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Abstract

Secondary beams of ^3He, ^4He, ^6He, and ^8He were produced through the projectile fragmentation of 800 MeV/nucleon ^{11}B primary. Interaction cross sections(σ_I) of all He isotopes on Be, C, and Al targets were measured by a transmission-type experiment. The interaction radii of He isotopes ,R(He)=$\sqrt{\sigma_I/\pi}-R(T)$ where R(T) is of the target nucleus, have been deduced from the present σ_I and the known σ_I of $^4He+{}^4He$ and $^{12}C+{}^{12}C$ reactions; $R(^3He)=1.59\pm0.06$,$R(^4He)=1.40\pm0.05$,$R(^6He)=2.21\pm0.06$,and $R(^8He)=2.52\pm0.06$ in fm.

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Since high-energy heavy-ion beams became available, the projectile fragmentation process has been studied extensively.[1,2] It was then realized that a wide variety of isotopes can be produced through that process,[3] in which the fragments are emitted into a very narrow cone in the incident direction with velocity nearly equal to the projectile: The momentum spread of light nuclear fragments is typically a few per cent and the angular spread is of the order of a few degrees when the projectile energy is about 1 GeV/nucleon. This 'persistence of velocity' of the projectile fragments opens a new possibility of using unstable nuclear beams for the studies of nuclear properties. In this paper we report the first results of measurements of interaction cross sections using secondary beams of all known He isotopes. The nuclear matter radii of He isotopes , ^{3}He,^{4}He,^{6}He, and ^{8}He, have been deduced from the interaction cross sections.

Secondary beams of He isotopes were produced through the projectile fragmentation of 800 MeV/nucleon ^{11}B primary. A secondary beam line at the Bevalac of Lawrence Berkeley Laboratory is schematically shown in Fig. 1a. The primary ^{11}B beam was focused at F1 where a production target of Be(2.54 cm in thickness) was positioned. The thickness of the target was chosen to optimize the yield under the condition that the momentum spread of the product nuclei, due to the difference of dE/dx of the incident and the produced nuclei, is comparable to the momentum spread due to the production reaction. The produced fragments were transported to F2, which is the second focus with momentum dispersion, by a bending magnet(X2M5) and a set of Q magnets(X2Q4). An analyzing slit made of a pair of Cu blocks of 35 cm in thickness was located at F2, and other isotopes with rigidity different from the isotope of interest were degraded in their energy. A clean-up slit was placed at an achromatic focus F3 after another bending magnet(X2M7) and a set of Q magnets(X2Q5). Rigidity separated isotopes were then guided to the HISS(heavy-ion spectrometer system) experimental area.

The interaction cross section(σ_I), defined as the total cross section for the process of nucleon(proton and/or neutron) removal from the incident nucleus, was measured by a transmission-type experiment. The experimental arrangement is shown in Fig. 1b. The individual nuclear species were identified before incidence on the reaction target.

The identification and the selection were made by the following three criteria: (1) The pulse heights of all four plastic scintillators (SBT) are in a proper range. (2) Only one track is observed by the multi-wire proportional chambers(MWPC's; PBT1 and PBT2). (3) The time-of-flight (TOF) between the scintillators SF3 and SBT is in a proper range. As a result, mixture of any other isotopes in a selected-isotope beam was well less than 10^{-3}.

A large volume magnet(HISS; the pole gap of 1 m and the pole diameter of 2 m), MWPC's(PAT1,PAT2,PAT3,PAT4), and plastic scintillation counters(SAT), were used after the reaction target to identify the nuclides by the bending angle in the magnet, the TOF between SBT and SAT, and the pulse heights of SAT. The counter SAT consisted of six layers of plastic scintillators, which were large enough to cover the spread due to multiple Coulomb scatterings and nuclear elastic scatterings. When the same nuclide was detected as observed before the target, the event was counted as non-interacting. To minimize the reaction rate other than the target, the magnet gap was kept in vacuum and a helium bag was placed between PAT2 and PAT4. The cross section was then calculated by the equation,

$$\sigma_I = \frac{1}{N_t}\log(\gamma_0/\gamma)\,, \tag{1}$$

where γ is the ratio of the number of non-interacting nuclei to the number of incoming nuclei for a target-in run, and γ_0 is the same ratio for an empty-target run. The number of the target nuclei per cm^2 is written as N_t. The values of γ_0 were larger than 0.95 in all the cases of measurements. By taking ratio γ_0/γ, uncertainties due to the counter inefficiencies and reactions occurred anywhere other than the target can be eliminated.

Interaction cross sections at 790 MeV/nucleon were measured by all the known He isotopes (^{3}He, ^{4}He, ^{6}He, and ^{8}He) on Be, C, and Al targets. Purities of the targets were better than 99.46%* for Be, and 99.9% for C and Al. The target diameter was 7.7 cm and various thicknesses with the same materials were used to examine and correct the effects due to multiple Coulomb scatterings. The scattering-out probabilities of non-interacting nuclei outside of the scintillation counters(SAT) were estimated from the position distribution of the nuclei at the last wire chambers(PAT3,4), and were found to be at most 2% even for the thickest Al(20.197 g/cm^2) target. After the correction, no significant dependence of the cross sections on the thickness was observed. The interaction cross sections σ_I thus determined are listed in Table I.

It has been known that σ_I between stable nuclei are essentially independent of the beam energy above ~200 MeV/nucleon.[2,4] Also the nucleon-nucleon cross section reaches a saturated value at the present beam energy. It is therefore considered that σ_I reflects a well defined nuclear size. We operationally define a nuclear radius by the equation,

$$\sigma_I(p,t) = \pi(R(p) + R(t))^2, \tag{2}$$

where $R(p)$ and $R(t)$ are the radii of the projectile and the target nuclei, respectively. It has been found[5] that the nuclear radii calculated by this formula from the known data[6] of σ_I between stable isotopes are systematically larger by 0.2 fm in the whole mass range than the half-density radii determined by the electron scattering[7]. This indicates that the present definition corresponds to a certain radius where the density is smaller than the half of the central density. It is also shown[6,9] that the present radius definition is valid in the frame work of the optical model if the surface diffuseness is independent of mass number.

Under the definition of eq.(2), the difference of the radii between ^{A}He and ^{3}He was calculated as,

$$R(^A\text{He}) - R(^3\text{He}) = \sqrt{\sigma_I(^A\text{He,T})/\pi} - \sqrt{\sigma_I(^3\text{He,T})/\pi}\,, \tag{3}$$

where T denotes a target nuclei. The radius differences of ^{A}He isotopes from ^{3}He thus obtained are shown in Fig. 2. It is noted that the radius differences are essentially independent of target nuclei(except one case in ^{4}He) within ±0.02 fm , supporting that the target and the projectile parts are separable as defined in eq.(2).

A small but significant deviation is seen in one of the ^{4}He-radius data, which was primarily due to a large cross section for the ^{4}He+Be reaction.The deviation can qualitatively be understood as follows: Based on the electron-scattering data, the ^{9}Be nucleus has a larger diffuseness than other p-shell nuclei such as ^{12}C, and the ^{4}He nucleus has an unusually high central density(~1.8 times normal). Therefore, the lowdensity tail of a small mass-number nuclei ^{9}Be gives a relatively large contribution to the interaction cross section. Since the effect of different diffusenesses is expected to be larger for smaller the nuclei, it seems reasonable to see a deviation in the ^{4}He+Be reaction, one of the smallest nuclear combinations in the present measurement. In fact the same kind of diffuseness effect was clearly seen in the data of d+d, d+^{4}He, and d+C reactions.[4] No such deviation was practically seen for the data with C and Al targets. All other He isotopes showed no such a trend in the present measurements, which suggested that they have no sharp-density profile like ^{4}He.

The absolute value of the ^{4}He radius was calculated to be R(^{4}He)=1.40±0.05 fm from the existing data of the ^{4}He+^{4}He and ^{12}C+^{12}C cross sections[4] and the present value of the ^{4}He+^{12}C cross section. The scale of the absolute value thus derived is also shown on the right-hand side of Fig.2. The He radii thus determined are R(^{3}He)=1.59±0.06, R(^{4}He)=1.40±0.05, R(^{6}He)=2.21±0.06, and R(^{8}He)=2.52±0.06 in fm. For the calculations of the He-isotope radii, the interaction cross section of ^{4}He+Be collision was not included because of the reason discussed above.

A dotted curve, in Fig.2, shows the $A^{1/3}$ dependence of nuclear radii. It is seen that the radii of ^{6}He and ^{8}He show larger increase than $A^{1/3}$ from ^{3}He. The radius of ^{3}He is larger than that of ^{4}He in agreement with the known electron-scattering data.[8] The rms, $\sqrt{<r^2>}$, and half-density, $r_{0.5}$, charge radii determined from the electron scattering[7,8] are also shown for ^{3}He and ^{4}He in the figure. It is seen that the presently determined radii appears between $\sqrt{<r^2>}$ and $r_{0.5}$. The rms radii of He isotopes were calculated by a Hartree-Fock method using the Skyrme potential.[10] The results showed a reasonable increase of the radius from ^{4}He to ^{6}He, however the further increase from ^{6}He to ^{8}He was not well reproduced. The radii were also calculated by a Hartree method based on relativistic field theory,[11] which showed that the symmetry energy played an important role to reproduce the radii of large (N-Z)/(N+Z) nuclei such as ^{6}He and ^{8}He.

In summary, we have successfully demonstrated, for the first time, the use of unstable-isotope beams produced by the projectile fragmentation in high-energy heavy-ion collisions. Interaction cross sections of He isotopes(^{3}He,^{4}He,^{6}He, and ^{8}He) on

Be, C, and Al targets were measured. The radii of He isotopes have been deduced from the interaction cross sections. A larger increase in the nuclear radii than $A^{1/3}$ was observed from ^{3}He to ^{6}He and ^{8}He.

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References

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* Number % of the atomic content. The major contaminant was Oxygen (0.33 %) as BeO.

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Table I. Interaction cross sections(σ_I) of He isotopes

σ_I in mb

target	beam ^3He	^4He	^6He	^8He
Be	498± 4	485± 4	672± 7	757± 4
C	550± 5	503± 5	722± 6	817± 6
		527±26[a]		
Al	850± 9	780±13	1063± 8	1197± 9
^4He		262±19[a]		

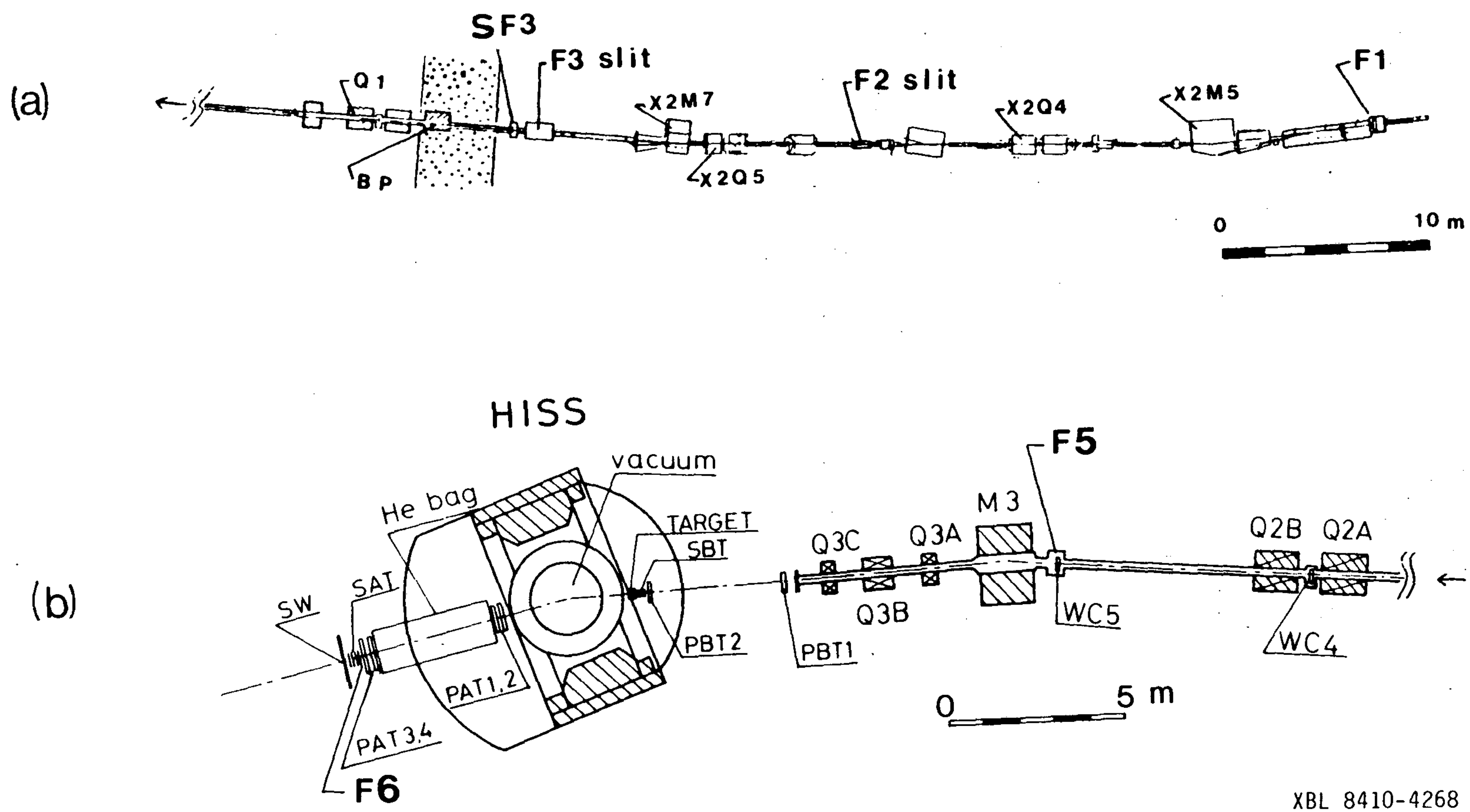
[a] ; data from ref. 4.

Present value of ^4He+C cross section agrees with the known value within quoted errors.

Figure captions

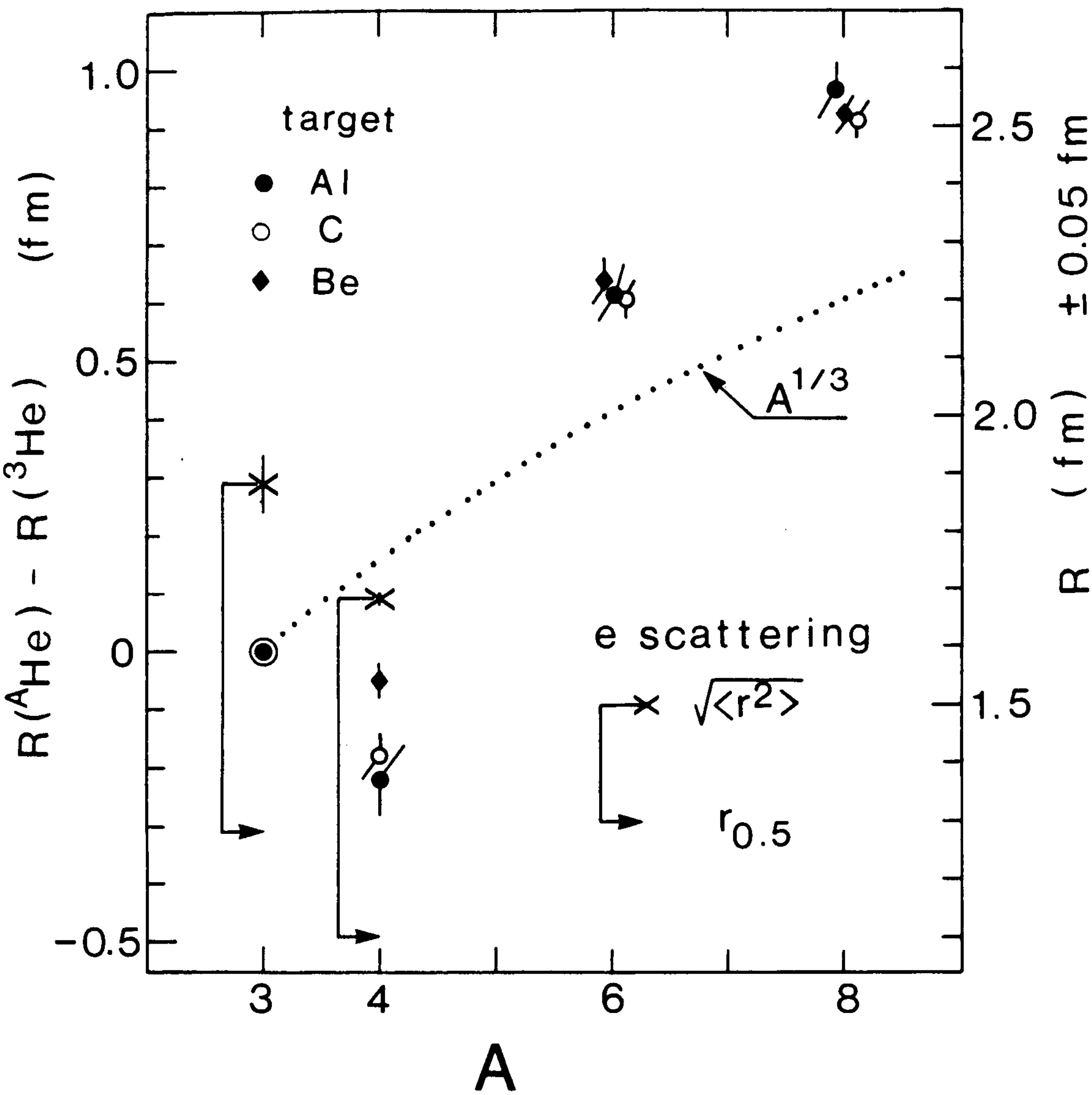
Fig.1. The secondary beam line(a) and the experimental arrangement(b). All the scintillation counters(SF3,SBT's,and SAT's) were 3 mm in thickness. Dimensions of counters, in cm, were ; SF3 (3×3); SBT1,SBT2; SBT4 (5×7); SBT3 (4.3×5.2); SAT1-SAT6 (40×30); and the veto counter before the target (20×20 with 5×5 hole in the middle). The SBT3 and the veto counters defined the maximum size of the incident beam.

Fig.2. Radius differences of the ^{4}He isotopes from ^{3}He. The absolute value of the radius is also shown on the right-side axis. A dotted curve shows the $A^{1/3}$ dependence of nuclear radii. The rms $\sqrt{\langle r^2 \rangle}$ and half-density $r_{0.5}$ charge radii determined from electron scattering are also shown for comparison. The uncertainty on the right-side scale indicated is not applied to the electron-scattering data.



XBL 8410-4268

FIG. 1



XBL 8412-5232

FIG. 2

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