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ARTICLES

Trinucleon cluster knockout from ^{6}Li

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The momentum-transfer dependence of the ^{3}H and ^{3}He knockout reactions from ^{6}Li via exclusive electron scattering has been measured, and the two reactions are compared. In the absence of two-step processes, the ratio of the fivefold cross sections for these mirror reactions should simply scale by the ratio of the ^{3}H and ^{3}He electron-scattering cross sections. A significant deviation from this simple expectation is seen at low momentum transfer. Possible explanations for this dramatic difference in cross sections for these mirror reactions are discussed. [S0556-2813(98)02204-3]

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The ^{6}Li nucleus has long been considered to be an ideal testing ground for the cluster model of light nuclei. It is natural to think of it in terms of an alpha-particle core and a deuteron or a proton-neutron pair in the (valence) p shell. Various experiments have shown the cluster probability for this configuration to be high [1]. Another cluster-model view of ^{6}Li, the ''heavy-deuteron'' model of a ^{3}He-^{3}H pair, is not as popular, although the idea is not a new one [2]. The most compelling evidence for this model is that the total photoneutron plus photoproton cross section for ^{6}Li shows no evidence for ^{2}H or ^{4}He substructures [2], but looks strikingly like the photodisintegration cross sections for ^{3}He and ^{3}H [3]. It should be pointed out that large values for the cluster probabilities for both ^{2}H-^{4}He and ^{3}He-^{3}H configurations are not mutually exclusive, because the corresponding wave functions are not orthogonal. Likewise, one should not take these models literally, in the sense that real physical clusters exist inside the ^{6}Li nucleus, because the cluster wave functions must be antisymmetrized and this destroys their identity as physical clusters. This question has been the subject of several cluster-model studies of the ^{6}Li nucleus [4–6], where it has been described as a superposition of ^{2}H-^{4}He and ^{3}He-^{3}H configurations.

Although much work has been done on the $(e,e'p)$ reaction in light nuclei and a good deal can be said about both the primary and second-order reaction mechanisms for this process, less is known about the reaction mechanism for the $(e,e'X)$ reaction, where X is itself a light nucleus such as a deuteron, trinucleon, or alpha particle. However, since ^{6}Li is such a good candidate for such studies, our groups have measured the $(e,e'd)$ [7,8], $(e,e'\alpha)$ [9], and $(e,e'\,^3\mathrm{H})$ [10] cluster knockout channels previously. The present report of our measurements of the $(e,e'\,^3\mathrm{He})$ channel [together with our previously reported but not hitherto published $(e,e'\,^3\mathrm{H})$ data] completes this picture. The momentum-transfer (q^2) dependence of the $^6\mathrm{Li}(e,e'd)\,^4\mathrm{He}$ and $^6\mathrm{Li}(e,e'\alpha)\,^2\mathrm{H}$ reactions shows that both the deuteron and the α knockout reactions on ^{6}Li proceed via quasielastic knockout. In this paper we compare the q^2 dependence of the mirror $^6\mathrm{Li}(e,e'\,^3\mathrm{H})\,^3\mathrm{He}$ and $^6\mathrm{Li}(e,e'\,^3\mathrm{He})\,^3\mathrm{H}$ reactions.

The possibility of studying both the ^{3}He and ^{3}H knockout from ^{6}Li is fortuitous in that the expulsion of either one of these three-body nuclei leaves the other one as a spectator. We have measured both reactions at kinematics designed to minimize elastic final-state interactions (FSI's), with the goal of understanding the cluster-formation process in ^{6}Li and the importance of two-step processes in cluster formation. By two-step processes, we mean the knockout of another particle followed by a secondary reaction that produces the detected ^{3}He or ^{3}H cluster. Examples are proton knockout followed by pickup of two additional nucleons or knockout of one three-nucleon cluster followed by a charge-exchange process producing the other one. These processes should be distinguished from elastic FSI effects, by which we mean the interaction of the cluster after its formation with the residual nucleus. In terms of elastic FSI's, noting that both ^{3}H and ^{3}He have spin $\frac{1}{2}$, these two reactions are identical. In a comparison of the ratio of the cross sections, the elastic FSI's will cancel, leaving only the two-step and direct cluster formation processes.

In a naive model, where only direct cluster formation contributes to the trinucleon knockout, the ratio of the cross

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sections as a function of q can be accurately predicted. In the plane-wave impulse approximation (PWIA), the coincidence cross section for the trinucleon knockout can be written [11] as

$$\frac{d^6\sigma}{de'\,dp_X}=K\sigma_{e,3N}S(E_m\,,p_m),$$

where e' is the momentum of the outgoing electron, p_X is the momentum of the outgoing trinucleon, K is a kinematical factor, and $\sigma_{e,3N}$ is the elastic electron-trinucleon cross section corrected for (small) off-shell effects according to the prescription of de Forest [12]. The q^2 dependence of the cross section may be analyzed by keeping the momentum of the outgoing cluster constant and allowing the four-vector momentum of the virtual photon to vary. Integrating the sixfold differential cross section over the elastic peak of the trinucleon cluster in the missing-energy spectrum, one obtains the fivefold differential cross section

$$\frac{d^5\sigma}{dE_{e'}\,d\Omega_{e'}\,d\Omega_{X'}}=R\int_{\Delta E_m}\frac{d^6\sigma}{dE_{e'}\,d\Omega_{e'}dE_{X'}\,d\Omega_{X'}}dE_m,$$

where R is the recoil factor, and the fivefold cross section is expressed as a function of q^2.

It has been observed in deuteron-knockout experiments on ^{3}He [13], ^{4}He [8], and ^{6}Li [7,8] that the rate of decrease of the cross sections with momentum transfer scales globally with the average distance between the proton and the neutron in the appropriate shell of the target nucleus. In the naive cluster description of the trinucleon-knockout reactions from ^{6}Li, the ratio of the fivefold cross sections as a function of q^2 should simply scale by the ratios of trinucleon form factors squared. These form factors have about the same q dependence, so that the fivefold cross sections should just differ in absolute magnitude by about a factor of 4 due to the charge difference. For a detailed analysis, the actual form factors of the ^{3}H and ^{3}He nuclei, which are well known from elastic electron-scattering experiments [14,15], can be used. The inclusion of two-step processes may cause a deviation away from this expectation. Assuming that the two-step processes have a significantly different momentum-transfer dependence than the direct cluster formation, we can gain an insight into the role of two-step processes in cluster formation by examining this ratio.

The measurements reported here were performed at the NIKHEF-K electron accelerator. The incident electron energies were 484.5 MeV for the ^{3}He knockout measurements and 456 MeV and 524 MeV for the ^{3}H knockout measurements. The high-resolution QDD spectrometer was used to detect the scattered electrons, while the knocked-out trinucleon clusters were detected in the large solid-angle QDQ spectrometer [16]. We used the standard detector setup in the QDQ spectrometer to detect the ^{3}H particles. To measure the low-energy ^{3}He particles the QDQ spectrometer was modified to include a low-pressure recoil detector to detect low-energy knocked-out clusters. It is a low-pressure time-projection chamber, constructed to work adjacent to the vacuum of the magnetic spectrometer in order to detect low-energy particles. The detector consists of a multiwire proportional chamber for tracking information, a parallel-plate avalanche chamber used as a trigger, and a scintillator for energy determination. The intrinsic resolutions of the detector are 0.3–0.5 mm in position and 0.3°–0.5° in angle, both full width at half maximum (FWHM). However, the measured resolution is both energy and particle dependent. The detector is by design virtually insensitive to the large proton production rate accompanying the low-energy ^{3}He knockout rate. A complete description of the setup is given in Ref. [17].

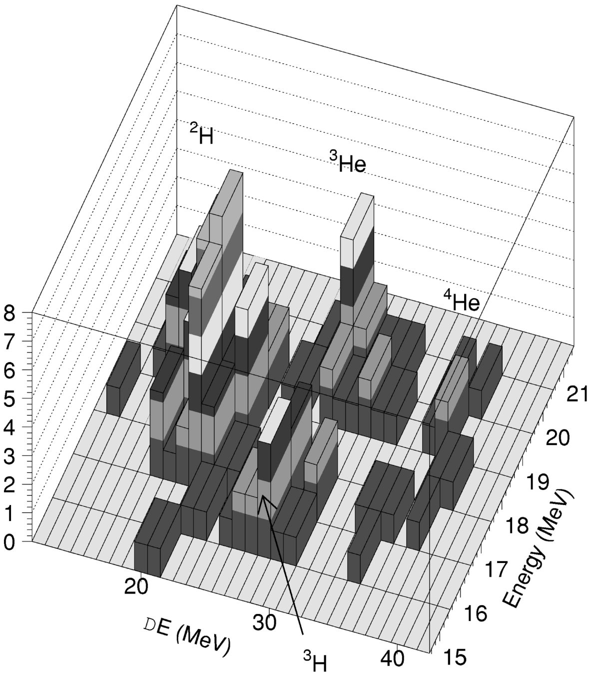

FIG. 1. Correlation between the pulse-height spectra of the two scintillators in the hadron spectrometer. Data are from the ^{6}Li$(e,e'{}^3\mathrm{H})^3$He measurement [10].

The measurements were performed in parallel kinematics ($\mathbf{p_X}$ parallel to $\mathbf{q}$) at a central missing-momentum value p_m of 75 MeV/c. The $(e,e'{}^3\mathrm{He})$ data were taken at four different center-of-mass energies, the $(e,e'{}^3\mathrm{H})$ data at five different center-of-mass energies. The targets for the respective measurements were self-supporting foils of 6.1 and 8.3 mg/cm^2, enriched to 98.7% in ^{6}Li. For the ^{6}Li$(e,e'{}^3\mathrm{H})$ experiment, particle identification was accomplished by pulse-height discrimination in the two scintillator layers behind the multiwire proportional drift chambers. For the ^{6}Li$(e,e{}^3\mathrm{He})$ experiment, particle identification was accomplished by discrimination of deposited signals in the parallel-plate avalanche counter and the thin scintillator. Figure 1 shows a correlation plot from the ^{3}H knockout experiment. The triton, deuteron, alpha-particle, and ^{3}He peaks can be identified clearly. In addition to software cuts on the cluster of interest, the data analysis included subtraction of accidentals and unfolding of the radiative tail [16]. Figure 2 shows a (radiatively unfolded) missing-energy spectrum from the ^{6}Li$(e,e'{}^3\mathrm{He})$ reaction, at a center-of-mass energy of 27 MeV. One can see the transition to the ^{3}H ground state and the onset of the ^{3}H breakup channels. In the remainder of this article we will only discuss the transition to the ^{3}He or ^{3}H ground state.

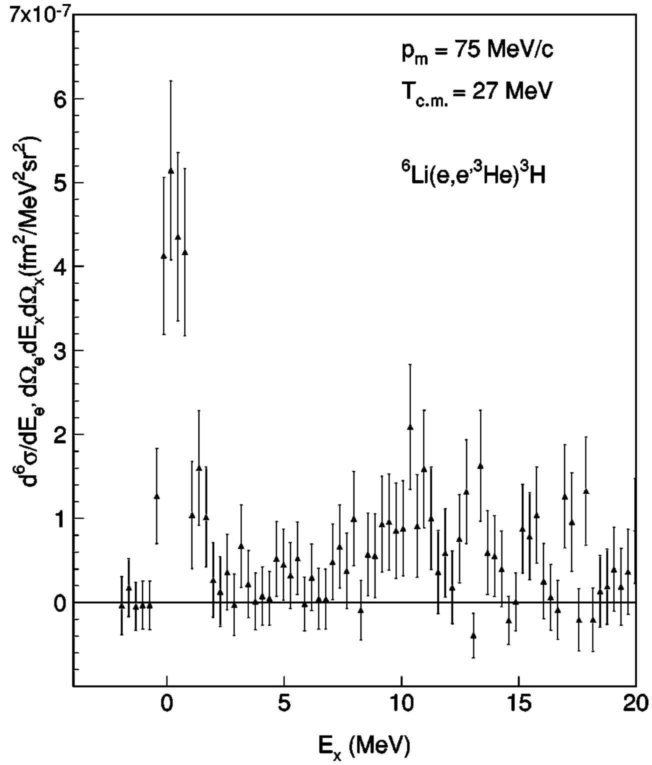

FIG. 2. Excitation-energy spectrum of the reaction ^{6}Li(e,e'^3He) at a center-of-mass energy of 27 MeV. Accidentals have been subtracted. Detector acceptance and radiative tails have been unfolded.

The fivefold cross sections for the ^{6}Li(e,e'^3H)^{3}He and the ^{6}Li(e,e'^3He)^{3}H reactions are shown as a function of q^2 in Fig. 3. The curves represent the expected behavior (normalized to the data point at intermediate q) of the cross section for direct trinucleon knockout, assuming a direct-knockout model. The expected behavior takes the variation of the recoil factor R and the experimentally determined ^{3}H and ^{3}He form factors [14,15] into account. When comparing the ^{6}Li(e,e'^3H)^{3}He and the ^{6}Li(e,e'^3He)^{3}H fivefold cross sections, one sees that the experimental falloff of the data is far steeper for the (e,e^3He) case. For comparison, we have also included the previously obtained results of the ^{6}Li(e,$e'd$)^{4}He and the ^{6}Li(e,e'^4He)^{2}H reactions, together with the expected behaviors assuming a direct-knockout mechanism [7,9]. As in the (e,e'^3He) knockout case, the experimental falloff of these reactions is reasonably well described by the direct-knockout curves. In contrast, the experimental falloff of the (e,e'^3H) reaction is far shallower than the direct-knockout mechanism predicts.

To emphasize the deviation of the ^{6}Li(e,e'^3He)^{3}H cross section from the ^{6}Li(e,e'^3H)^{3}He cross section, we show in Fig. 4 the ratio of these cross sections with respect to the ratio of the direct trinucleon cluster-knockout curves [approximately equal to the cluster charges squared ($Z^2_{\mathrm{He}}/Z^2_{\mathrm{H}}=4$)]. Especially at the lowest value of q, the (e,e'^3H) knockout channel is significantly weaker than the (e,e'^3He) knockout channel. The large deviation of the ratio of the trinucleon knockout cross sections at the lowest q gives reason to believe that the role of two-step processes is large in either one of the reaction channels or both. Since the α particle is a very tight system, one would expect ^{6}Li to be,

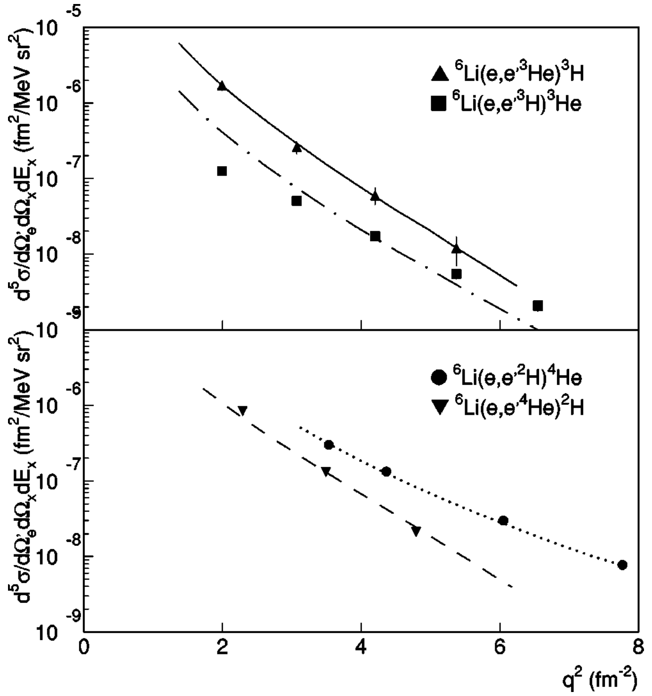

FIG. 3. Dependence of the fivefold cross sections on the value of q^2 for electron-induced knockout of ^{2}H, ^{3}H, ^{3}He, and ^{4}He from ^{6}Li. The present data on ^{3}H knockout (squares) and ^{3}He knockout (upwards triangles) are shown in the top plot. Curves are calculations assuming a direct cluster-knockout mechanism, normalized to a data point at intermediate momentum transfer. Data for ^{2}H (circles) and ^{4}He (downwards triangles) are taken from Refs. [7] and [9], respectively, and are shown in the bottom plot.

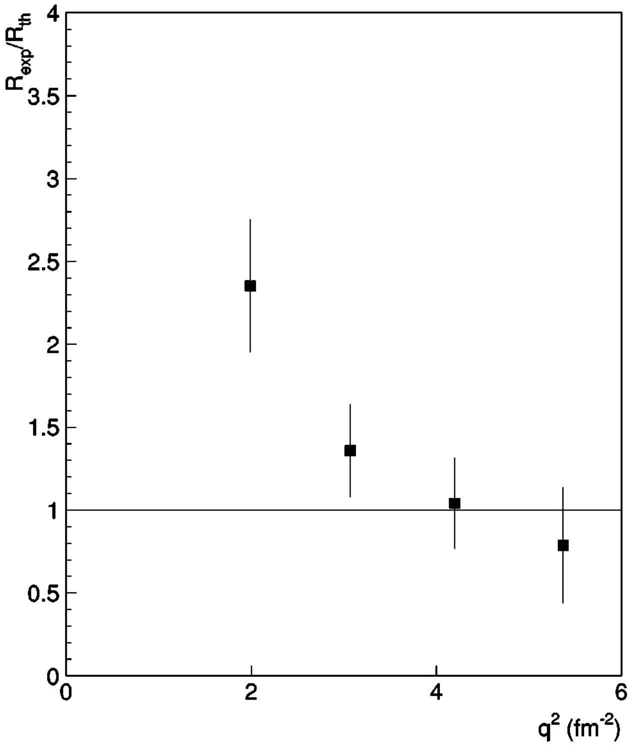

FIG. 4. Ratio R_{expt} of the fivefold cross sections for electron-induced knockout of ^{3}He and ^{3}H from ^{6}Li with respect to the ratio R_{th} of the trinucleon electromagnetic form factors squared [14,15].

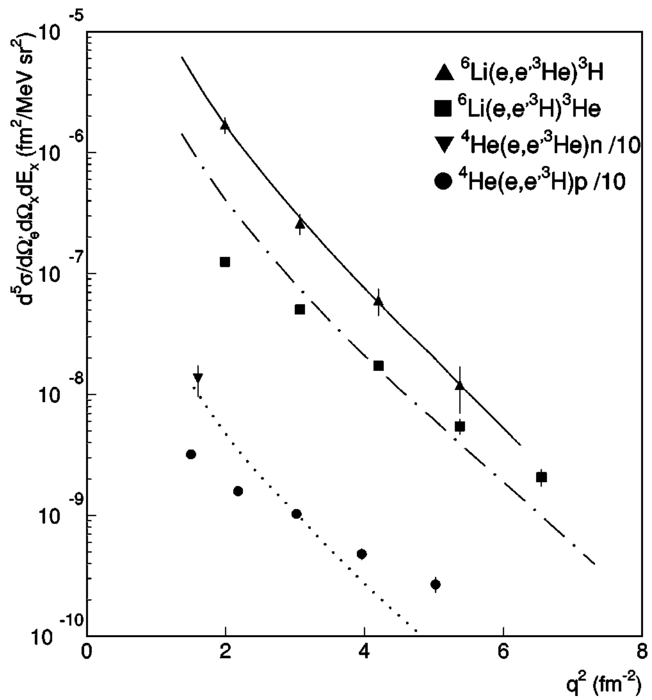

FIG. 5. Momentum-transfer dependence of the fivefold cross sections for the ^{6}Li$(e,e'{}^3$He$)^3$H, ^{6}Li$(e,e'{}^3$H$)^3$He, ^{4}He$(e,e'{}^3$He$)n$ and ^{4}He$(e,e'{}^3$H$)p$ reactions. Note that the data for the latter two reactions, taken from Ref. [19], have been rescaled by a factor of 1/10. Curves are calculations assuming a direct cluster-knockout mechanism, normalized to a data point at intermediate momentum transfer. Since only one data point is available for the ^{4}He$(e,e'{}^3$He$)n$ reaction, no curve has been added for this case.

most of the time, in an α-d configuration (even though the ^{3}H-^{3}He configuration occurs some of the time) [18]. Assuming this α-d configuration and assuming the initial process to be single-nucleon knockout, the most likely two-step process would be $(e,e'p)(p,X)$, where the initial struck proton picks up a two-nucleon pair. If initially striking a proton in the deuteron cluster, there is no obvious difference between later picking up a deuteron or a two-neutron cluster to form either a knocked-out ^{3}He or a ^{3}H cluster. However, if initially striking a proton in the ^{4}He core, pickup of the preexisting deuteron cluster may be enhanced with respect to pickup of two neutrons. Thus, one may think the most likely explanation of the enhanced ratio of ^{6}Li$(e,e'{}^3$He$)^3$H knockout with respect to ^{6}Li$(e,e'{}^3$H$)^3$He knockout to be the role of the $(e,e'p)(p,{}^3$He$)$ pickup process. However, it is the ^{6}Li $(e,e'{}^3$He$)^3$H reaction channel which seems to have the momentum-transfer dependence that the direct cluster knockout model prescribes. Therefore, the large deviation found in the cross-section ratio indicates that a reduction of the ^{6}Li$(e,e'{}^3$H$)^3$He channel is more likely than an enhancement of the $(e,e'{}^3$He$)$ channel.

In Fig. 5 we show the q dependence of the present data in combination with ^{4}He$(e,e'{}^3$He$)n$ and ^{4}He$(e,e'{}^3$H $)p$ data [19,20]. The ^{4}He data shown here were measured at a central missing momentum p_m of 180 MeV/c. The internal comparison of the ^{4}He data sets and the ^{6}Li data sets reveals two observations: (1) The $(e,e'{}^3$He$)$ cross sections are far larger than the $(e,e'{}^3$H$)$ cross sections at low momentum transfer, and (2) the momentum-transfer dependence of the ^{4}He$(e,e'{}^3$H $)p$ cross sections is far shallower than that of the ^{6}Li$(e,e'{}^3$He$)^3$H cross sections, and slightly shallower than that of the ^{6}Li$(e,e'{}^3$H$)^3$He cross sections. The large difference in the q dependence of the cross sections for both $(e,e'{}^3$He$)$ knockout reactions and both $(e,e'{}^3$H$)$ knockout reactions seems to confirm the influence of an additional reaction mechanism. Such a mechanism could be charge exchange in the final state, which transforms a triton into a ^{3}He particle or vice versa. This mechanism has been suggested to explain the behavior of the ^{4}He$(e,e'{}^3$He$)$ and ^{4}He$(e,e'{}^3$H$)$ cross sections [20]. The inclusion of the final-state charge-exchange process $^3\text{He}+n\leftrightarrow{}^3\text{H}+p$ was shown to reduce the ^{4}He$(e,e'{}^3$He$)$ cross section only slightly, but to yield a far larger reduction in the ^{4}He$(e,e'{}^3$H$)$ cross section, the effect being largest at lower values of q. This differential effect on the cross sections results from the fact that the direct $(e,e'{}^3$He$)$ cross section is much larger than the direct $(e,e'{}^3$H$)$ cross section, so that the charge-exchange contribution to the $(e,e'{}^3$He$)$ reaction is from the weaker channel into the stronger channel, but just reversed for the $(e,e'{}^3$H$)$ reaction. A qualitative coupled-channel calculation for this charge-exchange effect for the present reactions on ^{6}Li has been done in a PWIA formalism. Similar to the case of the ^{4}He target nucleus [20], we find that the $(e,e{}^3$He$)$ channel is little affected, while the $(e,e'{}^3$H$)$ channel is reduced easily by some tens of percent.

To summarize, we have measured the mirror ^{6}Li$(e,e'{}^3$He$)^3$H and ^{6}Li$(e,e'{}^3$H$)^3$He reactions. The momentum-transfer dependence of the measured $(e,e'{}^3$H$)$ cross section is in striking disagreement with the most simple direct-knockout expectations. Whereas the momentum-transfer dependence of the ^{3}He knockout channel conforms to a simple trinucleon knockout mechanism, the dependence of the ^{3}H knockout channel is far shallower. At low momentum transfer, the ratio of the ^{3}He knockout to the ^{3}H knockout channel seems to be far larger than the ratio of the trinucleon form factors squared. The behavior of the experimental cross sections for both trinucleon knockout channels resembles previous data for the ^{4}He target nucleus. The difference in the momentum-transfer dependence of the ^{3}He and ^{3}H knockout reactions seems to indicate a substantial role for two-step processes in these reactions. A likely candidate is charge exchange in the final state.

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