Derivation of breakup probabilities from experimental elastic backscattering data

V.V.Sargsyan¹, G.G.Adamian¹, N.V.Antonenko¹, W. Scheid², and H.Q.Zhang³

¹Joint Institute for Nuclear Research, 141980 Dubna, Russia
²Institut für Theoretische Physik der Justus–Liebig-Universität, D–35392 Giessen, Germany
³China Institute of Atomic Energy, Post Office Box 275, Beijing 102413, China

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Abstract

We suggest simple and useful method to extract breakup probabilities from the experimental elastic backscattering probabilities in the reactions with toughly and weakly bound nuclei.

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The fusion (capture) dynamics induced by loosely bound radioactive ion beams is being extensively studied \[1, 2\]. However, the long-standing question whether fusion (capture) is enhanced or suppressed with these beams has not yet been answered unambiguously. The study of the fusion reactions involving nuclei close to the drip-lines has led to contradictory results. The lack of a clear systematic behavior \[2, 3\] of the breakup probability as a function of the target charge requires additional experimental and theoretical studies. The quasi-elastic backscattering has been suggested \[2\] as an alternative to investigate the breakup probability. Since the quasi-elastic experiments are usually not as complex as the fusion (capture) and breakup measurements, they are well suited to survey the breakup probability.

In the present report we will show that by employing the experimental elastic backscattering data, one can extract the breakup probabilities of weakly bound nuclei. So, new method for the study of the breakup probability will be suggested.

There is a direct relationship between the capture, quasi-elastic scattering and breakup processes, since any losses from the elastic scattering and breakup channels contribute directly to other channels (the conservation of the total reaction flux at given bombarding energy $E_{\text{c.m.}}$ and angular momentum $J$):

$$P_{qe}(E_{\text{c.m.}}, J) + P_{\text{cap}}(E_{\text{c.m.}}, J) + P_{\text{BU}}(E_{\text{c.m.}}, J) =$$

$$= P_{\text{el}}(E_{\text{c.m.}}, J) + P_{\text{rest}}(E_{\text{c.m.}}, J) + P_{\text{BU}}(E_{\text{c.m.}}, J) = 1, \quad (1)$$

where $P_{\text{rest}} = P_{\text{cap}} + P_{\text{in}} + P_{\text{tr}}$, $P_{qe} = P_{\text{el}} + P_{\text{in}} + P_{\text{tr}}$ is the quasi-elastic scattering probability, $P_{\text{BU}}$ is the breakup probability, and $P_{\text{cap}}$ is the capture probability. The quasi-elastic scattering ($P_{qe}$) is the sum of all direct reactions, which include elastic ($P_{\text{el}}$), inelastic ($P_{\text{in}}$), and a few nucleon transfer ($P_{\text{tr}}$) processes. In Eq. (1), we neglect the deep-inelastic collision process, since we are concerned with low energies.

Equation (1) can be rewritten as

$$\frac{P_{\text{el}}(E_{\text{c.m.}}, J)}{1 - P_{\text{BU}}(E_{\text{c.m.}}, J)} + \frac{P_{\text{rest}}(E_{\text{c.m.}}, J)}{1 - P_{\text{BU}}(E_{\text{c.m.}}, J)} = P_{\text{el}}^{\text{noBU}}(E_{\text{c.m.}}, J) + P_{\text{rest}}^{\text{noBU}}(E_{\text{c.m.}}, J) = 1, \quad (2)$$

where

$$P_{\text{el}}^{\text{noBU}}(E_{\text{c.m.}}, J) = \frac{P_{\text{el}}(E_{\text{c.m.}}, J)}{1 - P_{\text{BU}}(E_{\text{c.m.}}, J)}$$

and

$$P_{\text{rest}}^{\text{noBU}}(E_{\text{c.m.}}, J) = \frac{P_{\text{rest}}(E_{\text{c.m.}}, J)}{1 - P_{\text{BU}}(E_{\text{c.m.}}, J)}$$
are the elastic scattering and other channels probabilities, respectively, in the absence of the breakup process. From these expressions we obtain the useful formulas

\[
P_{el}(E_{c.m.}, J) = \frac{P_{el}^{noBU}(E_{c.m.}, J)}{P_{noBU}^{rest}(E_{c.m.}, J)} = \frac{P_{el}^{noBU}(E_{c.m.}, J)}{1 - P_{el}^{noBU}(E_{c.m.}, J)}.
\] (3)

Using Eqs. (1) and (3), one can find the relationship between the breakup and elastic scattering processes:

\[
P_{BU}(E_{c.m.}, J) = 1 - \frac{P_{el}(E_{c.m.}, J)}{P_{noBU}^{el}(E_{c.m.}, J)}.
\] (4)

The last equation is the main result of the present report. Note that similar formula

\[
P_{BU}(E_{c.m.}, J) = 1 - \frac{P_{qe}(E_{c.m.}, J)}{P_{noBU}^{qe}(E_{c.m.}, J)}
\] (5)

was derived in Ref. [2] to relate the breakup and quasi-elastic scattering processes.

The reflection elastic or quasi-elastic backscattering probability \( P_{el,qe}(E_{c.m.}, J = 0) = \frac{d\sigma_{el,qe}}{d\sigma_{Ru}} \) for bombarding energy \( E_{c.m.} \) and angular momentum \( J = 0 \) is given by the ratio of the elastic or quasi-elastic scattering differential cross section \( \sigma_{el,qe} \) and Rutherford differential cross section \( \sigma_{Ru} \) at 180 degrees [4]. Employing Eq. (4) or (5) and the experimental elastic or quasi-elastic backscattering data in the reactions with toughly and weakly bound isotopes-projectiles and the same or almost the same compound nucleus, one can extract the breakup probability of the exotic nucleus. For example, using Eq. (4) or (5) at backward angle, the experimental \( P_{el,qe}^{noBU}[{}^{4}\text{He} + {}^{4}\text{X}] \) of the \( {}^{4}\text{He} + {}^{4}\text{X} \) reaction with toughly bound nuclei (without breakup), and the experimental \( P_{el,qe}[{}^{6}\text{He} + {}^{A-2}\text{X}] \) of the \( {}^{6}\text{He} + {}^{A-2}\text{X} \) reaction with weakly bound projectile (with breakup), and assuming approximate equality \( V_b[{}^{4}\text{He} + {}^{4}\text{X}] \approx V_b[{}^{6}\text{He} + {}^{A-2}\text{X}] \) for the Coulomb barriers of very asymmetric systems, one can extract the breakup probability of the \( {}^{6}\text{He} \):

\[
P_{BU}(E_{c.m.}, J = 0) = 1 - \frac{P_{el,qe}(E_{c.m.}, J = 0)[{}^{6}\text{He} + {}^{A-2}\text{X}]}{P_{el,qe}^{noBU}(E_{c.m.}, J = 0)[{}^{4}\text{He} + {}^{A}\text{X}]}.
\] (6)

or

\[
P_{BU}(E_{c.m.}, J = 0) = 1 - \frac{P_{el,qe}(E_{c.m.}, J = 0)[{}^{6}\text{He} + {}^{A-2}\text{X}]}{P_{el,qe}^{noBU}(E_{c.m.}, J = 0)[{}^{4}\text{He} + {}^{A-2}\text{X}]}.
\] (7)

Comparing the experimental elastic or quasi-elastic backscattering probabilities in the presence and absence of breakup data in the reaction pairs \( {}^{6}\text{He} + {}^{68}\text{Zn} \) and \( {}^{4}\text{He} + {}^{68,70}\text{Zn} \), \( {}^{6}\text{He} + {}^{122}\text{Sn} \) and \( {}^{4}\text{He} + {}^{122,124}\text{Sn} \), \( {}^{6}\text{He} + {}^{236}\text{U} \) and \( {}^{4}\text{He} + {}^{236,238}\text{U} \), \( {}^{8}\text{He} + {}^{204}\text{Pb} \) and \( {}^{4}\text{He} + {}^{204,208}\text{Pb} \),
8Li+207Pb and 7Li+207,208Pb, 7Be+207Pb and 10Be+204,207Pb, 9Be+208Pb and 10Be+207,208Pb, 11Be+206Pb and 10Be+206,207Pb, 8B+208Pb and 10B+206,208Pb, 8B+207Pb and 11B+204,207Pb, 9B+208Pb and 11B+206,208Pb, 15C+204Pb and 12C+204,207Pb, 15C+206Pb and 13C+206,208Pb, 15C+207Pb and 14C+207,208Pb, 17F+208Pb and 19F+206,208Pb, leading to the same or almost the same corresponding compound nuclei, one can analyse the role of the breakup channels in the reactions with the light weakly bound projectiles 6,8He, 8Li, 7,9,11Be, 8,9B, 15C, and 17F at energies near and above the Coulomb barrier.

One concludes that the elastic or quasi-elastic backscattering technique could be a very useful tool in the study of breakup. The breakup probabilities can be extracted from the elastic or quasi-elastic backscattering probabilities of systems mentioned above.

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