# Reaction cross sections on a deuteron as a probe of nuclear radii†

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Total reaction or interaction cross section measurement has been used as a standard tool to determine the nuclear radii of unstable nuclei. The total reaction cross section of a proton target is known to exhibit strong incident energy dependence that can be used to deduce both the neutron and proton radii.[1,2] A neutron target may also be useful for the structual study of the unstable nuclei as it has a different sensitivity compared to that of the proton target but no neutron target exists. Since the deuteron is composed of neutrons and protons, the total reaction cross section on a deuteron target must include both information on the nucleus-neutron and the nucleus-proton scattering profiles.

To describe high-energy nucleus-deuteron reactions, we employ the Glauber model,[3] wherein the nucleus-nucleon total reaction cross section $\sigma_N$ ($N = n, p$) can be obtained by $\sigma_N = \int d\boldsymbol{b}\ (1 - |e^{i\chi_N^P(\boldsymbol{b})}|^2)$. Under the optical-limit approximation, the optical phase-shift function $e^{i\chi_N^P(\boldsymbol{b})}$ at the impact parameter vector $\boldsymbol{b}$ can be evaluated using the projectile's density and nucleon-nucleon ($NN$) scattering profiles. A unique advantage of the deuteron target is that one can calculate the phase-shift function accurately using its ground-state wave function $\phi_d(\boldsymbol{r})$. The nucleus-deuteron total reaction cross section $\sigma_d = \int d\boldsymbol{b}\,(1 - P_d(\boldsymbol{b}))$, and it can be obtained with

$$P_d(\boldsymbol{b}) = \left| \int d\boldsymbol{r}\, |\phi_d(\boldsymbol{r})|^2 e^{i\chi_p^P(\boldsymbol{b}+\frac{1}{2}\boldsymbol{s})+i\chi_n^P(\boldsymbol{b}-\frac{1}{2}\boldsymbol{s})} \right|^2, \quad (1)$$

where $\boldsymbol{r} = (\boldsymbol{s}, z)$ with $z$ being the beam direction.

In most measurements, the interaction cross section $\sigma_{d:I}$ is observed but not $\sigma_d$. Since $\sigma_d$ includes all inelastic cross sections, $\sigma_d > \sigma_{d:I}$ always holds. However, a calculation of $\sigma_{d:I}$ demands all bound-state wave functions of the projectile, which is difficult in general. For the deuteron target, provided the projectile has only one bound state, *i.e.*, its ground state, one can evaluate $\sigma_d - \sigma_{d:I}$ with the same inputs required to evaluate $\sigma_d$ as $\Delta_0\sigma = \int d\boldsymbol{b}\,(P_0(\boldsymbol{b}) - P_d(\boldsymbol{b}))$ with

$$P_0(\boldsymbol{b}) = \int d\boldsymbol{r}\, |\phi_d(\boldsymbol{r})|^2 \left| e^{i\chi_p^P(\boldsymbol{b}+\frac{1}{2}\boldsymbol{s})+i\chi_n^P(\boldsymbol{b}-\frac{1}{2}\boldsymbol{s})} \right|^2. \quad (2)$$

If the projectile has more than one bound state, $\Delta_0\sigma$ gives the lower bound of $\sigma_d - \sigma_{d:I}$.

Figure 1 displays $\sigma_d$, $\sigma_p$, and $\sigma_n$ for $^{30}$Ne as a function of incident energy. $\sigma_d$ is always significantly smaller than $\sigma_p + \sigma_n$ by about 70–90% of $\sigma_p + \sigma_n$ due to the "eclipse" of the constituent neutron and proton.[3] The energy dependence of these cross sections follows that of the $NN$ total cross section. The information of the nucleus-neutron scattering profile is included in $\sigma_d$. As already mentioned, the deuteron target has the advantages that the upper bound of the interaction cross section can be evaluated reliably using the deuteron wave function. Further, Fig. 1 displays the upper bound of the interaction cross section $\sigma_{d:I}$ and $\Delta_0\sigma$ for $^{30}$Ne. $\Delta_0\sigma$ has at maximum 60–70 mb at around 80 MeV/nucleon, which is about 6% of $\sigma_d$. In addition, $\Delta_0\sigma$ decreases with increasing incident energy. The ratio $\Delta_0\sigma/\sigma_d$ becomes at most few percent beyond 300 MeV/nucleon. For the unstable nuclei near the dripline that has only one bound state, a reliable interaction cross section can be obtained, and this greatly improves the accuracy of the radius extraction. We conclude that measuring the total reaction cross sections on both deuteron and proton targets is the most unambiguous and promising approach to determine the neutron and proton radii of unstable nuclei.

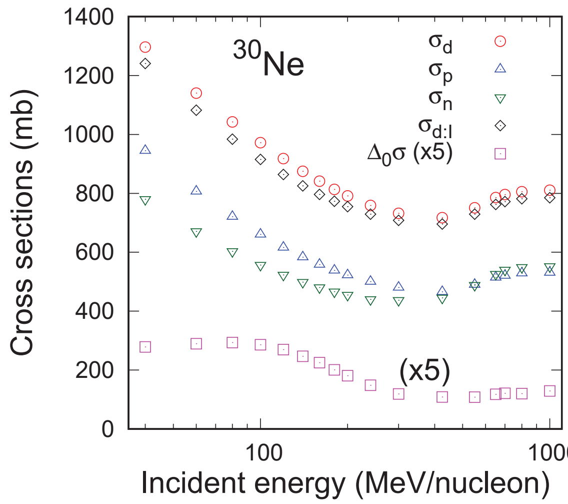


Fig. 1. Various cross sections for $^{30}$Ne adopted from the original paper. See text for details.

References


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