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NUCLEI
Experiment

Measurement of the Mean Free Path of Relativistic ^{12}C Nuclei Undergoing Coherent Fragmentation to Three Alpha Particles in a Nuclear Emulsion Filled with Lead Nuclei

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Abstract—A stack of track-photoemulsion layers was exposed to a beam of ^{12}C ions accelerated to a momentum of 4.5 GeV/c per nucleon at the synchrophasotron of the Laboratory of High Energies at the Joint Institute for Nuclear Research (JINR, Dubna). The mean free path of relativistic ^{12}C nuclei was measured for the reaction of their coherent fragmentation to three alpha particles in BR-2 nuclear track photoemulsion filled with lead nuclei in proportion of one lead atom per five silver atoms. The result was $\lambda_{(\mathrm{Em+Pb})} = (11 \pm 3)$ m. The cross section of $\sigma_{(\mathrm{Em+Pb})} = (18 \pm 3)$ mb averaged over all track-photoemulsion nuclei corresponds to this value of $\lambda_{(\mathrm{Em+Pb})}$. From a comparison of the value obtained in the present study for $\lambda_{(\mathrm{Em+Pb})}$ with the mean free path of ^{12}C nuclei in a standard BR-2 track photoemulsion, (10.3 ± 1.5) m, it follows that, in this channel, a nuclear fragmentation mechanism is dominant in the fragmentation of ^{12}C nuclei both off lead nuclei and off track-photoemulsion nuclei.

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The fragmentation of relativistic ^{12}C nuclei into three alpha particles in inelastic collisions with target nuclei that is not accompanied by the destruction of the target nucleus involved or by the production of other charged particles is assumed to be one of the most peripheral interactions and is classed with coherent reactions. It is natural to expect that the Coulomb mechanism of interaction between nuclei manifests itself with a high probability. A quadratic dependence of the reaction cross section on the electric charge of the target nucleus, $\sim Z_t^2$, is a feature that distinguishes the Coulomb disintegration of relativistic nuclei from the nuclear mechanism of interaction. The disintegration of relativistic ^{12}C nuclei to three alpha particles was detected and was studied in nuclear track photoemulsions in [1–3] and in inelastic collisions at the synchrophasotron of the Laboratory of High Energies (LHE) at the Joint Institute for Nuclear Research (JINR, Dubna) by means of a propane bubble chamber in [4, 5]. The cross sections for the dissociation of ^{12}C nuclei with a momentum of 4.2 GeV/c per nucleon through this channel in interactions with ^{12}C nuclei and with protons were measured in studies that employed a propane bubble chamber at the JINR LHE synchrophasotron.

In track photoemulsions, it is impossible to pinpoint a target nucleus on which this reaction occurs. In that case, one therefore measures the mean free path that is run by accelerated nuclei before undergoing interaction and which is averaged over all nuclei in the track emulsion being considered, $\lambda_{(\mathrm{Em})}$. The reaction cross section $\sigma_{(\mathrm{Em})}$ is related to $\lambda_{(\mathrm{Em})}$ by the equation

$$\sigma_{(\mathrm{Em})}\lambda_{(\mathrm{Em})}N_{(\mathrm{Em})} = 1,$$

where $N_{(\mathrm{Em})}$ is the total number of all complex nuclei in the track photoemulsion. A refined value of the mean free path in the coherent fragmentation of ^{12}C nuclei with a momentum of 4.5 GeV/c per nucleon to three alpha particle in a standard BR-2 track photoemulsion, (10.3 ± 1.5) m, was given in [3] along with the respective cross section averaged over all nuclei contained in the track photoemulsion. On the basis of a comparison of the cross section for this reaction on track-photoemulsion nuclei with the cross sections measured for the reaction on carbon and proton targets, it is concluded in the present study that, in the region of target nuclei that extends to silver nuclei, the reaction in question is dominated by the nuclear interaction mechanism. With the aim of revealing a Coulomb excitation mechanism in this

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Content of atoms in a standard BR-2 track photoemulsion and in a track photoemulsion filled with lead nuclei

Photoemulsion	No. of nuclei in 1 cm^3 ($\times 10^{22}$)						
	H	C	N	O	Ag	Br	Pb
BR-2	2.97	1.40	0.37	1.08	1.03	1.03	–
BR-2 + Pb	3.26	1.64	0.28	1.49	0.76	0.76	0.15

reaction, the reaction in a track photoemulsion filled with a lead-containing salt was studied by Belaga and his colleagues [3]. They indicated that the mean free path of ^{12}C nuclei for the fragmentation of ^{12}C nuclei with a momentum of 4.5 GeV/c per nucleon to three alpha particles is (4.8 ± 1.8) m. This value of the mean free path was obtained upon scanning 61.8 m of tracks, where 13 events of the required type were found [6].

This value of the mean free path of ^{12}C nuclei in a track photoemulsion filled with lead nuclei is more than two times shorter than the mean free path of nuclei in an ordinary track photoemulsion. Accordingly, the cross section for the reaction in question in a track photoemulsion containing lead nuclei is twice as large as the cross section for the reaction in a standard track photoemulsion. The authors explained so large an enhancement of the reaction cross section by the dominance of the Coulomb mechanism of fragmentation of ^{12}C nuclei on lead nuclei. For so strong a change in the cross section to occur, the number of events on lead nuclei introduced in the track photoemulsion should be approximately identical to the number of events on all other track-photoemulsion nuclei, while the cross section for the reaction on lead nuclei should be one to two orders of magnitude larger than the cross section for track-photoemulsion nuclei (since the number of lead nuclei is smaller than the number of track-photoemulsion nuclei).

Such a strong enhancement of the cross section for the Coulomb interaction mechanism at the collision parameters exceeding the radius of the target nucleus (Pb) requires a corroboration on the basis of vaster data samples. For this, it seems important to perform a remeasurement of the mean free path of ^{12}C nuclei for this reaction over a substantially greater length of scanned tracks in a nuclear photoemulsion filled with lead nuclei.

In the present study, we have measured the mean free path of ^{12}C nuclei with a momentum of 4.5 GeV/c per nucleon for the channel of coherent fragmentation to three alpha particles in a BR-2 nuclear track emulsion, which is sensitive to the ionization of singly charged relativistic particles and which is enriched in lead in proportion of one lead atom per five silver atoms. Track-photoemulsion layers about 400 μm thick arranged in a stack were exposed to a beam of ^{12}C ions accelerated to a momentum of 4.5 GeV/c per nucleon at the JINR LHE synchrophasotron. The plane of irradiated track-photoemulsion layers was aligned with the beam of accelerated ^{12}C nuclei. The ^{12}C nuclei hit the endface of the track-photoemulsion layers and traveled along their plane. The tracks of ^{12}C nuclei were viewed under a microscope at a 900-fold magnification from the points at which ^{12}C nuclei entered the track photoemulsion either to the points of ^{12}C interaction with photoemulsion nuclei or to the points at which they escaped from it without undergoing visible interaction. The number of inelastic interactions found over the total length of scanned tracks of relativistic ^{12}C nuclei, which was 239 m, was 1500. The detected interactions included 21 identified interactions in which ^{12}C nuclei decayed to three alpha particles and which did not not show any sign of the disintegration of the target nucleus or did not involve the production of other charged particles. An unambiguous identification of relativistic alpha particles was accomplished visually by the degree of track ionization in the track photoemulsion. On the basis of these results, the mean free path of ^{12}C nuclei for this reaction in the track photoemulsion containing lead nuclei, $\lambda_{(\mathrm{Em+Pb})}$, was estimated at (11 ± 3) m [7]. The value presented in [3] for the mean free path of nuclei in a standard track photoemulsion not containing lead nuclei, $\lambda_{(\mathrm{Em})}$ was (10.3 ± 1.5) m. The mean free path measured in the present study for the dissociation of ^{12}C nuclei to three alpha particles in the track photoemulsion containing lead nuclei in the above concentration is not shorter than the mean free path in the standard track photoemulsion. The reason for this is that, upon introducing a salt containing lead nuclei in the photoemulsion, the concentration of silver and bromine nuclei in it decreased substantially. Table 1 gives the atomic compositions of the standard BR-2 track photoemulsion and the photoemulsion filled with lead nuclei. In the standard track photoemulsion, the average mass number of nuclei is 47, the concentration of silver and bromine heavy nuclei is 42%, and the average charge number of nuclei is 21. In the track photoemulsion filled with lead nuclei, the average mass number of nuclei is 42, the concentration of silver and bromine heavy nuclei decreases to 30%, and the average charge of nuclei becomes 19. This is the reason why the additional number of interactions with lead nuclei does not fully compensate for the decrease in the number of interactions with silver and bromine nuclei.

The cross section of $\sigma_{(\mathrm{Em})} = (20 \pm 1.5)$ mb corresponds to the value of $\lambda_{(\mathrm{Em})} = (10.3 \pm 1.5)$ m for

the mean free path of nuclei in an ordinary track photoemulsion, while the cross section of $\sigma_{(\mathrm{Em+Pb})} = (18 \pm 3)$ mb corresponds to the mean free path of $\lambda_{(\mathrm{Em+Pb})} = (11 \pm 3)$ m in the track photoemulsion containing lead nuclei. The difference in the values of the mean free path of ^{12}C nuclei and the cross section between the standard track photoemulsion and the track photoemulsion filled with lead nuclei is smaller than the errors in the measured values of the mean free paths. In order to determine the quantitative relation between the cross sections for track-photoemulsion nuclei and for a lead nucleus, it is therefore necessary to improve the precision in measuring the mean free paths of nuclei. The estimate obtained in the present study for the mean free path of ^{12}C nuclei in the case of their fragmentation to three alpha particles indicates that, both for lead nuclei and for track-photoemulsion nuclei, it is the nuclear interaction mechanism rather than the Coulomb excitation of ^{12}C nuclei that is dominant in the reaction under study. This result may be used to analyze more comprehensive data on this reaction for other target nuclei. The result that we obtained may also be of use in planning experiments devoted to studying cross sections for reactions on heavy nuclei by employing nuclear track photoemulsions filled with heavy nuclei.

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