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ANALYSIS OF TIME OF FLIGHT OF ^{8}HE NUCLEI IN NUCLEAR EMULSION USING RANGE-ENERGY RELATION PROGRAM

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Abstract

A nuclear track emulsion (NTE) is exposed to 60MeV ^{8}He nuclei. Measurements of decays of ^{8}He nuclei stopped in nuclear track emulsion allow one to evaluate possibilities of alpha spectrometry. Thermal drift of ^{8}He atoms is observed in nuclear emulsion. Knowledge of the energy and emission ranges of alpha particles allows one to derive the energy distributions of alpha decays $Q_{2\alpha}$. The presence of a tail of large values is established. Presented in this report is the time of flight estimate for ^{8}He based upon data obtained from an emulsion stack exposed to 1.6GeV/c K^- mesons. The lifetime of ^{8}He is about 0.1 s and the decays of ^{8}He were obtained in a total estimated time of flight of ^{8}He ($\rightarrow^{8}$Li+β^-, ($\rightarrow^{8}$Be+β^-) 2.6±0.21 psec. The forward to backward ratio indicates isotropic emission of ^{8}Be (or ^{8}Li) fragments. The emission of short recoils at the primary vertex shows a definite correlation with the ^{8}Be (or ^{8}Li) fragments.

Keywords: Range-energy relation program, KEK 373's emulsion plates, Computer-aided microscope system

Introduction

There have been quite a few experiments on the emission of ^{8}He fragments from K^- interactions with emulsion nuclei at various incident beam energies. The experiments are helpful in understanding the nuclear structure and also the mechanism of fragmentation. For studying fragments with a charge greater than that of the a-particle,^{8}He(also ^{8}Li,^{9}Li, ^{8}B, ^{8}Be) fragments have been chosen because of their characteristic decay into two α-particles, usually known as 'hammer tracks'. The hammer (HT) and hammer like(HLT) make the identification of ^{8}He fragments very simple and unambiguous. In this paper we present the analysis on 60 HTs (HTLs) produced in the interaction of 1.6 GeV/c K^- with the emulsion nuclei. No effort, however, was made to distinguish between the ^{9}Li, ^{8}B, ^{8}He and ^{8}Li fragments in the HTs (HTLs).

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More than 55 years ago, hammer and hammer like tracks of $^{8}Be \rightarrow 2\alpha$ were observed in nuclear track emulsion. They resulted from β decays of stopped ^{8}Li and ^{8}B fragments produced in turn by high energy particles as emulsion nuclei underwent splitting [C.F.Powell]. Another example is the first observation of the $2\alpha + p$ decay of the ^{9}C nucleus via the 2+ state of the ^{8}Be nucleus [M.S.Swami]. Due to the development of facilities for producing beams of radioactive nuclei, nuclear track emulsion turned out to be an effective tool for studying decays of light exotic nuclei with both neutron and proton excess. As a first step within this approach, the nuclear track emulsion was exposed to ^{8}He nuclei with energy of ~60 MeV at the Kazuma Nakazawa Laboratory of Nuclear Reaction in July 2017. The features of ^{8}He decays are depicted in Fig. 1 in accordance with [F. Ajzenberg Selove]. After the ^{8}He nucleus is stopped and neutralized in the substance, the formed 8He atom remains unbound (noble gas) and, as a result of thermalization, can drift in the substance until it undergoes β decay. The half life of the ^{8}He nucleus is $\tau_\beta = (119.0 \pm 1.5) \times 10^{-3}$s[F. Ajzenberg Selove]. The lifetime of ^{8}He is about 0.1 s and the decays of ^{8}He were obtained in a total estimated time of flight of ^{8}He as 2.6 ± 0.21 psec. This nucleus undergoes β decay to the 0.98MeV bound level of the^{8}Li nucleus with a probability of 84% and energy $\Delta E = 9.7$ MeV. Then the ^{8}Li nucleus with its half life $\tau_\beta = (838 \pm 6) \times 10–3$ s undergoes β decay to the 2+ level of the ^{8}Be nucleus (3.03 MeV) with 100% probability and energy $\Delta E = 13$ MeV. Finally, the ^{8}Be nucleus decays from its 2+ state with the width of 1.5 MeV to a pair of α particle. Figure.2 shows a mosaic macro photograph of the decay of the ^{8}He nucleus stopped in nuclear track emulsion (one of 60 events observed in this investigation). The decay results in a pair of relativistic electrons (dotted tracks) and a pair of α particles (oppositely directed short tracks).

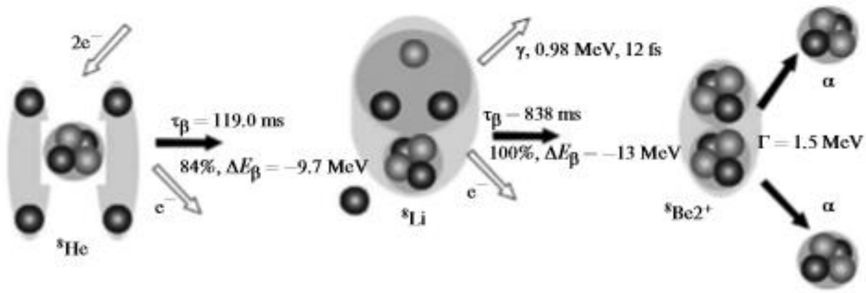
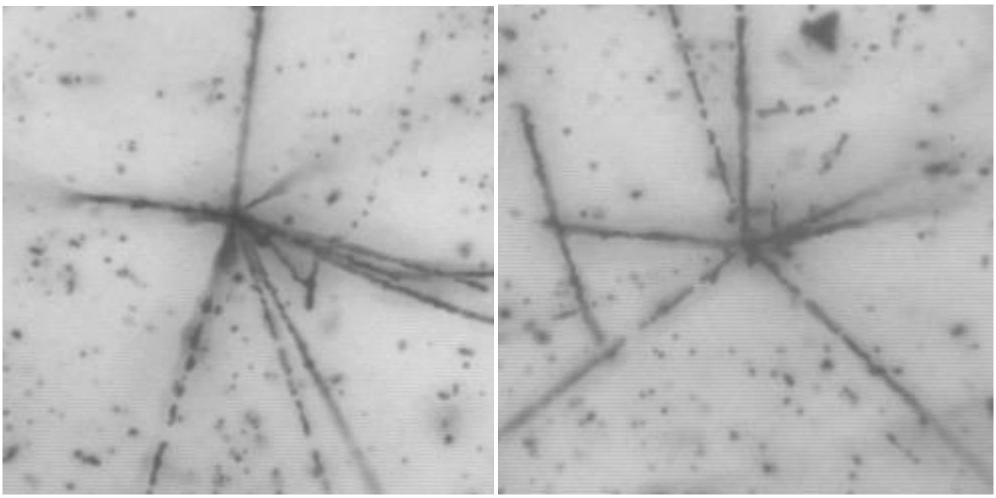


Figure1: Scheme of the main cascade decay channel for the ^{8}He isotopes (Circles are photons (light) and neutrons (dark). Darker background indicates clusters)



(a) (b)

Figure 2: Mosaic macrophotograph of the hammer (a) and hammerlike (b) decay of the ^{8}He nucleus stopped in the nuclear track emulsion (horizontal track)

Experimental Procedure

This work was done using a stack consisting of 12 nuclear pellicles, each of size 25cm*24.5cm (thickness (~1mm) before development and (~0.5mm) after developmentinFig.3) exposed to the K^- beam of momentum 1.6 GeV/c at Kazuma Nakazawa Laboratory. Approximately 60 interactions were picked up by an area scan using 50x magnifications with computer-aided microscope system in Fig 4. Each grey or black track which originated from a beam star was followed within the emulsion pellicle containing the primary star. The centre of each star was examined under a magnification of 100 x to detect the presence of a short hammer (hammer like) or recoil. All hammer and hammer like tracks were assumed to be due to ^{8}Li, ^{8}Be fragments. Only those ^{8}Li, ^{8}Be fragments which decayed at rest into two collinear α-particles (Space angle should be 180 ± 10 degrees) were picked up. In this respect the production rate given below is a lower limit.

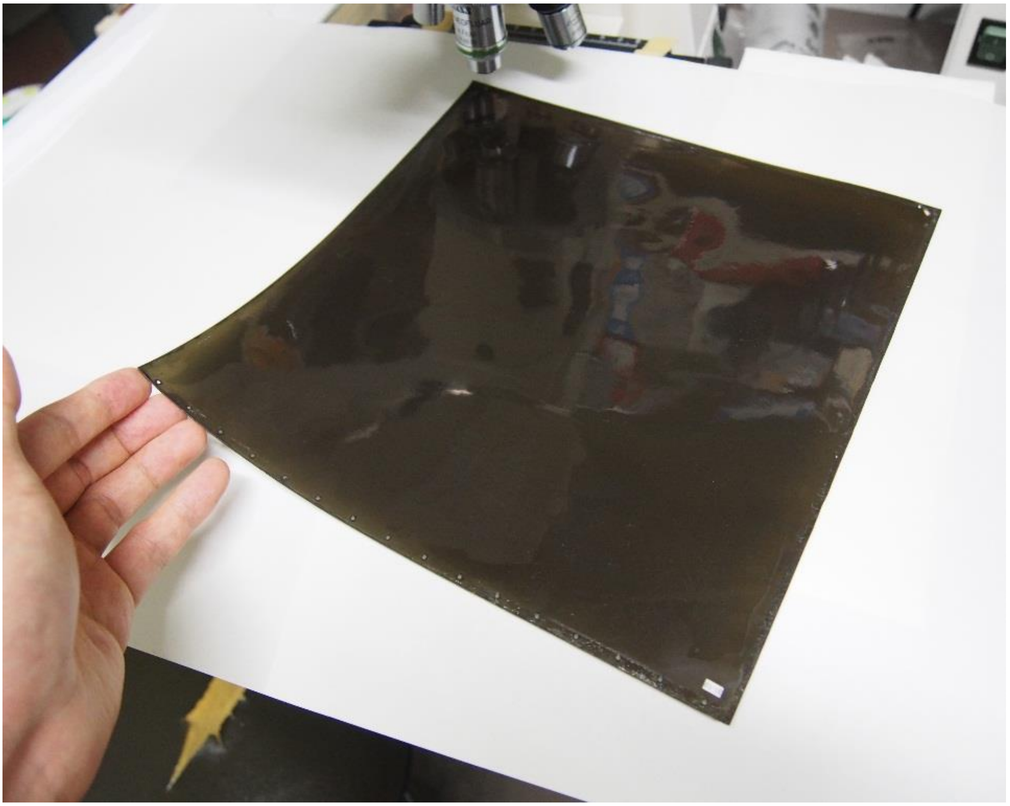


Figure 3: Nuclear emulsion plate of KEK 373(After development)

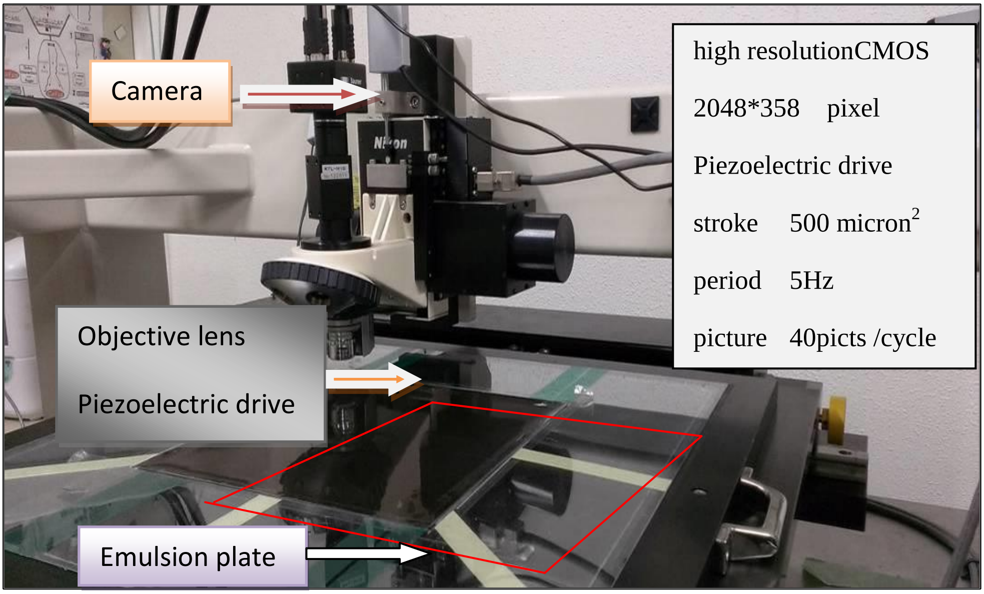


Figure 4: Computer-aided microscope

Results and Discussion

Analysis of Hammer and Hammer like Decays

As the pellicle was scanned using a computer-aided microscope with a 50× lens, the primary search for β decays of ^{8}He nuclei was focused on hammer and hammer like events (Fig. 2). The absence of tracks of a decay electron in the observed event was interpreted as a consequence of the inadequately effective observation of all decay tracks in the emulsion pellicle. The most problematic background for selection by this criterion could arise from decays of ^{8}Li nuclei. Figure 5 depicts the relation between the ranges L_α of α particles from the hammer decays and the energies E_α found from the splice interpolation of the range–energy calculation within the RER model. The average of the α particle ranges is 10.47 ± 0.64μm which corresponds to the average kinetic energy $\langle E\ (^{4}He)\rangle = 2.93 \pm 0.03$ MeV. The ranges $L_2$and L_3 of α particle in pairs exhibit a distinct correlation (Fig. 6). The distribution of the range differences $L_2 - L_3$ (Fig .7) has ~1 μm.

Knowing the energy and emission angles of α particle, we can obtain α decay energy distribution $Q_{2\alpha}$. The relativistically invariant variable Q is defined as a difference between the invariant mass of the final system M* and the mass of the primary nucleus M; i.e., Q = M* – M. Here M* is defined as a sum of all products of the fragment four momenta $P_{i,k}$,

$$M^{*2} = (\sum P_j)^2 = \sum (P_i P_k)$$

The $Q_{2\alpha}$ distribution (Fig. 12) mainly corresponds to the decays of ^{8}Be nuclei from the excited 2+ state. Its average value $\langle Q_{2\alpha} \rangle$, however, turned out to be slightly greater than expected, which results from a small tail in the region of large $Q_{2\alpha}$ that obviously does not fit into the description by the Gaussian function. Applying the selection criteria L_2 and $L_3 < 12.5$ µm and θ > 145°, we obtain $\langle Q_{2\alpha} \rangle = 3.01 \pm 0.1$ MeV which corresponds to the 2+ state. The reason why the tail arises in the $Q_{2\alpha}$ distribution is obscure and calls for further analysis. According to Fig. 6, the ranges L_2 and L_3correlate at values less than 12.5 µm as well. Therefore, an increase in ranges cannot be attributed to fluctuations of ranges due to recombination of He^{+2} ions. Radioactive ^{8}He gas can be used for measuring the ^{8}He half-life at a new level of accuracy and for the laser spectroscopy of ^{8}He. Of applied interest is the investigation of thin films by pumping ^{8}He atoms with their particular penetrating power and depositing them onto detectors.

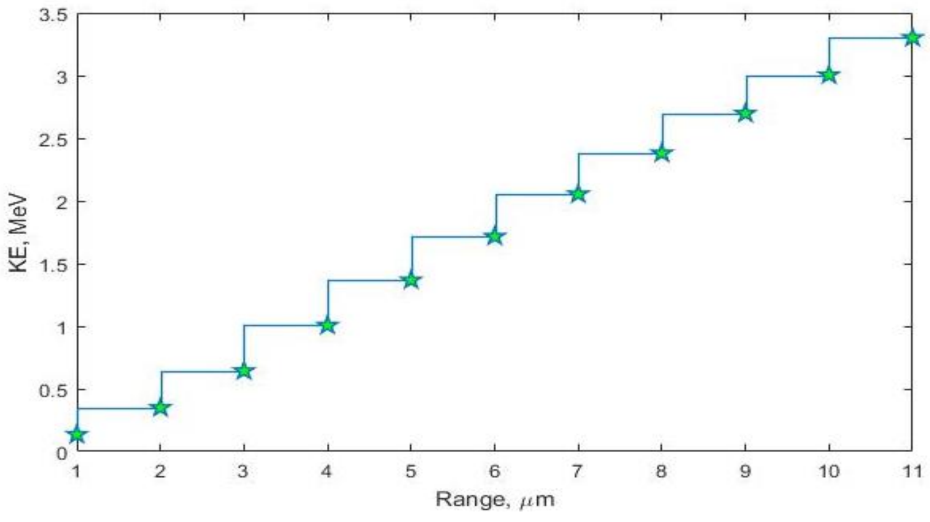


Figure 5: Determination of the α particle energy from the measured ranges

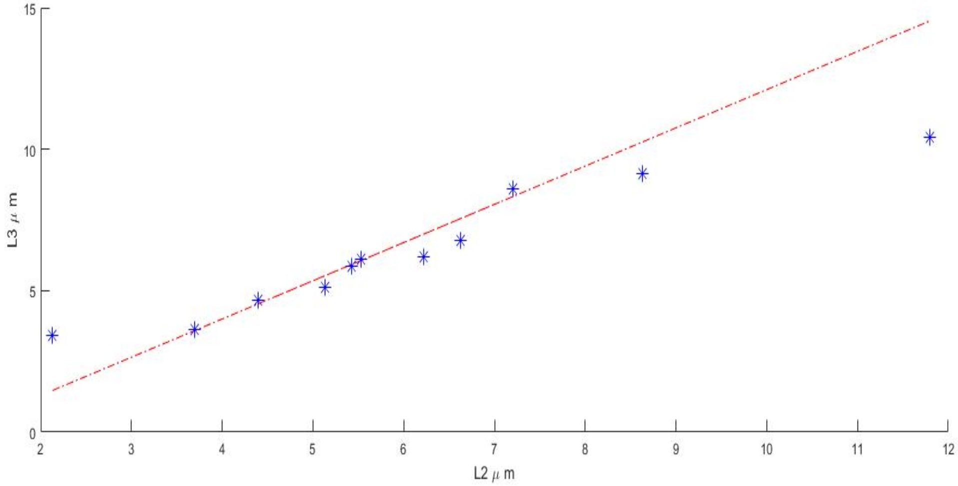


Figure 6: Distribution of ranges L_2 and L_3 in pairs of α particle.

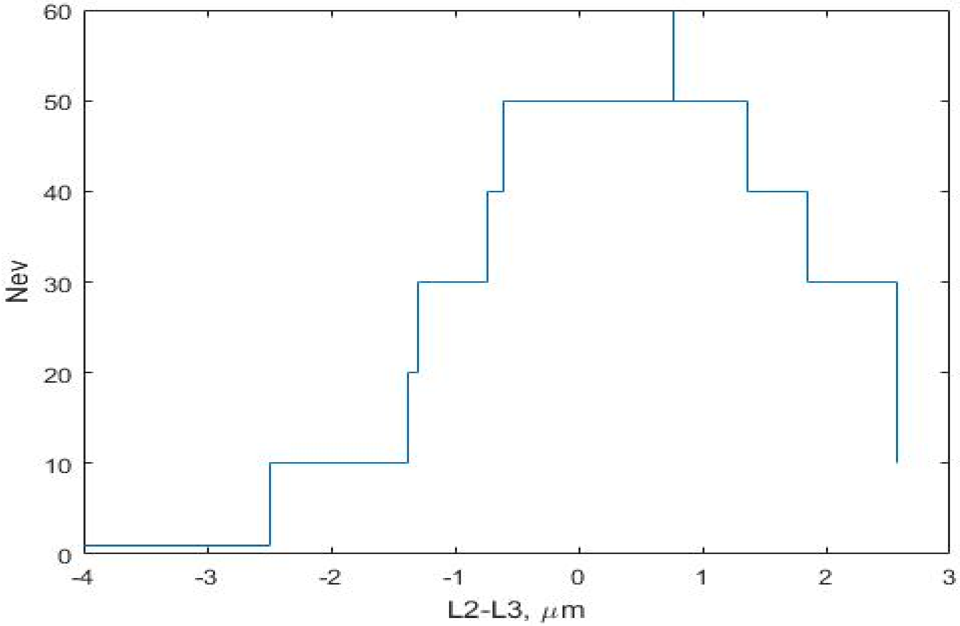


Figure 7: Distribution of range differences L_2-L_3 in pairs of α particle.

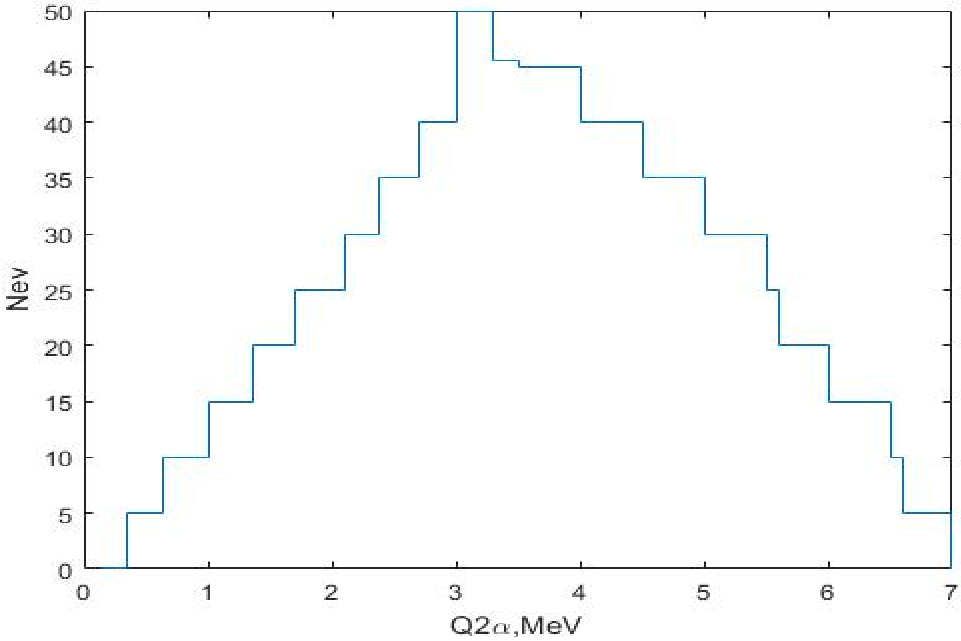


Figure 8: Energy $Q_{2\alpha}$ distribution of α particle pairs

Conclusions

This work demonstrates the capabilities of the recently reproduced nuclear track emulsion exposed to a beam of ^{8}He nuclei. The test experiment allowed radioactive ^{8}He nuclei to be independently identified by their decays as they stopped in the emulsion, the possibility of carrying out α spectrometry of these decays to be estimated, and the drift of thermalized ^{8}He atoms in matter to be observed for the first time. The experiment proved the high purity of the beam of radioactive nuclei formed at the J-PARC facility with an energy ranging from 10 to 30 MeV/nucleon. The analysis of 60 decays of ^{8}He nuclei can be a prototype for investigating decays of ^{8,9}Li, ^{8},^{12}B, ^{9}C, and ^{12}N nuclei in which the ^{8}Be nucleus serves as a marker. The nuclear track emulsion can be used for the diagnostics of beams of radioactive isotopes. The statistics of the hammer and hammer like decays observed in this work is a small fraction of the flux of ^{8}He nuclei, and the measured decays constitute of that fraction. This limitation was dictated by “reasonable” time and labor expenditure. At the same time the nuclear track emulsion with implanted radioactive nuclei offers the basis for using computer-aided microscopes and range-energy relation program, making it possible to hope for unprecedented statistics of analyzed decays.

The present work indicates that there exists a correlation between the short recoils at the primary star and the emitted HTs (HLTs). Moreover, Presented in this report is the time of flight estimate for ^{8}He based upon data obtained from an emulsion stack exposed to 1.6 GeV/c K^- mesons. And the decays of ^{8}He were obtained in a total estimated time of flight of ^{8}He as 2.6 ± 0.21 psec.

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