Interaction of relativistic helium projectile fragments in nuclear emulsions

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Estimates of the mean free path of relativistic ^{6}He in nuclear emulsion strongly suggest that it is much shorter than the ^{3}He or ^{4}He mean free path. A discussion is given of the important implications of this difference for the interpretation of recent data on secondary helium fragments produced in interactions of relativistic primary beams.

An important part of the controversy concerning the existence of anomalons involves the characteristics of relativistic helium projectile fragments in nuclear emulsions. These characteristics have been studied in several recent experiments.[1] The purpose of this Brief Report is to emphasize the possibility that an appreciable fraction of these helium fragments may be ^{6}He, and that the difference between the ^{6}He and ^{4}He mean free path (mfp) (isotope effect[2]) can play an important role in explaining the observed phenomena.

Our first task is to estimate the mfp of the isotopes ^{3}He, ^{4}He, and ^{6}He in nuclear emulsions.[3] We use the soft-spheres model of Karol.[4] For the isotope ^{4}He, we use a wave function calculated[5] with a nucleon-nucleon potential which contains a hard core of radius 0.5 fm. The average nucleon-nucleon total cross section at 2 GeV, which is one of the parameters of the model, is then adjusted to yield a ^{4}He mfp of 20 cm.[6] The resultant value turns out to be 40 mb, which is in good agreement with experiment. This supports the applicability of the model and the adequacy of our ^{4}He wave function.

With no further adjustable parameters, we compute next the mfp of ^{3}He, again with the wave function given in Ref. 5. Here we find an mfp of 20.81 cm. This value is very close to the mfp of ^{4}He. Hence, for our present discussion, it is not necessary to make any distinction between ^{3}He and ^{4}He. Whenever we speak of ^{4}He in the following, it should always be understood that a mixture of ^{3}He and ^{4}He is actually meant.

Because of its short half-life (0.8 sec),[7] the properties of the ^{6}He ground state are not well determined, and this introduces uncertainty into the calculation of its emulsion mfp. However, we do know that the ^{6}He ground state is the isobaric analog of the 3.56 MeV, $T=1$ excited state of ^{6}Li. Thus, we begin by constructing a simple model for ^{6}Li, and then proceed to the ^{6}He case by making relatively minor modifications.

For the ground state of ^{6}Li, we adopt a $\mathrm{d}+\alpha$ cluster model and employ a wave function of the form

$$\psi_6=\phi_{\mathrm{d}}\phi_\alpha\chi(\mathbf{s})\xi \quad , \tag{1}$$

where ξ is an appropriate spin-isospin function for $T=0$ and $S=1$, and $\chi(\mathbf{s})$ is a normalized intercluster relative-motion function. Also, ϕ_α denotes the α-cluster spatial wave function mentioned above and ϕ_{d} denotes the d-cluster spatial wave function chosen to be the $4G$ function given in Table I of Ref. 8. As indicated in Eq. (1), we have made the simplification of omitting the antisymmetrization between nucleons in different clusters. This is in fact not unreasonable, since the $\mathrm{d}+\alpha$ separation energy is small [1.47 MeV (Ref. 7)] and, therefore, the d and α clusters are expected to be spatially rather well separated.

With the wave function of Eq. (1), the ^{6}Li density distribution is given by

$$\rho_6(R)=\int|\chi(\mathbf{s})|^2[\rho_\alpha(\mathbf{R}-\tfrac{1}{3}\mathbf{s})+\rho_{\mathrm{d}}(\mathbf{R}+\tfrac{2}{3}\mathbf{s})]d\mathbf{s} \tag{2}$$

and the root mean square (rms) matter radius is

$$R_6=[\tfrac{2}{3}R_\alpha^2+\tfrac{1}{3}R_{\mathrm{d}}^2+\tfrac{2}{9}\langle s^2\rangle]^{1/2} \ . \tag{3}$$

Here R_α and R_{d} are the rms matter radii of the α and d clusters, respectively. To determine $\chi(\mathbf{s})$, we assume an intercluster interaction potential which has a nuclear part of Woods-Saxon form. The diffuseness parameter is found not to be critical and a reasonable value of 0.5 fm is assumed. The radius parameter and the strength parameter are then adjusted to yield the correct separation energy of 1.47 MeV and the correct rms matter radius of 2.44 fm.[9]

With $\chi(s)$ and thus $\rho_6(R)$ determined, we can then calculate the mfp of ^{6}Li in emulsion by using the soft-spheres model. The result is $\lambda(^6\mathrm{Li})=14.4$ cm, which agrees well with the experimentally determined value.[10]

Now, we consider the ^{6}He case. In analogy with our ^{6}Li procedure, we adopt a dineutron (or d*)-plus-α model; i.e., we use

$$\psi_6^*=\phi_{\mathrm{d}^*}\phi_\alpha\chi^*(\mathbf{s})\xi^* \tag{4}$$

and proceed to compute $\lambda(^6\mathrm{He})$ in the following two steps.

(i) In the first step, ϕ_{d^*} is assumed to be the same as ϕ_{d}. The strength parameter of the intercluster potential is adjusted to yield the experimental value[7] of 0.975 MeV for the $\mathrm{d}^*+\alpha$ separation energy. Using the resultant relative-motion function χ^*, we find that the rms matter radius and the mfp of ^{6}He are equal to 2.75 fm and 13.45 cm, respectively.

(ii) Since the d* cluster in ^{6}He is expected to be more spatially extended than the d cluster in ^{6}Li, the value of $\lambda(^6\mathrm{He})$ obtained above is probably an overestimate. However, we can get some further information about the size of ^{6}He by using the fact that the measured excitation energy of the first $L=2$ excited state of ^{6}He is only half as large as that of the corresponding excited state of ^{6}Li.[11] A simple calculation using a two-cluster rigid-rotator model then yields an estimate for the ^{6}He rms matter radius of 3.05 fm. To achieve this value within our $\alpha+d^*$ model of ^{6}He, we use a ϕ_{d^*} which has the same $4G$ form as ϕ_{d}, but with the nonlinear parameters α_i (see Ref. 8) scaled down by a factor of 0.41. Using this procedure, and the same relative-motion function χ^* as in the first step, we obtain $\lambda(^6\mathrm{He}) = 12.6$ cm, which is significantly smaller than the 20 cm mfp of ^{4}He.

This difference between $\lambda(^6\mathrm{He})$ and $\lambda(^4\mathrm{He})$ implies that the mfp for projectile fragments containing both isotopes will vary with the distance D from the point of creation (local-mfp effect). This variation is given by

$$\lambda(D) = \sum_{i=1}^{2} f_i \exp(-D/\lambda_i) \Big/ \sum_{i=1}^{2} (f_i/\lambda_i)\exp(-D/\lambda_i) \ , \quad (5)$$

where f_i denotes the initial fraction of the ith component and λ_i is the corresponding component mfp. Figure 1 shows $\lambda(D)$ for various choices of f_i, using the values of $\lambda(^4\mathrm{He})$ and $\lambda(^6\mathrm{He})$ estimated above (20 and 12.6 cm, respectively). We note that λ is a slowly increasing function of D in the D range of 0–12 cm, and that relatively small admixtures of ^{6}He can significantly decrease λ below the ^{4}He value of 20 cm.

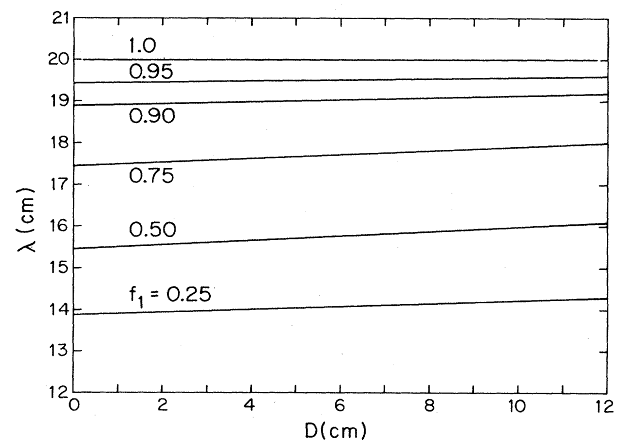

FIG. 1. Local mfp λ as a function of D, the distance from the point of creation. The quantity f_1 denotes the fraction of ^{4}He among the projectile fragments.

El-Nadi *et al.*[12] have recently measured the local mfp of the He projectile fragments produced by an incident 3.66*A*-GeV ^{12}C beam. They observed that the local mfp of fragments produced in "white-star interactions" (no heavy target fragments) is nearly constant at the surprisingly small value of 13 ± 2 cm. We see from Fig. 1 that this is consistent with a ^{6}He admixture of approximately 50%. Unfortunately, there exists no theory able to give quantitative predictions of the relative numbers of ^{4}He and ^{6}He produced in white-star interactions. However, according to the impulse production mechanism proposed in Ref. 2, it is not unlikely that the combined effects of nuclear and Coulomb impulses during a white-star interaction may cause the ^{12}C to be excited to a $^6\mathrm{He}+{}^6\mathrm{Be}$ binary cluster configuration, which subsequently decays to yield one ^{6}He, one ^{4}He, and two protons. Thus, it is possible that the production probability of ^{6}He may be quite large. Qualitatively, this is not inconsistent with the recent measurements of Olson *et al.*,[13] utilizing ^{12}C projectiles at 2.1*A*-GeV on targets ranging from Be to U. In these inclusive measurements, it was found that the production of ^{6}He is about half a percent of the total $Z=2$ yield. Considering that, in heavy-ion interactions, only about 10% of all events are white-star events[14] and that, due to the α-cluster structure of ^{12}C, several α particles and essentially no ^{6}He nuclei are expected to appear in a non-white-star event, one can conclude that, at relativistic energies, the assumption of a large ^{6}He production probability in white-star ^{12}C interactions does not seem to be unreasonable.

In our opinion, the result of Olson *et al.*[13] cannot be used directly to analyze the data of El-Nadi *et al.*,[12] because these two experiments were performed at quite different energies. Thus, it would indeed be interesting to measure the ^{6}He production probability with ^{12}C projectiles at 3.66*A*-GeV in an experiment similar to that carried out by Olson *et al.* The result of such an experiment should be very useful for our present consideration.

The above discussion suggests that ^{6}He fragments may be produced in relatively larger numbers in white-star interactions. Since the ^{6}He nucleus is rather diffuse, its subsequent collision with an emulsion nucleus may cause less excitation than collision due to ^{4}He. Thus helium fragments from primary white-star collisions may be more likely to initiate secondary white-star collisions. Indeed, such a correlation has been observed in the experiment of El-Nadi *et al.*[12]

In terms of target fragmentation, ^{4}He and ^{6}He should have rather distinct signatures. Because of the diffuse nature of ^{6}He, there is an appreciable probability that the target nucleus may fragment while receiving relatively little momentum from the ^{6}He nucleus. This would result in target fragments more isotropically distributed in a ^{6}He interaction than in a ^{4}He interaction. At present, there are no high-statistics measurements which can verify this prediction, but the experimental findings of Klein *et al.*[15] may be relevant.

Ismail *et al.*[16] have studied helium projectile fragments produced by 2*A*-GeV beams of ^{40}Ar and ^{56}Fe. Within the experimental uncertainty of about 1 cm, the fragment mfp are consistent with the mfp of primary helium (i.e., about 20 cm), and there seems to be no local-mfp effect. Figure 1 then implies that the ^{6}He abundance in the helium fragments is less than about 10%. A comparison of these results with those of El-Nadi *et al.*[12] discussed above indicates that the relative numbers of secondary ^{6}He and ^{4}He may depend strongly on the primary beam energy and/or nuclear species. It would, therefore, be valuable to have helium-fragment data for a 2*A*-GeV primary ^{12}C beam.

In conclusion, we note that it would be interesting to compare the properties of helium projectile fragments produced by relativistic ^{20}Ne and ^{22}Ne beams in nuclear emulsions. Because of the different cluster structures of these Ne isotopes, ^{22}Ne interactions can be expected to produce relatively more ^{6}He fragments. Thus, it is our expectation that the helium fragments from these two beams will exhibit different mfp behavior.

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