# Multinucleon transfer reactions with $^7Li + ^7Be$ in the exit channel

J. Jarczyk, B. Kamys, Z. Rudy, A. Strzałkowski, and B. Styczeń
*Institut for Physics, Jagellonian University, PL-30-059 Cracow, Poland*

G. P. A. Berg, A. Magiera,* J. Meissburger, W. Oelert, P. von Rossen, J. G. M. Römer, and J. L. Tain
*Institut für Kernphysik, Kernforschungsanlage Jülich, D-5170 Jülich, Federal Republic of Germany*

H. H. Wolter
*Sektion Physik, Universität München, D-8046 Garching, Federal Republic of Germany*

E. Kwaśniewicz
*Institute of Physics, Silesian Technical University, PL-40-019 Katowice, Poland*

J. Kisiel
*Institute of Physics, Silesian University, PL-40-007 Katowice, Poland*

(Received 3 July 1985)

The three-, four-, and five-nucleon transfers were investigated by studying the $^{10}B(\alpha,^7Li)^7Be$, $^{11}B(^3He,^7Li)^7Be$, and $^{12}C(d,^7Li)^7Be$ reactions, respectively. The measurements were performed in the entire center of mass angular region, at incident energies corresponding to 49.3 MeV in the center of mass system of the exit channel. A distorted-wave Born approximation analysis was performed including second-order transfer contributions for all investigated reactions.

Studies of direct multinucleon transfer reactions yield interesting information on some aspects of nuclear structure by shedding light on the problem of clustering in nuclei. On the other hand, they provide information on the reaction mechanism as, e.g., the role of the higher order processes.

In order to gain significant knowledge from such studies, however, a strong constraint should be applied on parameters of the reaction model used to analyze the experimental data. This can be achieved by extending the investigations on interdependent reactions leading, e.g., to the same final states.

Reactions with the $^7Li + ^7Be$ system in the exit channel offer a particularly favorable opportunity for such investigation. When studied in the forward and backward angular hemispheres, such reactions correspond to the effective transfer of various groups of nucleons with the same mass, i.e., 2n1p and 1n2p in $^{10}B(\alpha,^7Li)^7Be$, 3n1p and 2p2n in $^{11}B(^3He,^7Li)^7Be$, and 3n2p and 2n3p in $^{12}C(d,^7Li)^7Be$ reactions. Therefore, they enable one to make a direct comparison of different cluster transfers in a single experiment, e.g., $^4$H-like cluster transfer can be directly compared with that of an $\alpha$ particle by measuring the reaction $^{11}B(^3He,^7Li)^7Be$ in the entire angular region. Furthermore, some of these transfers treated as one-step reactions could be regarded as the first and/or the second step of two-step sequential process in another transfer reaction. A 90° symmetry in angular distributions for $^{10}B(\alpha,^7Li)^7Be$ and $^{12}C(d,^7Li)^7Be$ reactions can provide, according to the Barshay-Temmer theorem,[1] an additional test for the reaction mechanism. A complex, consistent analysis simultaneously including all investigated reactions, performed in the DWBA model extended to the second order, would deliver reliable information on the mechanism of transfer of complicated, multinucleon structures.

The experiment was performed at the cyclotron JULIC of the Kernforschungsanlage Jülich. A deuteron beam of $E_{lab}=78.0$ MeV, a $^3$He-particle beam of $E_{lab}=71.8$ MeV, and an $\alpha$-particle beam of $E_{lab}=91.8$ MeV were focused onto $^{12}C$ (100 $\mu$g/cm$^2$), $^{11}B$ (160 $\mu$g/cm$^2$ with 98.55% enrichment), and $^{10}B$ (60 $\mu$g/cm$^2$ with 96.35% enrichment on a 20 $\mu$g/cm$^2$ $^{12}C$ backing) targets, respectively. These incident energies in the laboratory system were chosen to achieve the same c.m. energy of 49.3 MeV in the exit channels of all reactions investigated.

The outgoing reaction products were momentum analyzed in the quadrupole-quadrupole-dipole-dipole-quadrupole (QQDDQ) magnet spectrometer BIG KARL.[2] For the particle identification a $\Delta E$-gas detector and an $E$-plastic scintillator counter were used in the focal plane of the spectrometer. The momentum spectra of $^7Li$ and $^7Be$, identified by events in the appropriate regions of the two-dimensional $\Delta E$ vs $E$ spectra, were measured in two multiwire proportional chambers. As can be seen from Fig. 1, the resolution was sufficient to resolve the first excited states of $^7Li$ or $^7Be$ from the ground states, leaving, however, unresolved excitations to the first excited state 0.478 MeV in $^7Li$ or 0.429 MeV in $^7Be$.

The absolute cross sections were obtained by comparison with known elastic scattering cross sections or by knowledge of the measured target thickness, the solid angle of the spectrometer, and the integrated charge calibration. The error of normalization was estimated to be 10%.

 

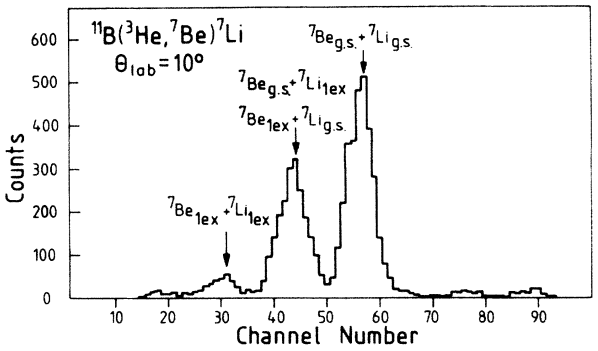


FIG. 1. A momentum spectrum of $^7$Be particles for the reaction $^{11}$B($^3$He,$^7$Be)$^7$Li at 10°.

The measured angular distributions for the ground state transitions are shown in Fig. 2. A DWBA analysis was performed, including the important two-step transfer contributions to each cluster transfer considered. The calculations were done using the exact finite range code JUPITER–5 written by Tamura and Udagawa according to the formalism in Ref. 3 and modified by Kamys *et al.*[4] to allow for particle spin in the entrance channel.

Special care was devoted to determine the essential components of the model in the most consistent way. Therefore, the parameters of the optical model potentials, which were used for the calculation of the distorted waves in different channels, were determined from elastic scattering data wherever possible. A linear energy dependence of the depth of the imaginary part was introduced to allow for different energies in various reaction channels.

As no elastic scattering data exist for the $^7$Li+$^7$Be system, the interaction in the exit channel was approximated by the optical model potential for the $^9$Be+$^7$Li system determined from the analysis of elastic scattering data at $E_{c.m.}=19.12$ MeV,[5] however, with an energy dependent term in the depth of the imaginary part, which was determined by reproducing the $\alpha$-transfer data in the $^{11}$B($^3$He,$^7$Be)$^7$Li reaction. The same potential was also used for all Li + Be partitions in the intermediate states of two-step reactions.

The binding potential of the transferred particle to the core was assumed to be of Woods-Saxon form with the geometrical parameters $R=0.85(A_p^{1/3}+A_c^{1/3})$ fm, $a=0.65$ fm, while the depth was adjusted to obtain the proper binding energy.

The spectroscopic amplitudes for all ground and excited states needed in the calculations were calculated according to the formalism outlined in Refs. 6 and 7.

Wherever possible, the cross sections of each of the single steps of the two-step processes were compared with experimental data. This was done for the following reactions: $^{11}$B($^3$He,$^6$Li)$^8$Be (the present experiment), $^{11}$B($^3$He,$\alpha$)$^{10}$B (Ref. 8), $^{12}$C(d,$^6$Li)$^8$Be (the present experiment), $^{12}$C(d,$^3$He)$^{11}$B (Ref. 9), and $^{12}$C(d,t)$^{11}$C (Ref. 10).

It was found to be impossible to simultaneously reproduce the energy dependence of the elastic scattering and the one-nucleon transfer reactions (d,$^3$He), (d,t), and

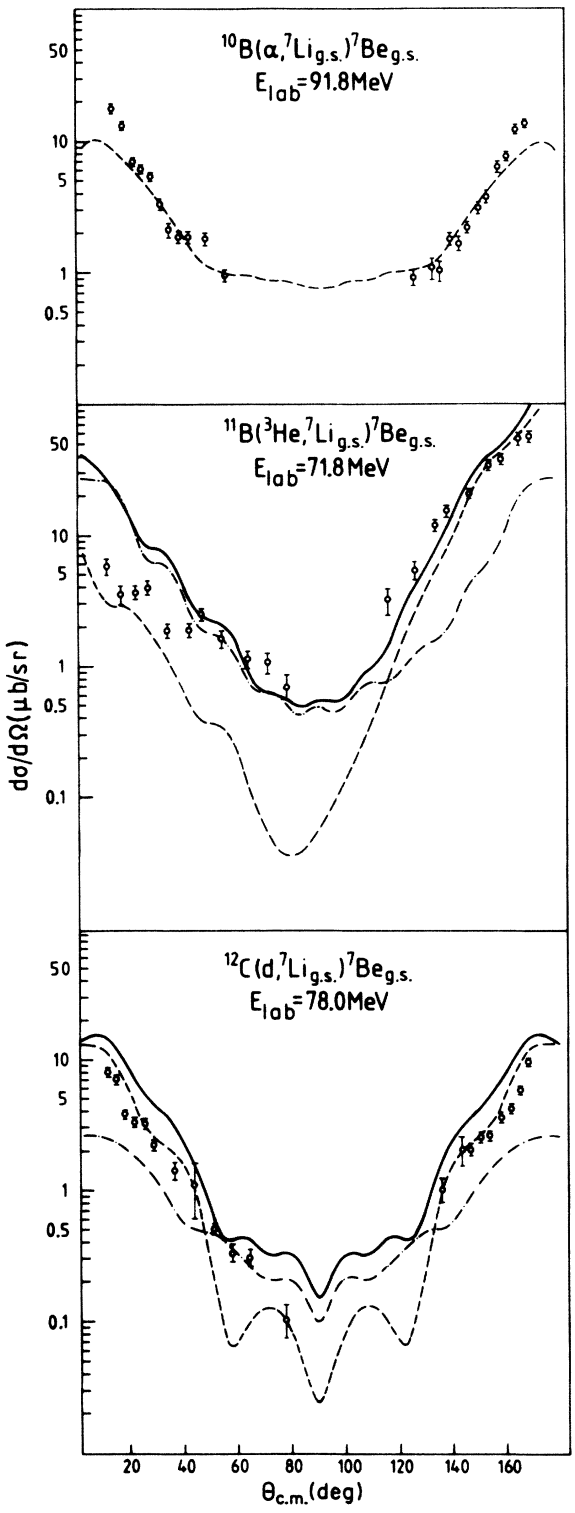


FIG. 2. Angular distributions for the reactions $^{10}$B($\alpha$,$^7$Li)$^7$Be, $^{11}$B($^3$He,$^7$Li)$^7$Be, and $^{12}$C(d,$^7$Li)$^7$Be leading to the ground states of the final nuclei. The curves represent the theoretical calculations for one-step cluster transfer (dashed line), two-step transfer contributions (dash-dotted line), and the coherent sum of both (solid line).

($^3$He,$\alpha$), in agreement with the ($^3$He,d) analysis in Ref. 11. Therefore a radial cutoff of about 4 fm was introduced in the calculation of the transfer amplitudes for these processes to reduce the contribution from the nuclear interior and to increase the $l$-space localization.

The comparison of the results of the calculation with experimental data for the ground state excitations is shown in Fig. 2. The conclusions can be summarized as follows:

1. In the $^{10}$B($\alpha$,$^7$Li)$^7$Be reaction (Ref. 12), only the one-step triton- and helion-cluster transfers were considered in the DWBA calculations. They account well for the measured differential cross sections, indicating the dominance of the single-step processes in this reaction. This reaction mechanism evidently conserves isospin, leading to the 90° symmetry of angular distributions observed with experimental accuracy up to 10%, in full accord with the Barshay-Temmer theorem.

2. In the reaction $^{11}$B($^3$He,$^7$Li)$^7$Be, $\alpha$-transfer contributes dominantly in the backward angular range. The two-step contributions, p-t, t-p, n-$^3$He, and $^3$He-n, on the other hand, were found to be relatively small. This justifies our procedure for determining the imaginary part of the $^7$Li + $^7$Be optical potential by means of fitting the single-step $\alpha$ transfer. The $^4$H-cluster one-step transfer calculated with the same potential and with the shell model spectroscopic amplitude reproduces only a fraction of the measured cross section in the forward hemisphere, leaving room for higher order processes. The second order calculations for n-t, t-n, 2n-d, and d-2n sequential transfers indicate a dominant role of the two-step transfer mechanism in the ($^3$He,$^7$Li) reaction. However, the agreement is not satisfactory, which could be connected with still other mechanisms than the assumed one; e.g., simultaneous transfer of $^4$H as four uncorrelated nucleons. No 90° symmetry in angular distribution is seen in this case, since this reaction does not fulfill the assumption of the Barshay-Temmer theorem.

3. In the $^{12}$C(d,$^7$Li)$^7$Be reaction, the contributions of single-step $^5$He- and $^5$Li-cluster transfer reproduce almost completely the measured cross section in the forward and backward directions, respectively. The inclusion of the two-step transfers, $\alpha$-n and n-$\alpha$ accompanying $^5$He transfer, and $\alpha$-p and p-$\alpha$ accompanying $^5$Li transfer, lead to a slight overestimate of the experimental angular distribution. In accord with the Barshay-Temmer theorem, the cross section shows a symmetry about 90° within the experimental accuracy of 8%.

It should be stressed that we have performed the analysis of all the experimental data in as consistent a way as possible. The constraint of reproducing the elastic scattering, the one- and two-step processes simultaneously, leads to very little freedom in the choice of the parameters. It is then seen that we are able to draw some interesting conclusions on the mechanism of heavy cluster transfer.

---

*On leave from the Jagellonian University, Cracow, Poland.

[1]S. Barshay and G. M. Temmer, Phys. Rev. Lett. **12**, 728 (1964).

[2]S. A. Martin, A. Hardt, J. Meissburger, G. P. A. Berg, U. Hacker, W. Hürlimann, J. G. M. Römer, T. Sagefka, A. Retz, O. W. B. Schult, K. L. Brown, and K. Halbach, Nucl. Instrum. Methods **214**, 281 (1983).

[3]T. Tamura, Phys. Rep. **14**, 59 (1959); T. Tamura, T. Udagawa, and M. C. Mermaz, *ibid.* **65**, 345 (1980).

[4]B. Kamys, H. H. Wolter, and W. Zittel (unpublished).

[5]K. W. Kemper, G. E. Moore, R. J. Puigh, and R. L. White, Phys. Rev. C **15**, 1726 (1977).

[6]Y. F. Smirnov and Y. M. Tchuvilski, Phys. Rev. C **15**, 84 (1977).

[7]E. Kwaśniewicz and L. Jarczyk, Nucl. Phys. **A441**, 77 (1985).

[8]D. Dehnhard, N. Williams, and J. L. Yntema, Phys. Rev. **180**, 967 (1969).

[9]F. Hinterberger, G. Mairle, U. Schmidt-Rohr, P. Turek, and G. J. Wagner, Nucl. Phys. **A106**, 161 (1968).

[10]C. Détraz, M. Gaillard, R. Bouché, L. Feuvrais, P. Gaillard, M. Gouanère, M. Gusakow, and J. R. Pizzi, Phys. Lett. **22**, 638 (1966).

[11]N. Matusoka, K. Hatanaka, M. Fujiwara, Y. Fujita, T. Saito, K. Hosono, A. Shimizu, M. Kondo, F. Ohtani, H. Sakaguchi, A. Goto, N. Nakanishi, and Y. Toba, Nucl. Phys. **A373**, 377 (1982).

[12]L. Jarczyk, B. Kamys, Z. Rudy, A. Strzałkowski, B. Styczeń, G. P. A. Berg, A. Magiera, J. Meissburger, W. Oelert, P. von Rossen, J. G. M. Römer, and E. Kwaśniewicz, Z. Phys. A **322**, 221 (1985).