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MEASUREMENTS OF INTERACTION CROSS SECTIONS
AND NUCLEAR RADII OF Li ISOTOPES

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Abstract

Interaction cross sections ($\sigma_I$) for all known Li isotopes ($^6Li$-$^{11}Li$) and $^9Be$ on targets Be, C, and Al have been measured at 790 MeV/nucleon. Nuclear radii ($R_I$) of these isotopes have been deduced from the $\sigma_I$. The differences of radii among isobars ($^6He$-$^6Li$, $^8He$-$^8Li$, and $^9Li$-$^9Be$) have been found for the first time. A comparison of $R_I$ with the $rms$ radii obtained from electron-scattering is presented.

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Recently, exotic-isotope beams, produced through the projectile-fragmentation process in high-energy heavy-ion reactions, were successfully used to measure the interaction cross sections for all the known He isotopes ($^3$He, $^4$He, $^6$He, and $^8$He)$^1$. The nuclear radii of those isotopes were deduced from the measured cross sections. This novel technique of using exotic nuclear beams opened a new possibility of systematically studying properties of unstable nuclei. In the present experiment, we have measured the interaction cross sections for all the known Li isotopes ($^6$Li, $^7$Li, $^8$Li, $^9$Li, and $^{11}$Li) and $^9$Be on target nuclei Be, C, and Al at 790 MeV/nucleon. Nuclear radii of these isotopes have been deduced from the interaction cross sections.

The secondary beams of $^{11}$Li and $^9$Be were produced through projectile fragmentations of the 800-MeV/nucleon $^{20}$Ne primary beam. The other Li isotopes were produced from a $^{11}$B primary. The primary beams were accelerated by the Bevalac at the Lawrence Berkeley Laboratory. The secondary isotopes were produced in a production target of Be and were separated by rigidity using the beam-line magnet system as described in previous papers$^{1,2}$. The rigidity separated isotopes were identified before incidence on a reaction target using their velocity (time-of-flight(TOF)) and their charge (pulse height in scintillation counters). No contamination more than $10^{-3}$ was observed in any selected isotope beams.

The interaction cross section ($\sigma_I$), which is defined as the total cross section for the change of proton and/or neutron number in the incident nucleus, was measured using a large acceptance spectrometer which is the same one used for the measurement of He-isotopes$^1$. The $\sigma_I$ was determined from the attenuation of the incident beam by the reaction target as,

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

where $N_t$ is the number of the target nuclei per unit area, $\gamma$ is the attenuation factor of the incident beam for a target-in run, and $\gamma_0$ is the same factor for a target-out run.
The non-interacting nuclei could suffer small angle deflections due to multiple Coulomb scattering and nuclear elastic scattering in the reaction target. The angular acceptance of the present detection system downstream from the target was designed large enough to detect most of the non-interacting nuclei. A small amount of the non-interacting nuclei were, however, scattered out of the detectors. The number of undetected non-interacting nuclei was estimated from the comparison of the measured position distribution of the detected non-interacting nuclei in the target-in run with that of the target-out run. The scattering-out probability was found to be at most 3% of the non-interacting nuclei. This correction procedure for the scattering-out nuclei was further verified by measurements using targets of various thicknesses.

The measured cross sections are listed in Table I. The errors shown in the table include the counting statistics as well as the systematic errors. The largest systematic error, which is about 0.3% of $\sigma_f$, was due to uncertainty in estimating the scattering-out probability. All other systematic errors were estimated to be less than 0.2% of the $\sigma_f$.

The interaction nuclear radius $R_I$ is defined as,

$$\sigma_I(p,t) = \pi [ R_I(p) + R_I(t) ]^2 ,$$

where $R_I(p)$ is the radius of the projectile and $R_I(t)$ is that of target. The separability of projectile and target radii is the assumption made in the equation, which can be examined by using $\sigma_I$ of various projectile-target combinations. As an example, Fig. 1 shows the radius differences of the target nuclei, which were obtained from the present data as well as the data from Ref.1 using the relation,

$$R_I(t_i) - R_I(t_j) = \sqrt{\frac{\sigma_I(p,t_i)}{\pi}} - \sqrt{\frac{\sigma_I(p,t_j)}{\pi}} ,$$

plotted against the mass number of the projectile nucleus. Except for one case obtained from the $^4$He beam$^3$, it is clearly seen that the values are independent of projectile variation. It is also clear that the projectile radii are independent of the target variation within the present...
experimental uncertainties. Thus the assumption of the separability of projectile and target radii is valid within $\pm 0.02$ fm.

The $R_1$'s of Li isotopes as well as those of He isotopes are plotted in Fig. 2, where values obtained from the Be, C, and Al targets were averaged and the interaction cross sections of He isotopes were taken from Ref. 1. The absolute scale of the radius is determined from a least squares fitting of $^4$He+$^4$He, $^9$Be+$^9$Be, $^{12}$C+$^{12}$C, $^4$He+$^{12}$C, and $^9$Be+$^{12}$C interaction cross sections$^{1,4,5}$. The radii of $^9$Be and $^{12}$C are also plotted.

The $R_1$ of Li-isotopes, except $^{11}$Li, already follow the $A^{1/3}$ dependence even though they have small mass-numbers. A much larger radius has been observed for $^{11}$Li than would be expected from $A^{1/3}$ dependence. It might be due to a large deformation in $^{11}$Li, due to the long tail in the matter distribution of the weakly-bound last nucleons, or simply due to the weak binding of the last nucleons.

For the first time we can directly compare the differences of radii between pairs of isobars, i.e. $R_1(^8\text{He})-R_1(^8\text{Li})=(0.10\pm 0.03)$ fm, $R_1(^8\text{He})-R_1(^8\text{Li})=(0.12\pm 0.03)$ fm, and $R_1(^9\text{Li})-R_1(^9\text{Be})=(-0.08\pm 0.04)$ fm. The larger radii of the neutron rich isotopes $^8$He and $^8$He, which have only two protons, suggest the existence of thick neutron skins.

Figure 3 shows the comparison, for stable isotopes, of the $R_1$ and the root-mean-square (rms) radii $R_{\text{rms}}$ obtained by electron scattering$^6$. The dependence of $R_1$ on the mass-number ($A$ ) and that of $R_{\text{rms}}$ show a notable discrepancy: $R_1$ increases with $A$ whereas $R_{\text{rms}}$ stays almost constant for $A \geq 6$. This discrepancy is not due to the difference between the charge distribution and the nucleon distribution because $Z \approx N$ in these nuclei. The discrepancy is due to the definition of radius: the rms radius depends only on the relative shape of a density distribution, while $R_1$ depends strongly on the absolute value of the nucleon density at the nuclear surface. In the following we relate the interaction cross section data to a rms radius
through a Glauber type calculation and show that the $A$ dependence of $R_{\text{rms}}^G$ is reproduced.

To obtain the $r_{\text{rms}}$ radius from the interaction cross section, semiclassical optical-model calculations were made using Karol's prescription\(^7\), in which the nuclear density distribution $\rho(r)$ was assumed to be a Gaussian of the form,

$$\rho(r) = \frac{A}{(a \sqrt{\pi})^3} e^{-\frac{(r/a)^2}{2}}. \quad (4)$$

The width parameter $a$ can be related to the $r_{\text{rms}}$ radius $R_{\text{rms}}^G$ of the distribution by

$$R_{\text{rms}}^G = \sqrt{1.5} \ a \quad (5)$$

Calculations were made for the collisions of identical stable isotopes, i.e., $^4\text{He}+^4\text{He}$, $^6\text{Li}+^6\text{Li}$, $^7\text{Li}+^7\text{Li}$, $^9\text{Be}+^9\text{Be}$, and $^{12}\text{C}+^{12}\text{C}$. The width parameter $a$ ($=a_p=a_n$) was taken as the fitting parameter in order to reproduce the value of $\sigma_I$. Here $\sigma_I(6\text{Li},6\text{Li})$ and $\sigma_I(7\text{Li},7\text{Li})$, which were not directly measured, were calculated from the $R_I(6\text{Li})$ and $R_I(7\text{Li})$ using Eq. (2). Those values are believed to be reliable within a few % due to the projectile-target separability discussed above.

The $r_{\text{rms}}$ radii($R_{\text{rms}}^G$) calculated by Eq.(5), using the fitted parameter $a$, are shown in Fig. 3 by triangles. Although the absolute values of $R_{\text{rms}}^G$ are slightly smaller than $R_{\text{rms}}^e$, the $A$ dependence is well reproduced. In the optical-model calculations the free nucleon-nucleon value was used for the average nucleon-nucleon cross section ($\bar{\sigma}$). This assumption, however, is not necessarily valid, and the effective value of $\bar{\sigma}$ may differ from its free nucleon-nucleon value due to nuclear-matter effects. A very good agreement of absolute values was obtained with $\bar{\sigma}$ which was 85 % of the free nucleon value. The present calculations show also that $R_I$ is a radius where the nucleus has a matter density about 0.045 fm\(^{-3}\) for $A \geq 6$ nuclei.

It was reported that the mean free path of the 800-MeV protons inside the nuclear matter is longer than the value expected from the free nucleon-nucleon cross sections\(^8\). Also the smaller effective value of $\bar{\sigma}$ was reported in uranium reactions at 900 MeV/nucleon\(^9\). Our present
observation is qualitatively consistent with those data. The value of \( \bar{\sigma} \), however, has not been determined by the present analysis. Calculations based on a realistic matter distribution are necessary to determine the appropriate value of \( \bar{\sigma} \).

In summary, we have successfully used the secondary beams of unstable Li isotopes as well as stable isotopes of Li and Be for the measurement of the interaction cross sections \( \sigma_I \) of nucleus-nucleus collisions. The interaction nuclear radii \( R_I \) of all the known Li isotopes and \(^{9}\text{Be}\) have been determined from these \( \sigma_I \). It has been observed that the radius of \(^{11}\text{Li}\) is much larger than the value expected from the \( A^{1/3} \) dependence of other Li-isotope radii. The differences of the radii between isobars, \(^{6}\text{He}-^{6}\text{Li}\), \(^{8}\text{He}-^{8}\text{Li}\), \(^{9}\text{Li}-^{9}\text{Be}\) have been observed for the first time. The semiclassical optical model has been shown to give the \textit{rms} radius which is consistent with that obtained from the electron scattering. It has also been shown that the \( R_I \) gives a constant density \((\rho \sim 0.045 \text{ fm}^{-3})\) radius of a nucleus. It is thus demonstrated that the measurement of \( \sigma_I \) combined with the appropriate model calculation provides a new method to study the nuclear density distribution of stable isotopes and unstable isotopes which could not be accessed before.

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References

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3. The anomaly in $^4$He was presented and discussed in Ref.1.
Table I. Interaction cross sections ($\sigma_I$)

$\sigma_I$ in mb

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<th>beam</th>
<th>target</th>
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<th></th>
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<td></td>
<td>Be</td>
<td>C</td>
<td>Al</td>
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<tr>
<td>$^6$Li</td>
<td>651± 8</td>
<td>688±13</td>
<td>1010±11</td>
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<tr>
<td>$^7$Li</td>
<td>686± 4</td>
<td>736± 6</td>
<td>1071± 7</td>
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<td>$^8$Li</td>
<td>727± 6</td>
<td>768± 9</td>
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<td>$^9$Li</td>
<td>739± 5</td>
<td>796± 6</td>
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<td>$^{11}$Li</td>
<td>1056±30</td>
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<tr>
<td>$^9$Be</td>
<td>755± 6</td>
<td>806± 9</td>
<td>1174±11</td>
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The listed errors include statistical and systematic errors. The largest systematic errors were due to uncertainties in the estimation of scattering-out probabilities of non-interacting nuclei.
Figure Captions

Fig. 1 Radius differences of target nuclei are plotted against the projectile mass number $A$. It is seen that the radius differences are independent of the projectile variation.

Fig. 2 Interaction nuclear radii $R_I$ are plotted for all the He and Li isotopes as well as for $^9$Be and $^{12}$C. Dotted lines in the figure show the $A^{1/3}$ dependence of the radii. Differences of radii between pairs of isobars are seen for the first time.

Fig. 3 The interaction radius ($R_I$) and the $rms$ radius ($R_{rms}^e$), which is obtained by electron scattering, are plotted for $^4$He, $^6$Li, $^7$Li, $^9$Be, and $^{12}$C. Triangles in the figure show the $rms$ radii ($R_{rms}^G$) of Gaussian matter distributions which reproduce the present $R_I$ values. The $R_{rms}^G$ shows good agreement with the $R_{rms}^e$. 
$\bullet$ = He
$\square$ = Li
$x$ = Be

Fig. 1
Fig. 2
Fig. 3

- \( ^6\text{Li} \)
- \( ^7\text{Li} \)
- \( ^9\text{Be} \)
- \( ^{12}\text{C} \)

Radius (fm)

\( R_I \)

\( R_{rms}^e \)

\( R_{rms}^G \)
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