enables one to select events decaying via the $^{14}\text{N}(n, ^7\text{Li}_2^*(\alpha t)) ^8\text{Be}_{gs}(2\alpha)$ »double-final-state interaction«. In this case, the phase space comprises 30% of the total area, introducing an uncertainty of the same order in the value of the cross section. The angle of emission of ^7Li is computed from the momenta of the products of the decay of the 4.63 MeV state (the α -particle and the triton). The angular distribution of the emitted $^7\text{Li}_2^*$ nucleus is shown in Fig. 3.

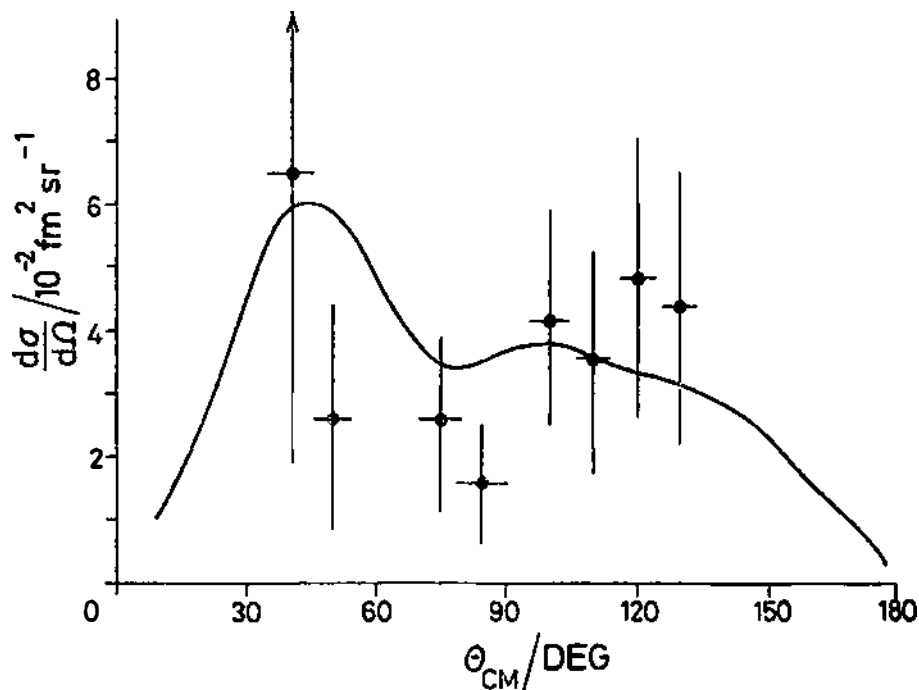


Fig. 3. Angular distribution of ^7Li emitted in the $^{14}\text{N}(n, ^7\text{Li}_2^*) ^8\text{Be}_{gs}$ reaction. The full line is the calculated angular distribution for the $2D_1 \rightarrow 1P_4 (I_x = 3)$ transition to the $7/2^-$ state at 4.63 MeV.

Vertical bars in Figs. 2 and 3 represent statistical errors. The angular spread is due to arbitrarily chosen angular intervals at which the events are sorted. All data are corrected for the loss of events due to the experimental low-energy cutoff at $E = 0.4$ MeV, imposed by the detecting system⁸⁾. This correction, based on kinematical considerations, is negligible at an incident energy of 18.2 MeV and with ^7Li in their ground state. The correction increases at lower incident energy or at higher ^7Li excitation. However, no correction is needed at backward angles of the ^7Li angular distribution; this is a fact to be borne in mind in fitting theoretical distributions to experimental data.

The absolute values of the cross sections were obtained by calibrating the plates with the well-known $^{12}\text{C}(n, n')^{12}\text{C}_{9.6}(\alpha\ ^8\text{Be}_{gs}(2\alpha))$ reaction chain⁸⁾ which was recorded simultaneously. The measured cross sections for the $^{14}\text{N}(n, ^7\text{Li}_{gs,1})^8\text{Be}_{gs}$ reaction at 14.4 and 18.2 MeV amount to $(1.8 \pm 0.7)\text{ fm}^2$ and $(1.4 \pm 0.6)\text{ fm}^2$, respectively. The error includes the statistical error, the error in the calibration value and the uncertainty due to the total breakup of ^{14}N (Fig. 1). For the $^{14}\text{N}(n, ^7\text{Li}_2^*)^8\text{Be}_{gs}$ reaction we have obtained a cross section of $(0.4 \pm 0.2)\text{ fm}^2$ at 18.2 MeV. Schmidt et al.⁹⁾ measured the reaction cross section for the $^{14}\text{N}(n, \alpha\alpha)^7\text{Li}$ three-body breakup at 14.1 MeV. From their data we have deduced a cross section of 0.7 fm^2 for the $(n, ^7\text{Li}_{gs,1})$ two-body reaction.

3. Discussion

In order to extract some information about the reaction mechanism involved, the measured angular distributions have been analyzed assuming a direct pickup process in which a six-nucleon cluster (^6Li) is transferred. Earlier investigations showed that the $n + ^6\text{Li}$ cluster configuration was also present in the wave functions of the ^7Li states^{10,11)}. On the other hand, in γ -induced nuclear reactions, excited states of ^{14}N were found¹²⁾ to decay via the intermediate nuclei ^6Li and ^8Be . With this in mind, the angular distributions of the pickup process mentioned above have been analyzed within DWB theory using the Saturn-Mars 1 computer code for EFR-DWBA calculations¹³⁾. The main assumptions in this analysis are that the nucleon transfer occurs as a one-step process and that the rearrangement of nucleons can be treated as a perturbation¹⁴⁾. The Woods-Saxon optical potential of the standard form has been used in the analysis. The spin-orbit term has been omitted because then the contributions from different channels are independent. The best suited interaction potential parameters are given in Table 1. The depth of the well is adjusted so as to obtain proper binding energies of the clusters in relevant nuclei. Table 1 also shows optical-model parameters for the entrance and exit channels. In the latter case, these have been deduced from elastic scattering data on the nearest nuclei¹⁵⁾. The quantum numbers of the bound-state wave functions have been chosen in accordance with the selection rules based on the conservation of shell-model oscillation quanta and on parity conservation. The allowed transferred angular momenta j, s, l have been calculated from the

TABLE 1

Interaction	V_0/MeV	a/fm	r_0/fm	W_s/MeV	a'/fm	r'_0/fm	r_c/fm	Ref.
Bound state								
$^8\text{Be} + ^6\text{Li}$		0.7	1.28				1.28	15
$n + ^6\text{Li}$		0.9	1.38				1.38	16
Channel								
entrance $n + ^{14}\text{N}$	45	0.57	1.32	11	0.73	1.32		17
exit $^7\text{Li} + ^8\text{Be}$	190	0.7	1.28	7	0.9	2.5	1.28	15

total spins of the particles involved in the given reaction¹⁴⁾. When the spin-orbit interaction is neglected, as in the present case, the sum over j , s and l in the transition amplitude is incoherent.

In the reaction in which the emitted ${}^7\text{Li}$ particle is in the ground state ($J^\pi = 3/2^-$), possible transitions occur from the $3S_1$ or/and $2D_1$ bound state in the entrance channel to the $1P_{1,2}$ bound states in the exit channel. We have computed angular distributions for all allowed transitions with an appropriate intrinsic spin I_x of the transferred cluster. However, the measured angular distribution can be fitted only for the $3S_1 \rightarrow 1P_2$ ($I_x = 1$) and $2D_1 \rightarrow 1P_2$ ($I_x = 1$) transitions (Fig. 2).

The question remains to what extent the shape of the angular distributions for the transition to the ground state is influenced by the presence of the transition to the neighbouring first excited state of ${}^7\text{Li}$ ($J^\pi = 1/2^-$) which could not be separated experimentally. According to our calculations, the differential cross sections for all allowed transitions to the $1/2^-$ state are smaller than the differential cross sections for transitions to the $3/2^-$ state. The shape of the calculated angular distribution for the ground state is not appreciably affected by adding the angular distribution for the first excited state. Thus, the assumption of a pickup process involving either the $3S_1 \rightarrow 1P_2$ ($I_x = 1$) transition and/or the $2D_1 \rightarrow 1P_2$ ($I_x = 1$) transition to the ground state of ${}^7\text{Li}$ seems to be in reasonable agreement with experimental results.

The characteristic feature of the angular distribution for the ${}^{14}\text{N}$ ($n, {}^7\text{Li}_2^*$) ${}^8\text{Be}_{gs}$ reaction is the lack of experimental points at angles larger than 130° . In view of the experimental method described in Section 2, this cannot be due to the loss of events. Rather, it is a significant feature which enables one to select, among all allowed transitions, the calculated angular distribution which best fits the experimental data. Thus we have found that the ${}^{14}\text{N}$ ($n, {}^7\text{Li}_2^*$) ${}^8\text{Be}_{gs}$ reaction is dominated by the $2D_1 \rightarrow 1P_4$ ($I_x = 3$) transition (Fig. 3). The high value of the intrinsic spin of the transferred particle is not surprising in view of the high spin of the ${}^7\text{Li}$ second excited state of ${}^7\text{Li}$ ($J^\pi = 7/2^-$).

4. Conclusion

The pickup mechanism with the transfer of the ${}^6\text{Li}$ cluster in the ($n, {}^7\text{Li}$) reactions on ${}^{14}\text{N}$ is in agreement with our experimental data. The less pronounced diffraction pattern in the angular distributions, usually present in such processes¹⁸⁾, can be explained by low incident energy, so that only a few intrinsic states are excited. However, because of the large statistical errors in the angular distributions a compound mechanism can not be ruled out.

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MOGUĆNOST IZMJENE ŠEST NUKLEONA U REAKCIJI ^{14}N ($n, ^7\text{Li}$) ^8Be

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Izmjerena je kutna raspodjela i ukupni udarni presjek za reakcije $n + ^{14}\text{N} \rightarrow ^7\text{Li} + ^8\text{Be}$ inducirane s neutronima energije 14.4 i 18.2 MeV. Razlučeno je drugo pobuđeno stanje ^7Li od osnovnog i prvog pobuđenog stanja. Emulzija je služila kao meta i detektor. Izračunate su kutne raspodjele uz pretpostavku transfera grozda od šest čestica. Račun je proveden u ERF-DWB aproksimaciji. Izmjerenе kutne raspodjele ukazuju na moguće postojanje direktnog procesa, iako procesi preko složene jezgre nisu isključeni.