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$(e,e'p)$ Study of Triton + Deuteron + Proton Clustering in ^{6}Li

J. B. J. M. Lanen,(1) R. G. Lovas,(1,2) A. T. Kruppa,(1,2) H. P. Blok,(3,4) J. F. J. van den Brand,(3)
R. Ent,(3,4) E. Jans,(3) G. J. Kramer,(3) L. Lapikás,(3) E. N. M. Quint,(3) G. van der Steenhoven,(3)
P. C. Tiemeijer,(1) and P. K. A. de Witt Huberts(1,3)

(1)*Fysisch Laboratorium, Rijksuniversiteit Utrecht, 3508 TA Utrecht, The Netherlands*
(2)*Magyar Tudományos Akadémia Atommagkutató Intézete (ATOMKI), Debrecen, H-4001, Hungary*
(3)*Nationaal Instituut voor Kernfysica en Hoge Energiefysica (NIKHEF-K),*
1009 AJ Amsterdam, The Netherlands
(4)*Natuurkundig Laboratorium, Vrije Universiteit, 1007 MC Amsterdam, The Netherlands*

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Cross sections have been measured for the quasielastic $^6\mathrm{Li}(e,e'p)$ reaction in the missing-energy region beyond the $t+d$ threshold, which is dominated by the $\frac{3}{2}^+$ resonance. The data are compared with distorted-wave impulse-approximation calculations, which involve nuclear overlap functions derived from a cluster-distortion model extended to the continuum. The measured recoil-momentum dependence of the $\frac{3}{2}^+$ resonance can only be reproduced if an anomalous longitudinal-transverse ratio is taken into account.

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The electron-induced quasielastic nucleon knockout reaction is one of the cleanest probes of the single-particle (SP) structure of a nucleus.[1-3] For light $0p$-shell nuclei like ^{6}Li this reaction assumes a further dimension: It may reveal the relative importance of SP aspects and clustering aspects. In a previous publication[4] $^6\mathrm{Li}(e,e'p)$ data, for excitation energies below the $t+d$ threshold of the residual system ^{5}He at 16.7 MeV, were compared with the predictions of the shell model[5] and an $\alpha+n+p$ three-body model.[6] The $\alpha+n+p$ model reproduced the data well, whereas the shell model was much less successful. At energies above the $t+d$ threshold, however, the reaction may involve α breakup, and so the $\alpha+n+p$ model is not applicable.

In this Letter we present $^6\mathrm{Li}(e,e'p)$ data for the continuum states of ^{5}He that lie above the $t+d$ threshold. This region is dominated by the $\frac{3}{2}^+$ resonance, of total orbital momentum $L=0$, that lies 60 keV above the $t+d$ threshold.[7] It is well known for its role in nucleosynthesis, in energy-producing fusion, and in neutron generators.[8] In a simple shell model such a $L=0$ state can be viewed as a $(0s)^3(0p)^2$ two-particle–one-hole state, while, in a cluster model, it can be viewed as a $(t+d)$-type structure, which is to be treated as a continuum. Thus, by analyzing this transition, we probe the $0s$ SP orbit or, alternatively, the $(t+d+p)$-cluster component in the ground state of ^{6}Li.

We measured the $^6\mathrm{Li}(e,e'p)$ cross sections in the missing-energy range $0 \leq E_m \leq 30$ MeV and in the range $-100 \leq p_m \leq 200$ MeV/c of missing momentum p_m in parallel kinematics, which means that the proton of initial momentum $\mathbf{p}_m = \mathbf{p} - \mathbf{q}$ is knocked out with momentum $\mathbf{p}$ parallel to the electron momentum transfer $\mathbf{q}$. The relative p-^{5}He kinetic energy $T_{\mathrm{c.m.}}$ was kept constant at 64.8 MeV. The experiment[4] was performed at the coincidence facility at NIKHEF-K.[9] The novelty of the data in comparison with previous results of proton knockout experiments[10,11] on ^{6}Li is that we achieved a thoroughly improved energy resolution (120 keV) at a low level of final-state-interaction (FSI) effects. From the measured cross sections an experimental spectral function $S^{\mathrm{expt}}(E_m,\mathbf{p}_m)$, which contains the nuclear-structure information, was deduced by dividing out the off-shell electron-proton scattering cross section[12] σ_{ep} and a kinematic factor k. The data analysis included unfolding of the radiative tail.[2]

The essentials of the nuclear models considered are the following. The shell model is completely schematic;[4] we identify the ^{6}Li ground state (g.s.) and the $\frac{3}{2}^+$ state of ^{5}He by model states of Yamanouchi symbols[13] [42] and [32], respectively. The cluster model is dynamical and microscopic. It does not only include the Pauli principle but distortions of the clusters in each other's field as well. We describe ^{6}Li as an $\alpha+d$ structure and ^{5}He as a superposition of the $\alpha+n$ and $t+d$ clusterizations, with the scattering boundary condition treated properly.

For the nucleon-nucleon interaction we chose the "optimized" force of Ref. 14, which is a purely central interaction, with the Coulomb interaction included. The model is based on a description of the constituent clusters, d, t, and α, in terms of superpositions of N ($N=5$, 4, and 3, respectively) $0s$ intrinsic harmonic-oscillator (HO) shell-model states of different size parameters. The g.s. energies of these clusters, obtained by diagonalization of the corresponding intrinsic cluster Hamiltonians, are consistent with the experimental values, and the root-mean-square radii are reproduced within the experimental uncertainties.[15] The g.s. of ^{6}Li was described as a superposition of 3×5 $\alpha+d$ terms, corresponding to the various model states of α and d. The ^{5}He state of summed nucleon spin $S=\frac{3}{2}$ only allows clusterization $t+d$, whereas $S=\frac{1}{2}$ allows both $t+d$ and $\alpha+n$. For $S=\frac{1}{2}$ the $t+d$ clusterization is of minor importance and was therefore represented by a single configuration with the parameter of the HO wells chosen to reproduce the sizes of the free clusters. The functions representing the intercluster relative motion were determined by a linear variational method. For the scattering states the boundary condition was treated by Kamimura's method.[16]

Since the force employed exactly reproduces the g.s. energy of ^{6}Li too, the $\alpha+d$, $\alpha+p+n$, and $t+d+p$ separation energies are automatically correct. The remaining free exchange parameter of the force[17] was chosen so as to obtain the $S=\frac{3}{2}$, $L=0$ resonance at the measured energy.

The cross section of the knockout process involves the overlap of the intrinsic nuclear wave functions in the initial and final states, $g_{E_m}(\mathbf{r})=\langle {}^5\mathrm{He},p\,|\,{}^6\mathrm{Li}\rangle_{\mathbf{r}}$, which depends on the relative ^{5}He-p coordinate $\mathbf{r}$. The squared norm, $s(E_m)$, of $g_{E_m}(\mathbf{r})$ will be called the differential spectroscopic factor. In the plane-wave impulse approximation (PWIA) the spectral function $S(E_m,\mathbf{p}_m)$ is proportional to the squared Fourier transform of $g_{E_m}(\mathbf{r})$. It is useful to introduce the energy-integrated quantities

$$\rho_{E_1,E_2}(\mathbf{p}_m)=\int_{E_1}^{E_2} dE_m\, S(E_m,\mathbf{p}_m)\,, \tag{1}$$

which contains the momentum dependence of the spectral function, for given missing-energy interval (E_1,E_2), and

$$S_{E_1,E_2}=\int_{E_1}^{E_2} dE_m\, s(E_m)=\int d\mathbf{p}_m\, \rho_{E_1,E_2}(\mathbf{p}_m)\,, \tag{2}$$

which provides us with a measure of the overall strength in that interval (E_1,E_2).

Since S^{expt} involves FSI effects, for comparison with experiment one has to include these in the calculations. We therefore calculated the cross sections using an unfactorized distorted-wave impulse approximation (DWIA).[18] We used a ^{3}H-p optical potential[19] and an overlap function taken from either the shell model or the cluster model. After division of the calculated unfactorized DWIA cross sections by $k\sigma_{ep}$, the theoretical results can be compared with S^{expt}.

In Fig. 1 the experimental and theoretical values of $\rho(\mathbf{p}_m)$ for the on-resonance $(21.0\le E_m\le 22.0$ MeV) and off-resonance $(22.0\le E_m\le 27.0$ MeV) regions are shown separately. In addition to the statistical uncertainty, the error bars also account for the effect of the 75-keV uncertainty in the missing-energy calibration. To test the description of the FSI, two additional ^{6}Li$(e,e'p)$ measurements in the momentum range $20\le p_m\le 60$ MeV/c were performed at $T_{\mathrm{c.m.}}$ values of 85.8 and 94.2 MeV, respectively. The changes in the cross section (typically 18% beyond the $t+d$ threshold) due to the $T_{\mathrm{c.m.}}$ variation were well reproduced by DWIA calculations with the ^{3}H-p optical potential.

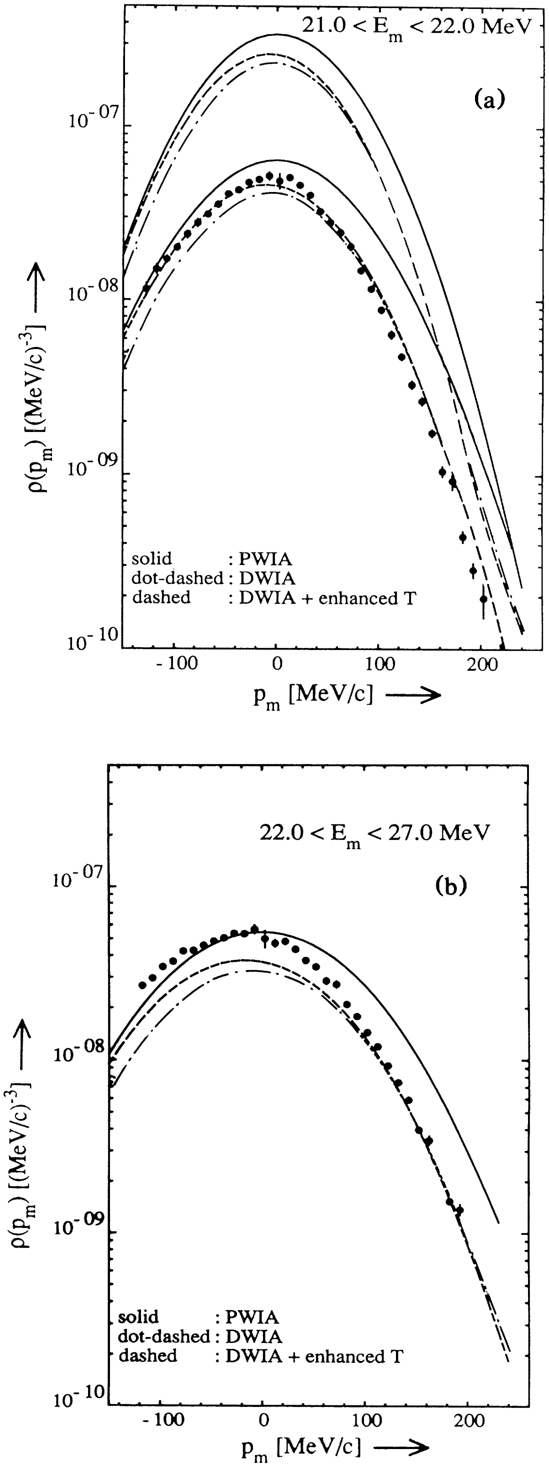

FIG. 1. Experimental and theoretical momentum distributions for (a) $E_1=21.00$, $E_2=22.00$ MeV and for (b) $E_1=22.00$, $E_2=27.00$ MeV. The dashed curves are calculated with a 22% enhanced transverse amplitude. [The upper three curves in (a) are shell-model calculations; the oscillator parameter is 2.03 fm. The other curves are cluster-model results.]

The lack of strength in the DWIA calculations at $p_m \leq 75$ MeV/c may be related to a previously measured longitudinal-transverse (L/T) anomaly, which was observed not only for ^{6}Li (Ref. 20), but for ^{4}He and ^{12}C as well.[3,21] In our measurements the transverse contribution to the cross section increases from 3% to 33% between $p_m = 100$ and -100 MeV/c. We therefore recalcuated the cross sections including a 22% enhancement of the transverse amplitudes, derived from on-resonance data in Ref. 20. While the prediction of the shell model remains poor, from Fig. 1 it is seen that in this way the on-resonance data are described very well by the cluster model, although there remains a discrepency in the off-resonance region. A larger enhancement might well be able to account for this anomaly as was also found in Ref. 22 for the 1s continuum strength in ^{12}C. Following the ideas of Ref. 22 this larger enhancement would be due to the onset of transverse multi-nucleon-knockout processes. We note that the discrepancy cannot be attributed to the nucleon-rescattering contributions[23] to the coincidence cross section, which is estimated to be 5%.

Since the cluster-model calculations are *absolute*, the improved description of the data, using a transverse enhancement, indicates that the previously measured *relative* L/T anomaly is most likely due to a T enhancement instead of a L quenching.

In the cluster-model calculation the major contributions to the wave function of the decaying ^{5}He come from the $S=\frac{3}{2}$ $(t+d)$ partial waves, which confirms that the transition does indeed come from the $t+d+p$ clustering in ^{6}Li. Figure 2 shows the theoretical differential spectroscopic factor $s(E)$ for $S=\frac{3}{2}$ for each partial wave $L \leq 2$. In the missing-energy dependence a comparison between theory and experiment can be made via the quantity

$$n(E_m)=4\pi\int_0^p dp_m\,p_m^2 S(E_m,p_m)\,,$$

with $p=185$ MeV/c, which differs from $s(E_m)$ not only in the truncation of the range of integration, but also in that FSI effects and the L/T anomaly are included. From Fig. 3 we conclude that the agreement is reasonable although the strength is somewhat overestimated in the resonance region.

The experimental on- and off-resonance spectroscopic factors are 0.30 ± 0.04 and 0.53 ± 0.07, respectively. The errors include the statistical uncertainty, a 6% systematical error,[4] and the uncertainties in the description of the FSI effects and in the extrapolation of the momentum dependency up to infinity. The cluster-model values are 0.35 and 0.48, respectively. The contribution of the $S=\frac{1}{2}$ partial waves to the former value amounts to 0.005. The schematic shell model predicts 1.33 for the on-resonance spectroscopic factor.

Our results indicate that the cluster-model interpretation of the results is clearly superior to the shell-model picture. The tendency of the experimental spectroscopic factors to be substantially smaller than the shell-model limits conforms to the systematics found in other $(e,e'p)$ experiments.[1-3] The cluster model reproduces both the momentum and energy distributions of the data quite well. Nevertheless, even the cluster-model spectroscopic factor overshoots the experimental value to some extent, just as in the case of $\alpha+d$ clustering[17,24] and ^{5}He$+p$ clustering below the $t+d$ threshold.[25] This can be explained by noting that the common cluster-model framework tends to trim the model states of ^{6}Li and of its fragments in a similar fashion. Therefore, their overlaps

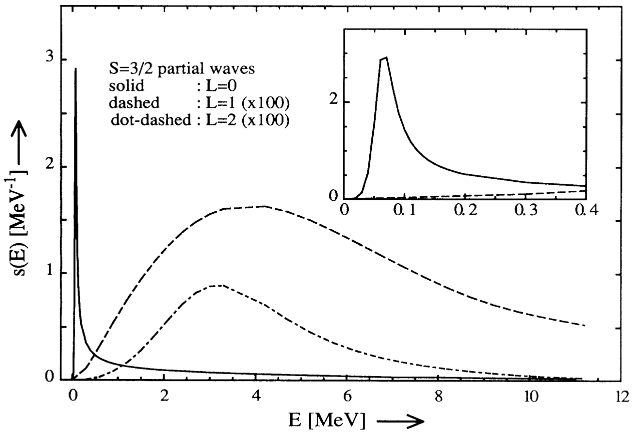

FIG. 2. Cluster-model differential spectroscopic factor $s(E)$ for each partial wave $S=\frac{3}{2}$, $L \leq 2$. Inset: The resonance region expanded. The energy of the $t+d$ threshold corresponds to $E=0$ MeV.

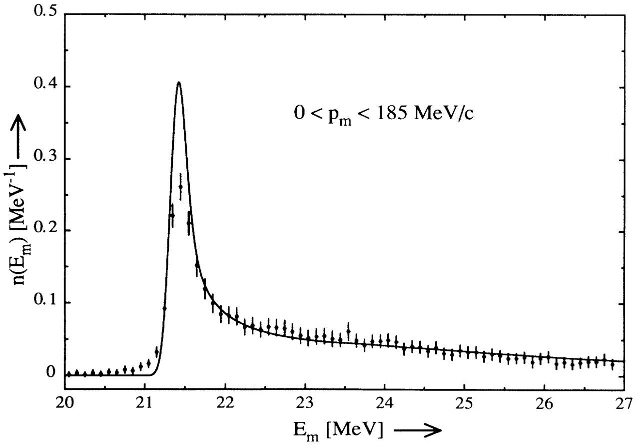

FIG. 3. Missing-energy dependence of the experimental and theoretical spectral functions integrated over the missing momentum up to $p_m = 185$ MeV/c. The theoretical curve has been folded with the 120-keV missing-energy resolution. Only the statistical uncertainty is included in the error bars.

tend to be larger than in reality although the sum rule for proton removal, $S_{0,\infty}=3$, does not allow this tendency to prevail for all energies.

The slight disagreement in the shape of the resonance (Fig. 3) seems to point to a limitation in its description. The most obvious defect of the model is that, for lack of a tensor force, it does not couple the $t+d$ channel of $S=\frac{3}{2}$ with the $\alpha+n$ channel. Thus it could not be used to describe the strong $t+d \rightarrow \alpha+n$ transition. In fact, however, this strong transition does not necessarily imply a strong channel coupling; it has indeed been shown recently[8] that it is due to a shadow pole associated with the $\alpha+n$ channel of $L=2$. In the absence of the coupling, this pole obviously recedes far away from the real energy axis, as we found that the contribution of the $\alpha+n$, $L=2$ channel is very weak and nonresonant. Our result shows that the neglected coupling cannot have a large effect, but there is room for improvement through inclusion of the tensor force in the coupling.

In summary, after including an anomalous L/T ratio consistent with previous measurements on ^{6}Li, the ^{6}Li$(e,e'p)$ transition to the $\frac{3}{2}^+$ resonance is described well by our microscopic cluster model. Beyond the resonance the missing-momentum data below 75 MeV/c indicate that a larger L/T anomaly is needed in this domain. From our cluster-model calculations we learned that the g.s. of ^{6}Li contains a substantial $(t+d+p)$-cluster component. The major part of this component corresponds to the $\frac{3}{2}^+$ resonance of ^{5}He, but the weight of the nonresonant $t+d$ continuum is also appreciable.

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