A QUASI-EXCLUSIVE MEASUREMENT OF ^{12}C(^{12}C, 3α)X AT 2.1 GeV/NUCLEON

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A study of the reaction ^{12}C(^{12}C, 3α)X at 2 1 GeV/nucleon has been completed The energy and momentum transferred to the ^{12}C projectile and the cross section for the dissociation of ^{12}C into three alpha particles have been measured, 9 7 (+5 0/−2 5) millibarns It is found that the results from this analysis are inconsistent with the predictions of current theoretical models for peripheral relativistic heavy ion collisions

In recent years several theoretical models [1–6] have been proposed to describe the reaction mechanism involved in relativistic heavy ion collisions. In these models, projectile fragments are produced in the decay of an excited projectile [3–6] or in the dissociation of participants and a spectator [1,2]. In the abrasion–ablation model [1,2] the participants and spectator are determined by viewing the impacting nuclei as overlapping spheres. The participants in the overlap region are knocked out and the resultant spectator is allowed to decay. This model has a rather soft excitation spectrum. The other models excite the projectile through the exchange of a "phonon" [3] of the strong force or through nucleon–nucleon collisions [4,6]. These models [3–6] predict excitation spectra which extend beyond 100 MeV. The main difference in the models is the range of the predicted energy spectra and not in the final particle yields, which are known to be comparable.

These theoretical studies were stimulated by the combination of emulsion studies [7,8] and the single-particle inclusive measurements [9–12] made in the last decade. Neither of the two sets of data were able to provide sufficient information to test the models. The Heavy Ion Superconducting Spectrometer (HISS) [13,14] at the Lawrence Berkeley Laboratory Bevalac

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was designed to measure simultaneously the charge, mass, and vector momentum of all charged-projectile fragments in a nuclear interaction. This provided a measure of both the yield and the excitation energy spectra.

We report here the first quasi-exclusive measurement of the three-alpha dissociation channel for 2.1 GeV/nucleon ^{12}C projectiles on a ^{12}C target. The possibility of separating direct reactions from sequential decays was expected to be particularly enhanced for this dissociation channel. The bombarding energy is above the threshold where the limiting fragmentation and factorization hypotheses have been found to apply for single-particle inclusive data [9].

The experimental setup at HISS is shown in fig. 1 and includes beam definition scintillators for defining an event trigger, drift chambers for determining particle trajectories and a time-of-flight (TOF) scintillation array. The event trigger of the experiment required a single ^{12}C projectile to strike the target and no uninteracted ^{12}C nucleus to be seen exiting the spectrometer. The rigidity, $\boldsymbol{R}$, of each projectile fragment was determined to 0.1% accuracy be employing the position information obtained from the drift chambers and tracing through the mapped field. The TOF scintillation array was used to measure the velocity, β, and the charge, Z, of the fast ions to an accuracy of $\Delta\beta/\beta = 0.9\%$ and $\Delta Z = 0.1$ charge units, respectively. The mass of each projectile fragment was then calculated from the measured values for rigidity, velocity and charge using the following equation

$$m = RZ(1/\beta^2 - 1)^{1/2} .$$

The standard deviation for the masses of the different isotopes with charge equal to two was approximately 175 MeV/c^2.

We measured a total cross section of 790 ± 35 mb for 2.1 GeV/nucleon ^{12}C scattering on a 0.9 g/cm^2 ^{12}C target, which agrees with the expected value of 810 ± 20 mb [11]. This measurement coupled with the agreement between a sample of our data and the single-particle inclusive data of Olson et al. [9], provided an excellent check on the results of this experiment. As a further check, the momentum distributions

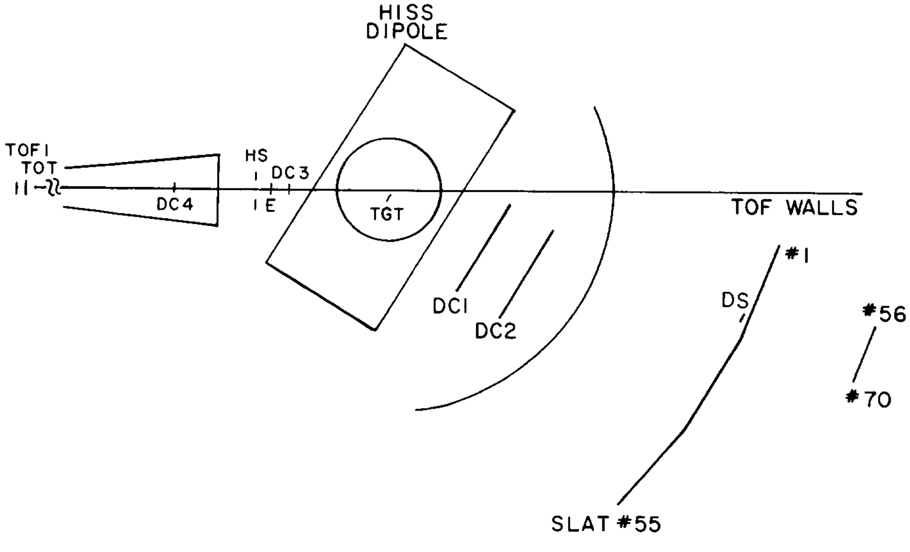

Fig. 1. Placement of the detectors in the ^{12}C dissociation experiment. Beam scintillators TOF 1, TOT, HS, E, and DS were used to define the logic trigger (TOF 1·TOT·E·$\overline{HS}$·$\overline{DS}$). Drift Chambers DC 4, DC 3, DC 1, and DC 2 were used to determine the trajectories of the incoming ^{12}C projectile and the outgoing projectile fragments. The TOF wall, an array of scintillators, was used to determine the charge and transit time of all the projectile fragments.

Table 1
A comparison of the momentum distribution for the alpha particles from three-alpha events with the momentum distributions of alpha particles from the single-particle inclusive studies of ^{12}C(^{12}C, α)X.

Experiment	Momentum distribution					
	center			width		
	$P_{\parallel}^{\mathrm{proj}}$	$P_{\mathrm{Y}}^{\mathrm{proj}}$	$P_{\mathrm{X}}^{\mathrm{proj}}$	$\sigma P_{\parallel}$	σP_{Y}	σP_{X}
This experiment	−5 ± 65	−15 ± 10	−5 ± 40	145 ± 45	145 ± 35	140 [a]
Greiner et al.	−25 ± 4	–	–	129 ± 1	–	–
Anderson et al. [b]	0	0	0	136.5	140.4	140.4

[a] The width of the $P_{\mathrm{X}}^{\mathrm{proj}}$ distribution reduces from 186 MeV/c to 140 MeV/c when the alpha particle loss due to the granularity of the detectors is taken into account.

[b] Uncertainties associated with the determination of the momentum and angle acceptances constitute the principle source of error (10–15%) in the data of Anderson et al.

of the alpha particles in the three-alpha dissociation channel were compared to the single particle results of Greiner et al. [10] and Anderson et al. [12]. As shown in table 1, the data were found to be consistent with both of those experiments. The anisotropy between the transverse and the longitudinal directions of the momentum transfer predicted by Feshbach and Zabek's phonon model [3] was not observed in this data set.

A comparison between the perpendicular momentum and the parallel momentum for all alpha particles in the three-alpha events was made. The results of that comparison are shown in fig. 2 overlaid with the theoretical predictions for α–nucleon and α–α elastic scattering. Within the resolution of the data, neither elastic curve is discernible. The absence of a clear elastic scattering signal is inconsistent with the alpha-particle model proposed by Faldt and Gislen [2] in which the basic interaction is assumed to be the α–nucleon interaction.

A second fundamental quantity whose measurement was made possible by the exclusive nature of this experiment was the excitation energy,

$$E^* = \left(\sum_{i=1}^{3} P_i^2(\alpha)\right)^{1/2} - M_{^{12}\mathrm{C}} \,.$$

The observed excitation energy spectrum is shown in fig. 3. Although the three-alpha dissociation channel was not affected by the angular acceptance of the spectrometer, it was greatly affected by the granularity of the detectors. Because of this granularity, we were unable the resolve alpha pairs with relative momentum of less than 75 MeV/c. The needed energy acceptance of the spectrometer for this dissociation channel was determined by tracking a set of simulated events through the system. The corrected spectra for the three-alpha cross section as a function of excitation energy is also shown in fig. 3. The effect of the granularity of the detectors is reflected in the

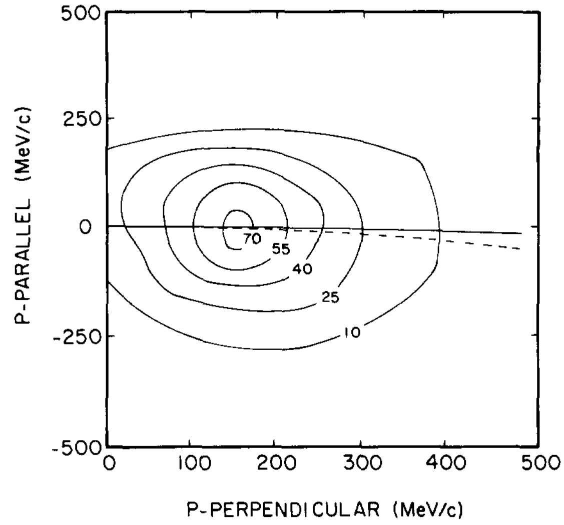

Fig. 2. A plot of the perpendicular versus parallel momentum for individual alpha particles in the projectile frame with the α–nucleon elastic scattering (solid) curve and the α–α elastic scattering (dashed) curve superimposed.

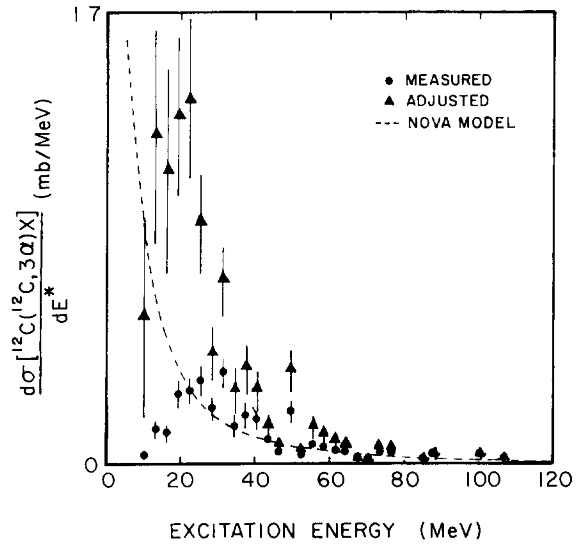

Fig. 3. Plot of the number of three-alpha events observed (●) and adjusted (△) versus the computed excitation energy, E^*, of their parent ^{12}C nuclei, where E^* is the difference between the invariant mass of the three-alpha system and the mass of the ^{12}C projectile. The corrected values were obtained by adjusting the observed energy spectrum to account for the losses due to secondary interactions and for the non-linear energy acceptance of the HISS spectrometer. The superimposed curve represents the best fit for the energy spectrum function from the nova model, $\rho_B(E^*) = \beta_B \exp(-\beta_B/E^*)/E^{*2}$, where β_B = 8 MeV, as proposed by Masuda and Uchiyama [5].

large error bars calculated for low excitation energies in fig. 3. Two independent methods [15] were used to calculate the low energy corrections to the measured $^{12}C \rightarrow 3\alpha$ cross section of 9.7 (+5.0/−2.5) mb. The first of these methods assumed a gaussian distribution for the alpha-particle momenta similar to that of the single-particle inclusive measurements. The second method assumed a smooth energy transfer spectrum with no structure between the 7.4 MeV threshold energy for the three-alpha channel and the 10 MeV excitation energy of our lowest data point. The values for the low energy correction calculated by the two methods were within 5% of one another.

The range of excitation energies exhibited in fig. 3 is consistent with the 120–150 MeV excitation energy cutoffs calculated in both the phonon [3] and cascade [4] models. The extent of these excitation energies, however, is well beyond the 3–22 MeV limits expected from the abrasion–ablation calculations of Hufner et al. [1] and similar bounds imposed by Morrissey et al. [4]. The general shape of the energy spectrum is also inconsistent with the nova model formula proposed by Masuda and Uchiyama [5].

In conclusion, none of the current theoretical models are in complete agreement with the data from the three-alpha dissociation channel of ^{12}C. The extent of the observed energy transfer spectrum is too large to be consistent with the abrasion–ablation calculations of Hufner et al. [1]. There is also no clear signature for the quasi-elastic scattering of alpha particles such as that implied in the abrasion–ablation calculations of Faldt and Gislen [2]. The excitation spectrum and the transferred momentum distribution are consistent with an excitation-decay process such as that proposed by Feshbach and Zabek [3]. However, the anisotropy between the transverse and longitudinal directions of the momentum transfer predicted by that model is not observed. Further, the extent of the excitation spectrum is above any known levels of ^{12}C [16]. An explanation of the larger excitation energies will probably involve either the cluster substructuring of the nucleus incorporated in the models of Masuda and Uchiyama [5] and Faldt and Gislen [2] or the post-collision clustering proposed by Kodama et al. [6]. Unfortunately, the data are inconclusive as to the presence of an intermediate ^8Be state.

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