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# Measurements of reaction cross sections for neutron-rich exotic nuclei by a new direct method ☆

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A new, simple, direct method for the measurement of reaction cross sections ($\sigma_R$) is presented. The $\sigma_R$ for neutron-rich exotic nuclei were measured and the reduced strong absorption radii $r_0^2$ were deduced. A strong isospin dependence of $r_0^2$ was observed for measured isobars with masses from $A=10$ up to $A=18$. For heavier nuclei, this dependence is strongly reduced.

The evaluation of nuclear radii is of fundamental interest in nuclear physics. The observation of an unexpectedly large interaction radius for $^{11}$Li has suggested the image of a neutron halo [1,2] in this nucleus. This very exotic matter distribution could be interpreted as a precursor of neutron matter, as suggested by Myers [3]. Therefore, the correct evaluation and interpretation of experimental measurements of interaction cross sections ($\sigma_I$), and the related interaction radii ($r_I$) are essential.

At high energies ($\approx 800A$ MeV), $\sigma_I$ was measured for several light ($2<Z<5$) isotopes using a transmission technique [1,4]. At intermediate energies ($\approx 60A$ MeV), $\sigma_I$ measurements were carried out for a wider atomic number range ($3<Z<15$), using the

☆ Experiment performed at GANIL.
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associated-γ method [5,6]. Although for stable nuclei the results using the associated-γ technique agree with $\sigma_I$ obtained by the transmission method or with the reaction cross section deduced from elastic scattering, they may disagree for very exotic neutron-rich nuclei which decay through neutron emission, leaving the final nucleus in the ground state or at low excitation energy. We recall that measurements of associated-γ cross section at intermediate energies [6] showed no evidence of an enhancement of the reduced radius ($r_0^2$) of $^{11}$Li, as in high energy data [1]. Therefore, it is important to develop a new technique in order to test the present results and conclusions obtained by these two methods.

The aim of this letter is to present new intermediate energy measurements of the reaction cross section $\sigma_R$ (instead of $\sigma_I$) for radioactive nuclei produced at GANIL, using a new, simple, direct technique and compare them with all previous results obtained for $\sigma_I$.

Secondary radioactive beams [7] were produced through the projectile fragmentation of a 55*A* MeV $^{48}$Ca primary beam on a 350 mg/cm$^2$ Ta target. Part of the secondary beam produced was transported to the spectrograph SPEG [8]. At the focal plane, all particles were detected with a telescope consisting of three solid state silicon detectors, which were a 50 μm Δ*E*, a 300 μm *x*–*y* position sensitive Δ*E* and a 6000 μm *E*. The telescope was cooled to about −10°C and surrounded by a 4π array of 14 NaI(Tl) 13.1 cm diameter and 23.5 cm long γ-detectors. The identification of incident particles was unambiguously given by the time of flight between two micro-channel plate detectors, located respectively just after the production target and just before the telescope, and by the energy loss in the first Δ*E* detector. The identification matrix $Z \times m/q$ is shown in fig. 1

The direct method for obtaining $\sigma_R$ is the following. All incident particles are stopped in the telescope which has the double function of detector and target. Events that correspond to reactions in the detector/target are easily identified, their energy being different from the no-reaction events (see fig. 2). The reaction probability ($P_r$) is given by dividing the number of reaction events (outside of the sharp elastic peak) by the total number of counts in this spectrum. This method is not sensitive to reactions with $Q=0$, or with $Q$ smaller than the energy resolution of the

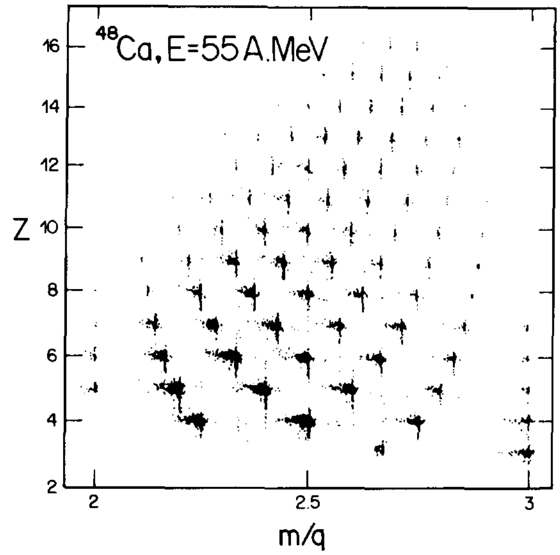


Fig. 1. Identification matrix $Z$ versus $m/q$ obtained by the combination of Δ*E*, magnetic rigidity and time of flight measurements.

detector system, except for the reactions that produce light particles or γ-rays, which are not stopped or detected in the telescope. To avoid the reduced energy resolution, due to the 1% energy acceptance of the beam line, the relevant parameter considered in the spectrum of the telescope was $ET^2$, where $E$ is the energy deposited in the telescope and $T$ is the time of flight of the incident particles. This gives a better resolution, being proportional to $m$. The resolution obtained for the quantity $ET^2$ is 0.23%, leading, for example, to an effective $Q$-resolution of 1.7 MeV for $^{18}$Ne. Fig. 2 shows the free spectra $ET^2$ for a $^{18}$N incident beam and the same $ET^2$ spectra in anti-coincidence and in coincidence with the 4π γ-detector array. In order to include quasi-elastic events, we added to the reaction events the number of γ-coincidences inside the elastic peak, after subtraction of random coincidences. This correction represents only 2% of the total number of reaction events, with a γ-detection efficiency of 73% for single photons of $^{60}$Co.

The quantity measured with this method is an energy-integrated reaction cross section. One could measure $\sigma_R$ for nearby energies and unfold the integrated reaction cross section, but due to the very low intensity of the exotic beams, it would increase significantly the errors of the final cross sections. Thus, we used a semi-empirical relationship for unfolding

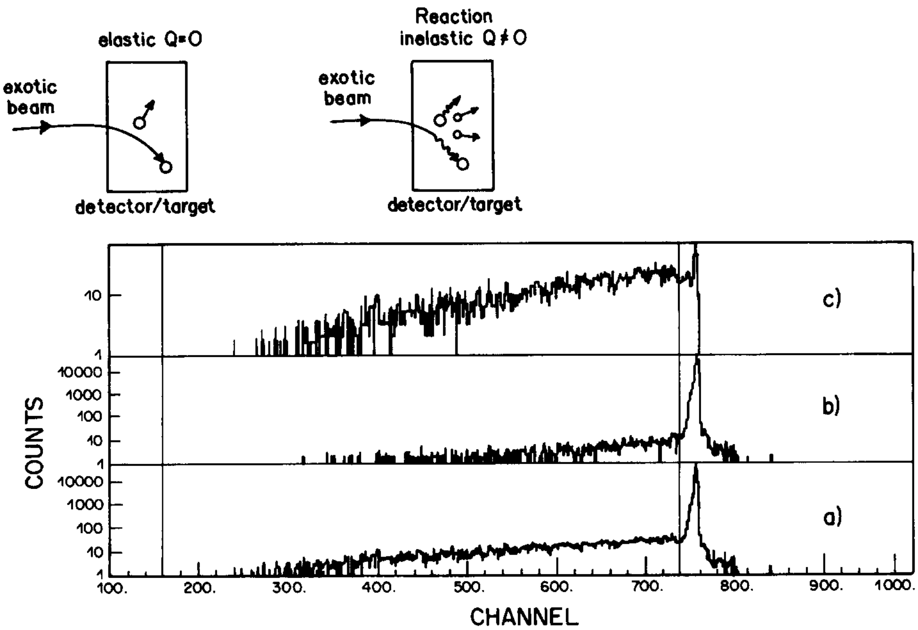


Fig. 2. Upper: scheme of the direct method. The reaction probability is the number of inelastic events divided by the total number of events. Lower: $ET^2$ spectrum. (a) Unconditioned detector/target spectrum; (b) anticoincidence spectrum with $4\pi$ γ-array; (c) coincidence spectrum with $4\pi$ γ-array. The two vertical lines delimit the region considered as reaction events.

the energy dependence of $\sigma_R$, as will be discussed in the following.

The mean energy-integrated reaction cross section is defined by the following equation:

$$\bar{\sigma}_R = \frac{\int^{E_{max}} \sigma_R(E)(\mathrm{d}R/\mathrm{d}E)\,\mathrm{d}E}{\int_0^{R_{max}} \mathrm{d}R}$$

$$= -\frac{m \log(1-P_r)}{N_A R_{max}}, \qquad (1)$$

where $m=28$ is the mol-weight of Si, $N_A$ the Avogadro number and $R_{max}$ the range of incident particles, calculated using the tables of Hubert et al. [9]. The uncertainty in the value of $R_{max}$ can introduce a maximum error of 2% in the $\sigma_R$ value.

The parameter that we will extract from the experimental data is the strong absorption radius $r_0$, defined as follows:

$$\sigma_R(E) = \pi r_0^2 f(E) . \qquad (2)$$

It has been shown [10] that $r_0 = 1.1$ fm$^2$ for all stable nuclear systems and that it is independent of the target for systems involving exotic nuclei [11]. We used the parametrization of Kox et al. [10] for the function $f(E)$ as has been done in our preceding paper. The parameters used in our calculation were obtained by Fernandez [12] by carefully fitting experimental data measured over a large energy range ($30A$–$200A$ MeV) and involving many colliding systems with $A_p$ ranging from 1 to 40 and $A_t$ from 9 to 209 and including the $\sigma_R$ values obtained from elastic scattering analysis [11]. The reaction cross section is written as

$$\sigma_R(E) = \pi r_0^2 \times \left(A_p^{1/3} + A_t^{1/3} + a\frac{A_p^{1/3}A_t^{1/3}}{A_p^{1/3}+A_t^{1/3}} - C(E)\right)^2 \times \left(1 - \frac{V_{cb}}{E_{CM}}\right), \qquad (3)$$

$$C(E) = 0.31 + 0.014E/A_p , \qquad (4)$$

where $A_p$ and $A_t$ are the projectile and target mass numbers, $a = 1.85$ is an asymmetry parameter, $C(E)$ is an energy dependent transparency and $V_{cb}$ is the Coulomb barrier. As an example of the meaning of this parametrization, we present in fig. 3 the $\sigma_R$ calculated using relation (3) for the system $^{16}O+^{28}Si$ at incident energy 41$A$ MeV as a function of the particle path in the Si target. The energy dependence of the parametrization (3) is contained in the transparency $C(E)$ and in the Coulomb correction, which are only 0.7% and 2.7% respectively (see fig. 3), when compared with the geometrical cross section. This feature ensures the reliability of extracting accurate information on the geometrical nuclear properties from the energy integrated cross section.

We show in table 1 $\sigma_R$ measured in this experiment and the mean value of $r_0^2$ obtained for each isotope. In fig. 4, we compare our new $r_0^2$ results with our previous results using the associated-γ technique [5,11], with results of associated-γ by Saint-Laurent et al. [6] and with results of the transmission technique at 800$A$ from Tanihata et al. [1,13,14] using for all measured data of $\sigma_R$ and $\sigma_I$ the same parametrization described above. For the data of Tanihata et al., the value of the energy dependent transparency was $C(E)=1.9$ (see ref. [8]). The $r_0^2$ results are plotted as a function of the isospin $T_z$.

The first conclusion to be inferred from fig. 4 is the agreement of values of $r_0^2$ deduced from different ex-

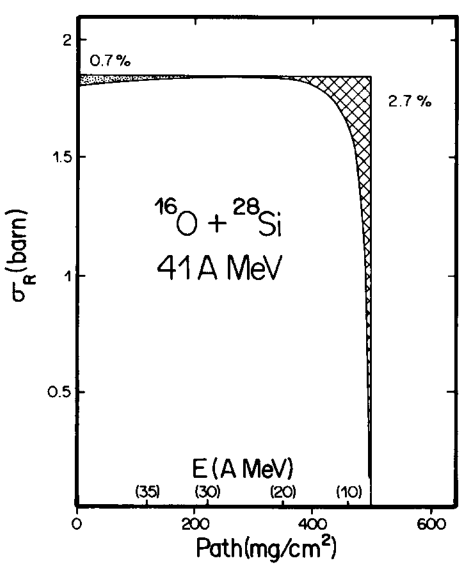


Fig. 3. $\sigma_R$ as a function of the particle path in the Si target, calculated using eq. (3). The marked zones correspond to the effect of transparency (0.7%) and Coulomb correction (2.7%) with respect to the geometrical cross section.

perimental techniques and different energies. However we do observe somewhat larger values of $r_0^2$ obtained from the new direct method (this work) when compared with results from associated-γ technique for the very neutron-rich nuclei (see $^9Li$, $^{11}Li$, $^{12}Be$). For these nuclei, the break-up reaction leading to a nucleus in the ground state or at low excitation energy plus one or several neutrons is expected to increase significantly [6,11]. This is a severe limitation on the associated γ-ray technique, which, in this case, will underestimate the reaction cross section and $r_0^2$. On the other hand, the $r_0^2$ for $^{11}Li$, deduced from the direct method is larger than the result of Tanihata at high energies.

Relations (3), (4), which were established in the stable nuclei region, allow us to relate the measured cross sections with a reduced radius $r_0$ supposing a fixed matter distribution. If the matter distribution is different in the region of very exotic nuclei, the deduced $r_0$ will be strongly dependent on the energy. At intermediate energies, the cross section will reflect the size of the nucleus at the tail of the mass distribution, i.e., around $\frac{1}{10}$ of the central mass density. For high energies, the $\sigma_I$ will reflect the size of the nucleus around $\frac{1}{4}$ of the central density, i.e., deeper inside the mass distribution. Thus, a larger diffuseness at the very exotic region can explain the discrepancy between the results at high and intermediate energies.

Some discrepancies should already be clarified for determining the importance of an increase of $r_0^2$ off stability. The value for $^{11}B$ of ref. [6] disagrees with the other values. Some systematic differences can be seen between ref. [5] and ref. [6] concerning nuclei near stability, as for example $A=12$, 14, $T_z=0$ and $A=11$, 15, $T_z=-\frac{1}{2}$.

For all the measured isobars, a strong influence of isospin is revealed. The isospin dependence of nuclear radii has been already observed by Tanihata [13] for $A=8$ and 12. We see an increase of $r_0^2$ when we go to the neutron-rich side of any of the measured isobars, mainly for masses from $A=10$ up to $A=18$. This observation agrees with our previous work [5,11], and does not agree with the conclusion of Saint-Laurent et al. [6]. Results from ref. [5] for nuclei heavier than $A=18$ present a systematic deviation from the actual measurements, despite the large error bars. This may be due to a change in the multiplicities of γ's and particles in this domain of $A$, which

Table 1
The mean energy-integrated reaction cross section and associated $r_0^2$, measured for each nuclei for the two magnetic rigidities ($B\rho$). The quoted errors correspond to the statistical errors.

| $A$ | $Z$ | $E/A$ (MeV) | $\overline{\sigma_R}$ (mb) | $\delta\sigma_R$ (mb) | $E/A$ (MeV) | $\overline{\sigma_R}$ (mb) | $\delta\sigma_R$ (mb) | $r_0^2$ (fm$^2$) | $\delta r_0^2$ (fm$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| 8.0 | 2.0 | | | | 21.526 | 2341 | 365 | 1.768 | 0.276 |
| 9.0 | 3.0 | 31.584 | 1839 | 32 | | | | 1.365 | 0.024 |
| 11.0 | 3.0 | | | | 25.507 | 2947 | 386 | 2.017 | 0.264 |
| 12.0 | 4.0 | 31.477 | 2097 | 92 | | | | 1.418 | 0.062 |
| 13.0 | 5.0 | 41.740 | 1809 | 19 | | | | 1.210 | 0.013 |
| 14.0 | 5.0 | 36.016 | 2236 | 91 | 43.386 | 2061 | 46 | 1.361 | 0.027 |
| 15.0 | 5.0 | 31.371 | 2621 | 241 | | | | 1.649 | 0.152 |
| 14.0 | 6.0 | 51.598 | 1722 | 14 | | | | 1.144 | 0.009 |
| 15.0 | 6.0 | 45.014 | 2081 | 26 | | | | 1.335 | 0.016 |
| 16.0 | 6.0 | 39.590 | 2049 | 37 | 47.687 | 1925 | 23 | 1.225 | 0.012 |
| 17.0 | 6.0 | 35.070 | 2193 | 126 | 42.289 | 1979 | 61 | 1.227 | 0.033 |
| 15.0 | 7.0 | 60.909 | 1659 | 55 | | | | 1.098 | 0.036 |
| 16.0 | 7.0 | 53.642 | 1830 | 33 | | | | 1.167 | 0.021 |
| 17.0 | 7.0 | 47.577 | 1888 | 21 | 57.247 | 1833 | 34 | 1.161 | 0.011 |
| 18.0 | 7.0 | 42.463 | 2002 | 34 | 51.148 | 1975 | 31 | 1.200 | 0.014 |
| 19.0 | 7.0 | 38.113 | 2053 | 57 | 45.956 | 2086 | 36 | 1.223 | 0.018 |
| 20.0 | 7.0 | 34.382 | 1853 | 179 | 41.499 | 2180 | 97 | 1.212 | 0.049 |
| 17.0 | 8.0 | 61.823 | 2053 | 264 | | | | 1.304 | 0.168 |
| 18.0 | 8.0 | 55.239 | 1890 | 50 | | | | 1.162 | 0.031 |
| 19.0 | 8.0 | 49.630 | 1988 | 33 | 59.724 | 1790 | 106 | 1.179 | 0.019 |
| 20.0 | 8.0 | 44.815 | 1997 | 31 | 53.984 | 1957 | 45 | 1.161 | 0.015 |
| 21.0 | 8.0 | 40.650 | 1999 | 60 | 49.016 | 1940 | 51 | 1.124 | 0.022 |
| 22.0 | 8.0 | 37.024 | 2303 | 144 | 44.688 | 2139 | 83 | 1.221 | 0.040 |
| 21.0 | 9.0 | 51.306 | 1956 | 43 | | | | 1.135 | 0.025 |
| 22.0 | 9.0 | 46.768 | 2014 | 39 | 56.344 | 1902 | 116 | 1.137 | 0.021 |
| 23.0 | 9.0 | 42.790 | 2048 | 45 | 51.600 | 2109 | 66 | 1.151 | 0.021 |
| 24.0 | 9.0 | 39.284 | 2122 | 113 | 47.418 | 2146 | 94 | 1.168 | 0.039 |
| 25.0 | 9.0 | | | | 43.711 | 2342 | 193 | 1.257 | 0.103 |
| 23.0 | 10.0 | 52.696 | 1927 | 108 | | | | 1.087 | 0.061 |
| 24.0 | 10.0 | 48.412 | 2038 | 55 | | | | 1.126 | 0.030 |
| 25.0 | 10.0 | 44.615 | 2174 | 70 | 53.808 | 2341 | 220 | 1.188 | 0.036 |
| 26.0 | 10.0 | 41.234 | 2298 | 97 | 49.776 | 2152 | 130 | 1.199 | 0.041 |
| 26.0 | 11.0 | 49.812 | 1989 | 111 | | | | 1.073 | 0.060 |
| 27.0 | 11.0 | 46.187 | 2241 | 75 | | | | 1.189 | 0.040 |
| 28.0 | 11.0 | 42.930 | 2399 | 104 | | | | 1.253 | 0.054 |
| 29.0 | 11.0 | 39.994 | 2305 | 134 | 48.329 | 2494 | 193 | 1.218 | 0.057 |
| 30.0 | 11.0 | | | | 45.160 | 2651 | 269 | 1.344 | 0.136 |
| 29.0 | 12.0 | 47.551 | 2427 | 173 | | | | 1.260 | 0.090 |
| 30.0 | 12.0 | 44.416 | 2337 | 111 | | | | 1.196 | 0.056 |
| 31.0 | 12.0 | 41.570 | 2304 | 154 | | | | 1.163 | 0.078 |
| 32.0 | 12.0 | 38.978 | 2931 | 221 | | | | 1.462 | 0.110 |
| 32.0 | 13.0 | 45.725 | 2199 | 170 | | | | 1.104 | 0.085 |
| 33.0 | 13.0 | 42.968 | 2752 | 134 | | | | 1.364 | 0.066 |
| 34.0 | 13.0 | 40.443 | 2427 | 196 | | | | 1.189 | 0.096 |
| 35.0 | 13.0 | 38.124 | 2890 | 262 | | | | 1.402 | 0.127 |
| 35.0 | 14.0 | 44.216 | 3052 | 269 | | | | 1.487 | 0.131 |
| 36.0 | 14.0 | 41.758 | 2468 | 170 | | | | 1.190 | 0.082 |
| 37.0 | 14.0 | 39.490 | 2274 | 253 | | | | 1.085 | 0.121 |
| 38.0 | 15.0 | 42.944 | 2426 | 186 | | | | 1.152 | 0.088 |
| 39.0 | 15.0 | 40.728 | 2485 | 162 | | | | 1.168 | 0.076 |
| 40.0 | 15.0 | 38.671 | 3011 | 325 | | | | 1.403 | 0.151 |

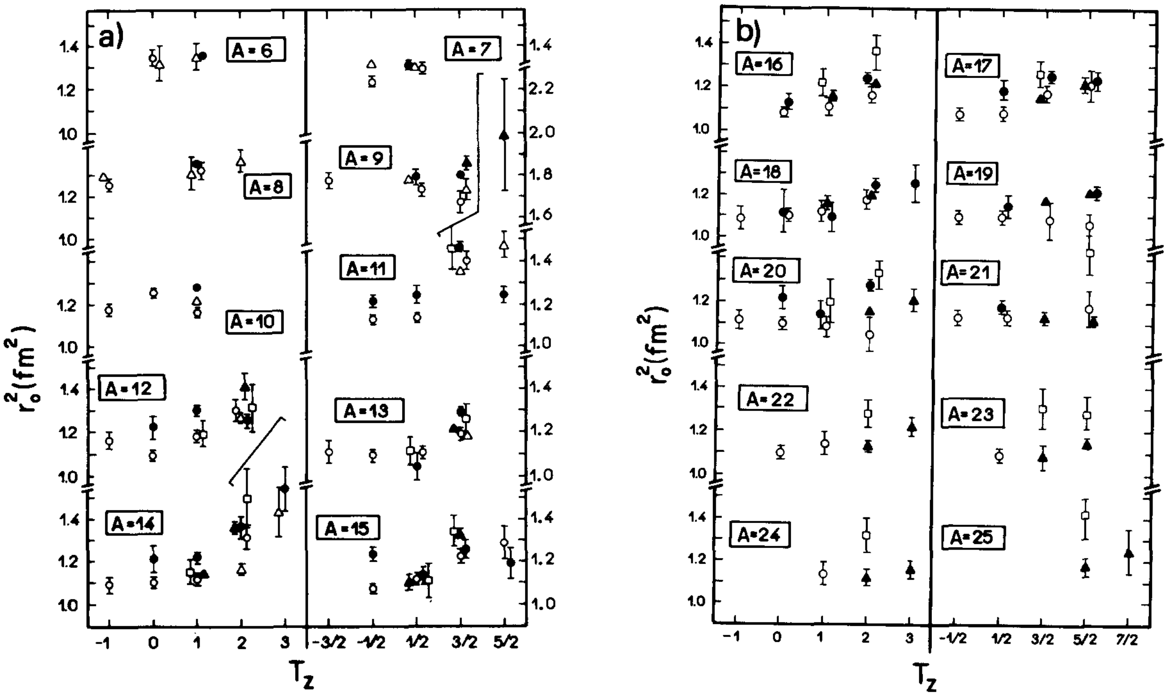

Fig. 4. Variation of $r_0^2$ as a function of isospin: square=associated-γ method (ref. [5]), open circle=associated-γ method (ref. [6]), closed circle=ref. [6], open triangle=Tanihata data (ref. [3]), closed triangle=this work (direct method).

may not have been corrected due to low statistics of these points.

In conclusion, we developed a new simple direct method for the measurement of the reaction cross section ($\sigma_R$). We measured $\sigma_R$ with this method for several exotic nuclei and we deduced the reduced absorption radii $r_0^2$. The values of $r_0^2$ obtained in this work agree well with those obtained by other techniques, except when compared with results from associated-γ method for the weakly bound nuclei $^9$Li, $^{11}$Li and $^{12}$Be. This may be explained by break-up reactions leading to a nucleus in the ground state or at low excitation energy plus one or several neutrons. The $r_0^2$ for $^{11}$Li obtained from the direct method is larger than that obtained from the attenuation technique at higher energy. This is most likely due to the large diffuseness of this nucleus. A more systematic measurement of the energy dependence of $\sigma_R$ should clarify this point.

We observed a strong isospin dependence of the nuclear radii. The radii increase significantly when we go to the neutron-rich side of any measured isobar with masses from $A=10$ up to $A=18$. For heavier nuclei, the effect is strongly reduced, at least in the isospin range measured.

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