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Mechanism of the ^{6}Li($e,e'\alpha$) reaction

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The ^{6}Li($e,e'\alpha$) reaction has been measured in parallel kinematics. The Q^2 dependence of both the two-body and three-body breakup of ^{6}Li has been studied at fixed recoil momentum. In addition, the recoil momentum dependence of the two-body α-d breakup has been investigated. The data indicate that the reaction mechanism is quasielastic in these kinematics.

I. INTRODUCTION

The strong interaction of nucleons in the nucleus gives rise to multinucleon correlations in the nuclear wave function. There are numerous experimentally measured processes which are sensitive to the presence of these correlations. For example, it appears that pion absorption proceeds through a multinucleon mechanism which involves two, sometimes three, four, or even more nucleons [1–3]. There also is evidence for multinucleon processes in measurements with electromagnetic probes. In particular, the observed strength at large values of the missing energy in the ($e,e'p$) reaction is thought to be a multinucleon effect [4].

The detailed investigation of multinucleon correlations in nuclei with electromagnetic probes is just beginning. Previously, deuteronlike N-N correlations have been studied with the ($e,e'd$) reaction [5]. In this paper the results of a ^{6}Li($e,e'\alpha$) experiment are presented. In the quasielastic regime the ($e,e'\alpha$) reaction should be sensitive to the presence of alphalike configurations in the ground-state wave functions of nuclei. The presence of such four-nucleon correlations in nuclei has long been established, having first been invoked to explain the alpha-decay process in heavy nuclei and the observed regularity in the binding energies of the even-even nuclei [6]. This phenomenon has been studied previously with hadronic probes in quasielastic-scattering experiments such as ($p,p'\alpha$) [7] as well as by four-nucleon pickup reactions such as (d,^{6}Li) [8]. These studies have shown an appreciable probability for alpha clustering and in some cases are thought to indicate an enhanced probability in the nuclear surface. However, the results from different hadronic probes are not always consistent, which is probably a result of an inadequate description of the reaction mechanism. The use of electrons as a probe of alphalike correlations has the advantage that the electromagnetic interaction is well known and that it is weak compared to the strong interaction, thus reducing the importance of multistep processes. Further, provided the recoil $A-4$ nucleus is bound, there is only one strong potential in the final state, which simplifies the treatment of distortion effects.

^{6}Li was chosen as the target for several reasons. First, it has a large probability for α-d factorization, $S_{\alpha\text{-}d}$ being greater than 0.60 [5]. Further, the α-d separation energy in ^{6}Li of only 1.47 MeV makes the interpretation of the reaction as a quasielastic process seem plausible. In addition, there is a large body of theoretical work on both two- and three-body descriptions of ^{6}Li [9–11]. Finally, the complementary ($e,e'd$) reaction has been measured previously [5], making ^{6}Li an ideal target for a pilot study of the ($e,e'\alpha$) reaction. The only previous measurement [12] of the ^{6}Li($e,e'\alpha$) reaction suffered from extremely low outgoing alpha energies, 11 MeV, and hence very strong final-state-interaction effects. The present results represent a significant improvement.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with the Medium Energy Accelerator (MEA) at NIKHEF-K. The electrons were detected in the quadrupole-dipole-dipole (QDD) spectrometer with its standard focal-plane instrumentation [13,14], while the coincident alphas were detected in the quadrupole-dipole-quadrupole (QDQ) spectrometer equipped with a recently developed detection system [15]. This low-pressure position-sensitive detector is comprised of a time-projection chamber followed by a parallel-plate avalanche counter (PPAC), which provides the trigger signal, and a thin plastic scintillator whose energy information can be used for particle identification. The drift chamber uses isobutane gas at 40 mbar pressure and provides a measurement of both the position in the dispersive direction, $x_{\text{focal plane}}$, and the angle relative to the central ray in the dispersive direction, $\theta_{\text{focal plane}}$. The position resolution is approximately 0.7 mm. The angular resolution is energy dependent but of order 40 mrad. Because of the spectrometer optics, a knowledge of $\theta_{\text{focal plane}}$ is necessary for an accurate calculation of the length of the particle trajectories through the spectrometer. The stated angular resolution in $\theta_{\text{focal plane}}$ limits the coincident timing resolution to approximately 15 ns full width at half maximum (FWHM) at the energies pertinent to the current experiment. The information measured at the focal plane does not allow the horizontal angle at the target, ϕ_{target}, to be reconstructed, which limits the resolution in the missing momentum, $\mathbf{p}_m = \mathbf{p}_\alpha - \mathbf{q}$. This leads to a resolution of about 65 MeV/c for the magnitude of $\mathbf{p}_m$ for typical alpha momenta of 400 MeV/c and the 140 by 140 mrad angular acceptance of the QDQ spectrometer. This is comparable to the total acceptance in $|\mathbf{p}_m|$. The missing-energy resolution is dominated by the energy loss of the ejected alphas in the 6 mg/cm^2 lithium target and is observed to be 1.5 MeV FWHM, good enough to allow a clean separation of events corresponding to the two-body α-d breakup of ^{6}Li from those with a three-body final state. A representative raw missing-energy spectrum is shown in Fig. 1.

The detector is intended for use with low-energy, $T \leq 45$ MeV, alphas or other moderately ionizing species such as ^{3}He. By design, the detector is virtually insensitive to the abundant protons which accompany the appropriate alphas. This greatly diminishes the accidental coincidence rate. The coincidence detection efficiency was determined by measuring the kinematically overdetermined reactions ^{4}He$(e,e'\alpha)$, and ^{3}He$(e,e'\,^{3}$He$)$. The high-pressure helium-gas target used in these efficiency measurements has been described elsewhere [16]. After corrections for dead time and transmission effects, the measured efficiency for detection of alphas with energies between 20 and 35 MeV was found to be 83±12 %.

III. FORMALISM

In the plane-wave impulse approximation (PWIA), the fourfold differential cross section for the $(e,e'\alpha)$ reaction can be written as

$$\frac{d^4\sigma}{dE_{e'}d\Omega_{e'}dE_\alpha d\Omega_\alpha} = K\sigma_{e\alpha}S(E_m,\mathbf{p}_m)\ , \qquad (1)$$

where E_m is the missing energy, $\mathbf{p}_m$ is the missing momentum (which in PWIA is equal to the initial momentum of the bound alpha particle), K is a kinematic factor, $S(E_m,\mathbf{p}_m)$ is the spectral function which represents the probability of finding a bound alpha in the nucleus with missing energy E_m and momentum p_m, and $\sigma_{e\alpha}(Q^2)$ is the (off-shell) electron-alpha cross section. It should be noted that the factorization of the PWIA cross section is exact for spin-zero ejectiles. This fact enhances the appeal of the $(e,e'\alpha)$ reaction as a tool for structure studies. If distortions are included, the cross section still is approximately factorizable, but the spectral function $S(E_m,\mathbf{p}_m)$ must be replaced by a distorted spectral function $S^D(E_m,\mathbf{p}_m,\mathbf{P}_\alpha^{\text{cm}})$, where $\mathbf{P}_\alpha^{\text{cm}}$ is the center-of-mass momentum of the alpha particle in the final state. Integration of the spectral function over an interval of E_m that corresponds to a bound state of the recoiling $A-4$ system yields the distorted momentum distribution $\rho^D(p_m)$. This quantity can be related to the alpha $(A-4)$ relative wave function in a cluster picture.

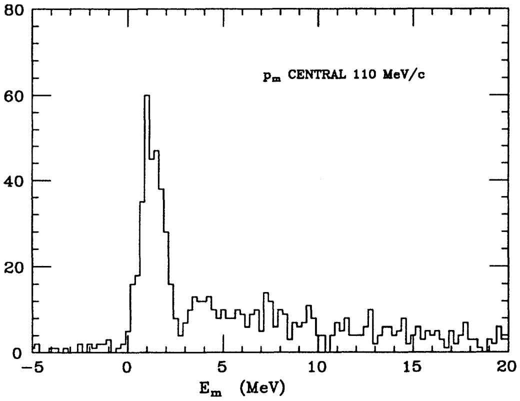

FIG. 1. Missing-energy spectrum for the reaction ^{6}Li$(e,e'\alpha)$ at a central missing momentum of 110 MeV/c. The ground-state peak and threshold for three-body breakup are clearly visible.

This formalism is the same as that employed in the analysis of $(e,e'p)$ reactions. Integration of the fourfold cross section over the missing energy (summing over a given state of the recoil nucleus or over a given range of the continuum, ΔE_m) introduces an additional recoil factor R:

$$\frac{d^3\sigma}{dE_{e'}d\Omega_{e'}d\Omega_\alpha} = \int_{\Delta E_m} \frac{d^4\sigma}{dE_{e'}d\Omega_{e'}dE_\alpha d\Omega_\alpha}\,\frac{1}{R}\,dE_m\ . \qquad (2)$$

If one makes measurements in which the four-momentum transfer Q is varied while the range of missing energy and missing momentum are held constant, one can check whether the Q^2 dependence is given by $K\sigma_{e\alpha}$ (corrected for distortion effects and the recoil factor R) as predicted by the expressions above. This provides a direct check of the assumed reaction mechanism. Similar studies have been made in the past for both the $(e,e't)$ [17] and $(e,e'd)$ reactions [5]. Alternatively, one can vary the missing momentum and study the distorted momentum distribution.

IV. RESULTS

The data presented in this paper were obtained during two separate time periods. In the first period the Q^2 dependence of the reaction was measured at a fixed central missing momentum of 110 MeV/c. During the second beam period, p_m was varied so that the α-d momentum distribution could be extracted. Table I gives a summary of the kinematics used in the Q^2-dependence check. All of the measurements in both periods were made in parallel kinematics, where the alpha is detected in the direction of $\mathbf{q}$.

Fig. 2(a) shows the threefold differential cross sections for the two-body α-d, breakup of ^{6}Li. In Fig. 2(b) the sum of the first 10 MeV of the three-body breakup is shown. In both cases the data were summed over the missing momentum range $85 \leq p_m \leq 135$ MeV/c, which is essentially the entire p_m acceptance of the experimental setup. The calculated curves utilize $\sigma_{e\alpha}$ calculated in the spirit of the σ_{cc1} expression for σ_{ep} as proposed by De Forest [18] using a parametrization of the ^{4}He form fac-

TABLE I. Kinematics for the Q^2-dependence measurements. The central value of the missing momentum was held constant at 110 MeV/*c*.

E_0 (MeV)	T_α (MeV)	$E_{\text{c.m.}}$ (MeV)	$\lvert\mathbf{q}\rvert$ (MeV/*c*)	θ_e (deg)	θ_α (deg)
537	21	16	300	33	69
537	30	20	375	42	64
537	38	25	435	50	60

tor [19]. Distortion effects have been incorporated via the distorted-wave impulse approximation (DWIA) and the global *α-d* optical potential of Hinterberger *et al.* [20] using the computer code PEEP [21]. The bound-state wave function used for both the two- and three-body calculations was the repulsive *α-d* wave function of Lehman and Rajan [11]. The curves were arbitrarily normalized to the middle Q^2 point. The fact that the data exhibit a Q^2 falloff that is consistent with that of the free form factor indicates that the ^{6}Li$(e,e'\alpha)$ reaction proceeds through the direct knockout of an alpha cluster or, equivalently, that the effects of final-state pickup and other multistep mechanisms are small. It was found that the results for the three-body breakup do not depend sensitively on the choice of integration region.

During the second run period, the detector did not function normally. Because of the tilt of the focal plane, the trajectories of incident particles are not normal to the detector face, but rather fall in the angular range 50°±10°. Thus one observes that a typical event produces signals on two to eight anode wires. It was found that a significant number of the coincident events from the second run period had a multiplicity of only 1. These events were analyzed separately from the events with

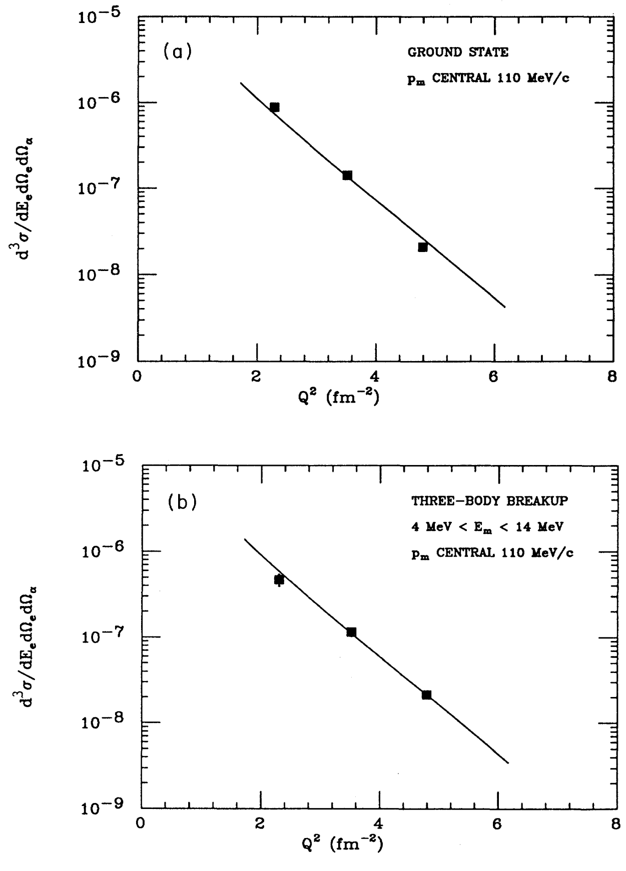

FIG. 2. Measured Q^2 dependence of the threefold differential cross section (a) for the ground-state ^{6}Li$(e,e'\alpha)d$ reaction and (b) for the first 10 MeV of the three-body breakup ^{6}Li$(e,e'\alpha)pn$. The curves are the DWIA calculations described in the text.

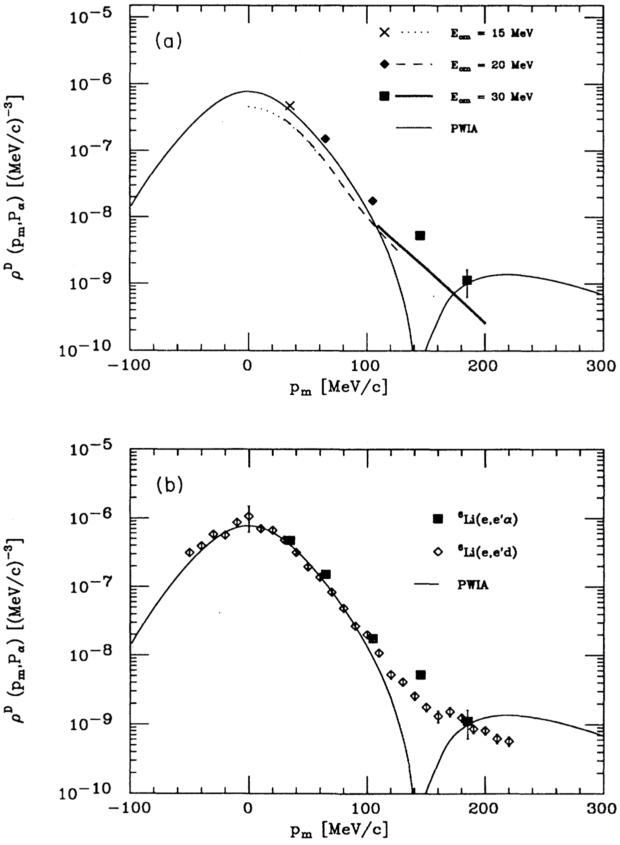

FIG. 3. *α-d* momentum distribution extracted from the ^{6}Li$(e,e'\alpha)$ reaction in parallel kinematics is compared (a) with the results of DWIA and PWIA calculations and (b) with the momentum distribution extracted from the complementary ^{6}Li$(e,e'd)$ reaction. The ^{6}Li$(e,e'\alpha)$ data points are averages over the entire missing momentum acceptance of the coincidence setup, which was typically p_m(central)±30 MeV/*c*. In (a) the energy in the *α-d* center-of-mass system is indicated for both the data points and DWIA calculations.

multiplicity 2 or more as it is not possible to calculate the track inclination for events which have only one anode signal. These low-multiplicity events are certainly real because they have a missing-energy spectrum which is indistinguishable from that of the events with higher multiplicity. The fraction of the multiplicity-1 events was approximately constant for all kinematics, being 45 ± 10 % of the total number of events. This effect could result from an improperly delayed timing signal. These low-multiplicity events were not present in the efficiency-determination data which were obtained several days before the actual data on ^{6}Li. Therefore, the normalization of the momentum distribution data was obtained by comparing the data taken at $p_m = 110$ MeV/c during the second run period with data acquired in almost identical kinematics in the first run period. Unfortunately, this technique increases the sensitivity to the exact value of the central missing momentum. Thus it is estimated that the uncertainty in the overall normalization of the momentum distribution data is ±30%.

Fig. 3(a) shows the α-d momentum distribution, along with both DWIA and PWIA calculations. The error bars shown represent all of the uncertainties which vary point to point. Specifically, they contain the statistical uncertainty, that due to background subtraction, and the systematical uncertainties associated with the dead-time correction. As with the Q^2-dependence data, the points are averages over the entire p_m acceptance of the system, which was typically p_m(central)±30 MeV/c. Both the DWIA and PWIA calculations utilize the α-d relative wave function of Lehman and Rajan [11], while in the DWIA the optical potentials of Ref. [20] were used. The distorted-wave calculation reproduces the drop-off of the data and the filling of the plane-wave minimum. However, given the uncertainty in the absolute normalization, it is not possible to make meaningful statements about the α-d probability in the ground state of ^{6}Li.

In Fig. 3(b) the data from this reaction are compared with those obtained from the $(e,e'd)$ reaction [5]. The two sets of data yield almost exactly the same values, and this agreement extends over nearly three orders of magnitude. Both reactions probe the same α-d momentum distribution in the ^{6}Li ground state. Thus this comparison provides a direct check of the assumed quasielastic reaction mechanism for both reactions that is largely independent of the nuclear structure. The agreement of the extracted results from the two reactions is a strong indication that both the ^{6}Li$(e,e'\alpha)$ and Li$(e,e'd)$ reactions proceed via a direct quasielastic mechanism.

In conclusion, the feasibility of using the $(e,e'\alpha)$ reaction to extract structure information has been demonstrated. We have measured the Q^2 dependence of the ^{6}Li$(e,e'\alpha)$ reaction for both two- and three-body breakup. In both cases the results are consistent with the quasielastic knockout of an essentially free alpha. Moreover, the extracted α-d momentum distribution has a shape which agrees with the prediction of three-body calculations and also with that observed in the complementary reaction ^{6}Li$(e,e'd)$.

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[1] G. Backenstoss *et al.*, Phys. Rev. Lett. **59**, 767 (1987).

[2] P. Weber *et al.*, Phys. Lett. B **230**, 31 (1989).

[3] L. C. Smith *et al.*, Phys. Rev. C **40**, 1347 (1989).

[4] R. W. Lourie *et al.*, Phys. Rev. Lett. **56**, 2364 (1986).

[5] R. Ent *et al.*, Phys. Rev. Lett. **57**, 2367 (1986).

[6] A. Arima, H. Horiuchi, K. Kubodera, and N. Takigawa, Adv. Nucl. Phys. **5**, 345 (1972).

[7] T. A. Carey, P. G. Roos, N. S. Chant, A. Nadasen, and H. L. Chen, Phys. Rev. C **29**, 1273 (1984).

[8] J. C. Vermeulen, A. G. Drentje, H. T. Fortune, L. W. Put, R. R. de Reyter van Steveninck, R. H. Siemssen, J. F. A. van Hienen, and H. Hasper, Nucl. Phys. **A362**, 189 (1981).

[9] D. R. Lehman, Phys. Rev. C **25**, 3146 (1982).

[10] W. C. Parke and D. R. Lehman, Phys. Rev. C **29**, 2319 (1984).

[11] D. R. Lehman and Mamta Rajan, Phys. Rev. C **25**, 2743 (1982).

[12] J. P. Genin, J. Julien, M. Rambaut, C. Samour, A. Palmeri, and Vinciguerra, Phys. Lett. **52B**, 46 (1974).

[13] C. de Vries, C. W. de Jager, L. Lapikas, G. Luijckx, R. Maas, H. De Vries, and P. K. A. de Witt Huberts, Nucl. Instrum. Methods **223**, 1 (1984).

[14] J. H. J. Distelbrink, E. Kok, H. Blok, J. L. Visschers, and P. K. A. de Witt Huberts, Nucl. Instrum. Methods **220**, 443 (1984).

[15] J. J. M. Steijger, M. A. Daman, M. Doets, G. van Gardener, E. Jans, E. Kok, J. H. Mitchell, and J. D. Schipper, Nucl. Instrum. Methods **A295**, 123 (1990).

[16] J. F. J. van den Brand, M. Doets, E. Jans, and J. Kuyt, Nucl. Instrum. Methods A **261**, 373 (1987).

[17] J. F. J. van den Brand, Ph.D. thesis, NIKHEF-K 1988.

[18] Tabor De Forest, Jr., Nucl. Phys. **A392**, 232 (1983).

[19] R. Ent, internal Report No. 85-15, 1985 (unpublished).

[20] F. Hinterberger, G. Mairle, U. Schmidt-Rohr, G. J. Warner, and P. Turek, Nucl. Phys. **A111**, 265 (1968).

[21] S. Boffi, C. Giusti, F. D. Pacati, and S. Frullani, Nucl. Phys. **A319**, 461 (1979).