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MEASUREMENT OF INTERACTION CROSS SECTIONS AND NUCLEAR RADII OF UNSTABLE p-SHELL NUCLEI

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Abstract

Secondary beams of p-shell nuclei (both stable and unstable) have been produced through projectile fragmentation of high-energy heavy-ion collisions. Interaction cross sections(σ_I) for all the known He and Li isotopes and ^{7,9,10}Be isotopes on targets Be, C, and Al have been measured at 790 MeV/nucleon. Root-mean-square radii of these isotopes have been deduced from the σ_I. The differences of matter radii among isobars (^{6}He-^{6}Li, ^{8}He-^{8}Li, and ^{9}Li-^{9}Be) have been observed for the first time. A pair of mirror nuclei (^{7}Li-^{7}Be) shows an equal radii. The radius of ^{11}Li has been found to be considerably larger than those of neighboring nuclei.

1. Introduction

Since high-energy heavy-ion beams became available, the projectile fragmentation process has been studied extensively.[1] It was then realized that a wide variety of isotopes can be produced through that process, 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 fragment 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 'persistency of velocity' of the projectile fragments give an opportunity of using unstable nuclear beams for the studies of properties of nuclei far from the stability line. In this paper we show the result of measurements of interaction cross sections using secondary beams of all the known He and Li isotopes and several Be isotopes. Interaction nuclear radii as well as the root-mean-square radii of the nuclear matter distribution will be deduced from the interaction cross section.

2. The Secondary Beam Line at The Bevalac

Secondary beams of He, Li, and Be isotopes were produced through the projectile fragmentation of 800 MeV/nucleon ^{11}B or ^{20}Ne primary beam. A secondary beam line at the Bevalac of Lawrence Berkeley Laboratory is schematically shown in Fig. 1. The primary beam was focused at F1 where a production target of Be (2.54 cm in thickness) was located. 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 a momentum dispersive focus F2. An analyzing slit made of a pair of copper blocks of 35 cm in thickness was located there, and other isotopes with rigidity different from the isotopes of interest were degraded in their energy. A clean-up slit was placed at an achromatic focus F3. This slit was very effective in reducing backgrounds. Rigidity separated isotopes were then guided to the HISS (heavy-ion spectrometer system) experimental area. After the selection by magnetic rigidity, the secondary beam is still a mixture of nuclei with different charges. The beam nuclei were, therefore, identified before incidence on a reaction target using their velocity (TOF) and their charge (pulse height in scintillation counters). No contamination more than 10^{-3} was observed in any selected isotope beam.

3. The Measurement of The Interaction Cross Sections

The interaction cross section (σ_I), defined as the total cross section for change of proton and/or neutron number in the incident nucleus, was measured using a large acceptance spectrometer. The experimental set up as well as the secondary beam line are described in Refs. 2,3. The interaction cross sections were obtained from the transmission type measurement as,

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

where γ is the ratio of the number of the 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 target nuclei in unit area is written as N_t. By taking the ratio γ_0/γ, uncertainties due to the counter efficiencies and reactions occurring anywhere other than the target can be eliminated.

The σ_I were measured by He (A =3,4,6,8), Li (A =6,7,8,9,11), and Be (A =7,9,10) isotopes on targets Be, C, and Al at 790 MeV/nucleon. The measured cross sections are listed in Table I.

4. Determination of The Nuclear Radii

It has been known that σ_I between stable nuclei is essentially independent of the beam energy above a few hundred MeV/nucleon.[1,4] 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 found that the interaction radius R_I, which is defined below, is in fact a well defined size parameter of nucleus.

The interaction nuclear radius R_I is defined as,

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

where $R_I(p)$ is the radius of a projectile and $R_I(t)$ is that of a target. It has to be noted that a black sphere is not assumed; only the separability of projectile and target radii is assumed in the equation. This separability can be examined by using σ_I of various projectile-target combinations. Figure 2 shows R_I obtained from different targets where 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.[2,4,5] It is clearly seen that a projectile radius is independent of target variation. The separability of He-isotope radii was shown in Ref.3. Thus the assumption of the separability is demonstrated to be valid within $\pm$0.02 fm. Because the separability holds well, average values of R_I deduced from the Be, C, and Al targets will be used for further discussion. The averaged R_I for He, Li, and Be isotopes are shown in Fig.3.

As shown above, the R_I is an experimentally well defined size parameter. A comparison of R_I with theoretical matter distribution is, however, somewhat remote at this moment. Therefore, in the following, we relate the σ_I to the *rms* radius by a Glauber type calculation and show that the *rms* radii of nuclear matter distribution, R^m_{rms}, can be determined independently from model density function.

In order to deduce the *rms* radius from the σ_I, Glauber type calculations were made using Karol's prescription.[6] Three types of nuclear density distributions were used to examine the functional dependence; a Gaussian,[6] the shell model harmonic oscillator,[7] and the droplet model[8] with the Yukawa folding function $(\frac{1}{r}e^{-r/b})$. In the following, we first deduce the *rms* radius using the Gaussian and the harmonic-oscillator distribution and show that the *rms* radii obtained from these two distributions are equal. Then, we show that the droplet model distribution also gives the same result.

In the Glauber type calculation nucleon-nucleon (NN) cross sections have to be given. However the free NN cross sections may not be appropriate because effective values may differ due to nuclear effects. To determine the effective values of NN cross sections, the calculations were firstly made for the collisions of identical stable isotopes, i.e., ^{4}He+^{4}He, ^{6}Li+^{6}Li, ^{7}Li+^{7}Li, ^{9}Be+^{9}Be, and ^{12}C+^{12}C. The width parameter a_G of the Gaussian (or a_{ho} of the harmonic oscillator) and a scaling factor of NN cross sections were taken as the parameters in order to fit the rms radius of the charge distribution R^c_{rms}, determined by electron scattering,[9] and σ_I.[10] It was found that effective values, which are 80 % of free NN cross sections, give a good fit in the present mass range. Therefore these effective NN cross sections were used for further discussion.

The σ_I was, then, fitted with only one free parameter a_G (or a_{ho}). The R_{rms} obtained after fitting σ_I using the Gaussian distribution are shown by the dashed line in Fig.4. The solid line in the figure indicates the R^c_{rms} obtained in the same way using the harmonic oscillator distribution. It is seen that the R^c_{rms} determined by electron scatterings are well reproduced using the fixed values of effective NN cross sections. The calculations were then extended to unstable nuclei. It was found that the R^m_{rms} obtained from the Gaussian and that from the harmonic oscillator agree very well for all nuclei.

In the droplet model we have two parameters, a size parameter (r_0) and a diffuseness parameter (b), so that no unique determination of the parameters can be made from a σ_I. Instead a given σ_I is expressed by a locus in the r_0–b plane. A constant R_{rms}^m gives another locus. It was found that these two loci lay almost in parallel over a wide range. For example in ^{9}Be, a change of b from 0.4 to 0.8 fm changes R_{rms}^m only by 0.025 fm under the fixed σ_I. Consequently the R_{rms}^m is not affected by the value of b (or r_0). Intuitively we can consider this relation holds because both σ_I and *rms* radius are sensitive to the surface region of the nuclear density. The R_{rms}^m, calculated using the droplet model, were equal to those obtained using the two other distributions.

From the preceding discussion we concluded that the deduced R_{rms}^m were insensitive to the selection of the model density distribution. Figure 5 shows the R_{rms}^m determined using the harmonic-oscillator distribution. The harmonic oscillator values are selected simply because this distribution is most likely to represent the density distributions of p-shell nuclei. For the first time we can directly compare the differences of radii between pairs of isobars. For isobars with different isospin, ^{6}He-^{6}Li, ^{8}He-^{8}Li, and ^{9}Li-^{9}Be, the R_{rms}^m is different by 0.1 to 0.2 fm. The larger radii of the neutron rich isotopes ^{6}He and ^{8}He, which have only two protons, suggest the existence of thick neutron skins. On the other hand, a pair of mirror nuclei ^{7}Li - ^{7}Be shows the same matter radii.

The ^{11}Li has a considerably larger radius than surrounding nuclei. It suggests the existence of a large deformation or of a long tail in the matter distribution due to weakly-bound nucleons. The weakly-bound nucleon may enhance the σ_I because it can be kicked out from the nucleus with a small momentum transfer. A rough estimation of the excitation-energy distribution of nucleons after a nucleon-nucleon collision, however, showed that the change in separation energy from 10 MeV to zero affect the σ_I only about 3 %. Therefore this effect does not explain the bulk part of the observed deviation.

Summary and acknowledgements

In summary, we have successfully used the secondary beams of unstable He, Li, and Be isotopes as well as stable isotopes for the measurement of the interaction cross sections σ_I of nucleus-nucleus collisions. The interaction nuclear radii R_I of these nuclei have been determined from the σ_I. The separability of projectile and target interaction nuclear radii was confirmed in these isotopes, and indicates that the R_I is a well defined size parameter of the nucleus. Root-mean-square radii of the nuclear matter distribution R^m_{rms} are deduced from the σ_I using three model density distributions: a Gaussian, the shell model harmonic oscillator, and the droplet model. These distributions gave essentially the same results for R^m_{rms}. It shows therefore that the R^m_{rms} can be obtained from the σ_I rather independent of assumed model density. The differences in R^m_{rms} between isobars of different isospin, ^{6}He-^{6}Li, ^{8}He-^{8}Li, ^{9}Li-^{9}Be have been observed for the first time. A pair of mirror nuclei ^{7}Li - ^{7}Be was found to have equal R^m_{rms}. An observed large radius of ^{11}Li suggests an existence of the a large deformation or of a long density tail of the nucleus.

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10. Here σ_I(^{6}Li,^{6}Li) and σ_I(^{7}Li,^{7}Li), which were not directly measured, were calculated from the R_I(^{6}Li) and R_I(^{7}Li) using Eq. (1). Those values are believed to be reliable within a few % due to the separability discussed above.

Table I. Interaction cross sections(σ_I)
σ_I in mb

	target		
beam	Be	C	Al
^{6}Li	651± 6	688±10	1010±11
^{7}Li	686± 4	736± 6	1071± 7
^{8}Li	727± 6	768± 9	1147±14
^{9}Li	739± 5	796± 6	1135± 7
^{11}Li		1040±60	
^{7}Be	682± 6	738± 9	1050±17
^{9}Be	755± 6	806± 9	1174±11
^{10}Be	755± 7	813±10	1153±16

Figure Captions

Fig.1 The secondary beam line at LBL Bevalac.

Fig.2 The interaction radii as a function of the mass number. Values obtained from three different target material agree with each other.

Fig.3 The interaction radii determined by the present measurement.

Fig.4 A comparison of the *rms* charge radii obtained from present experiment to those obtained by electron scattering.

Fig.5 The *rms* radii of matter distribution for He, Li, Be and C isotopes. Isobaric differences of the radii are observed for mass mass number 6,7,8, and 9.

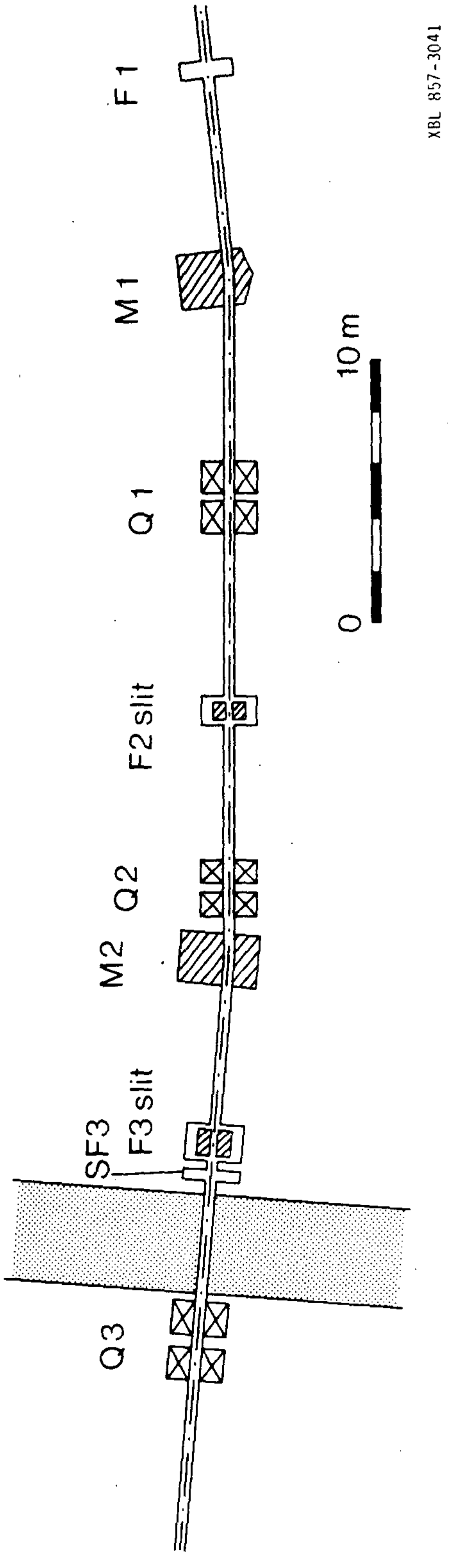
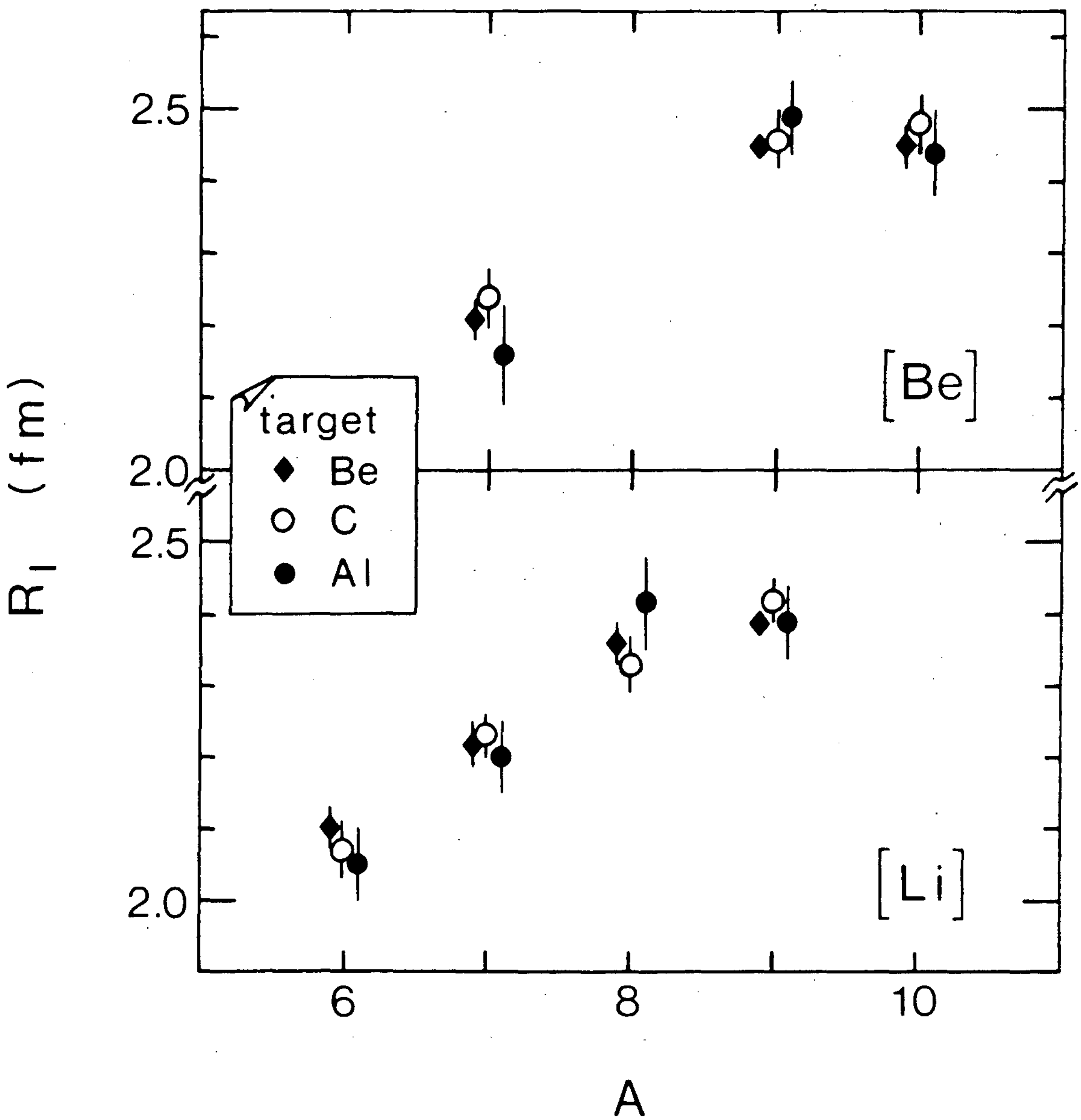
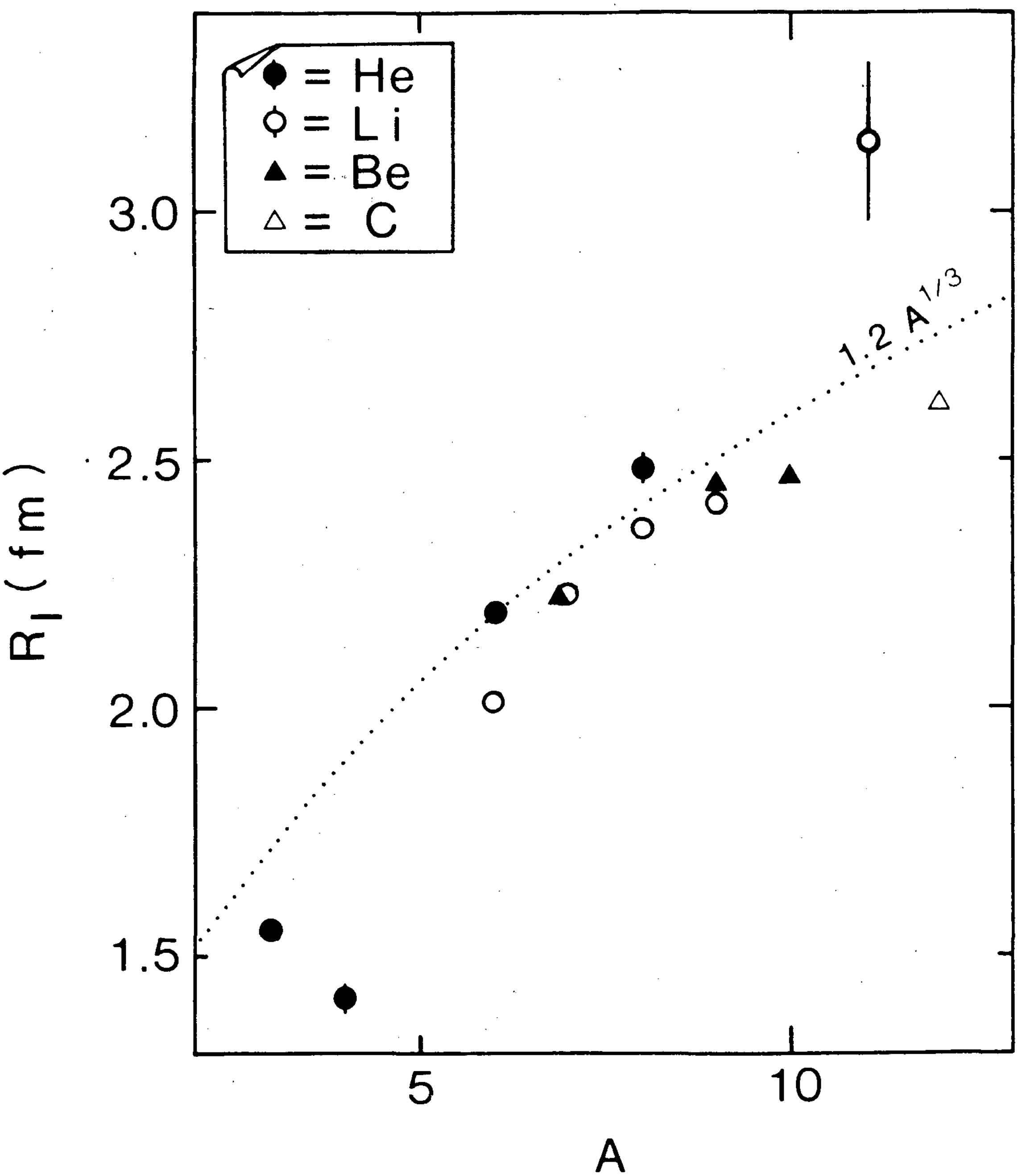


Fig. 1



XBL 856-3499

Fig. 2



XBL 858-3614

Fig. 3

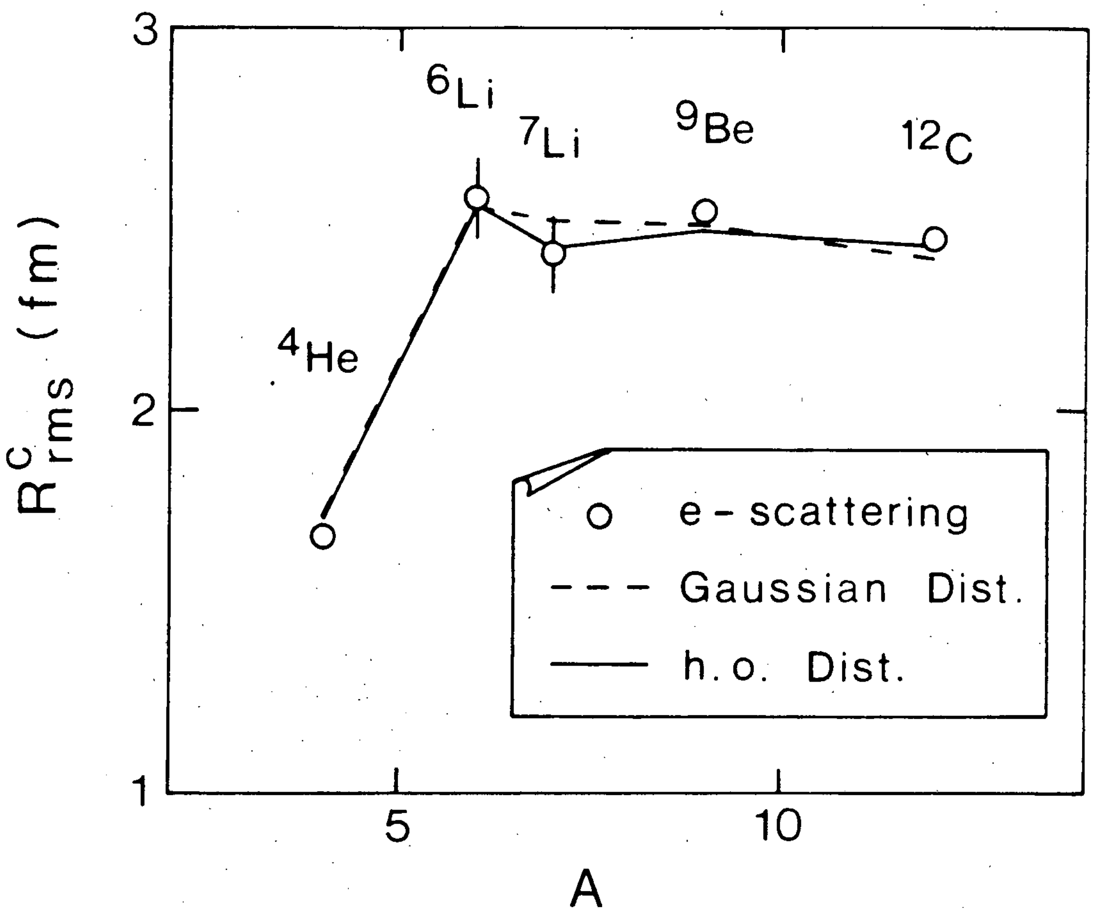


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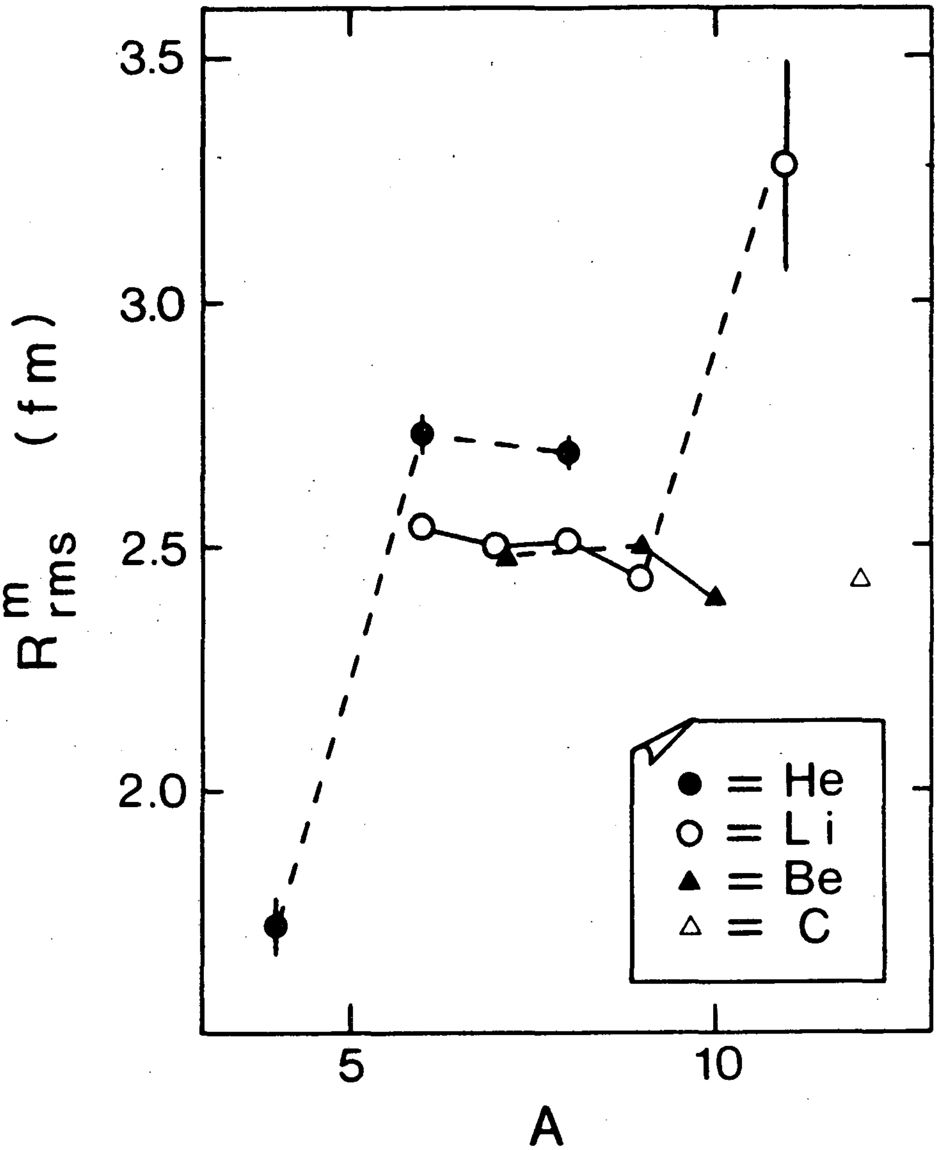
Fig. 4



XBL 858-3500

Fig. 5

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