Light charged particle production in reactions induced by weakly-bound projectiles: Still an open question.

N. Keeley

National Centre for Nuclear Research, Warsaw, Poland

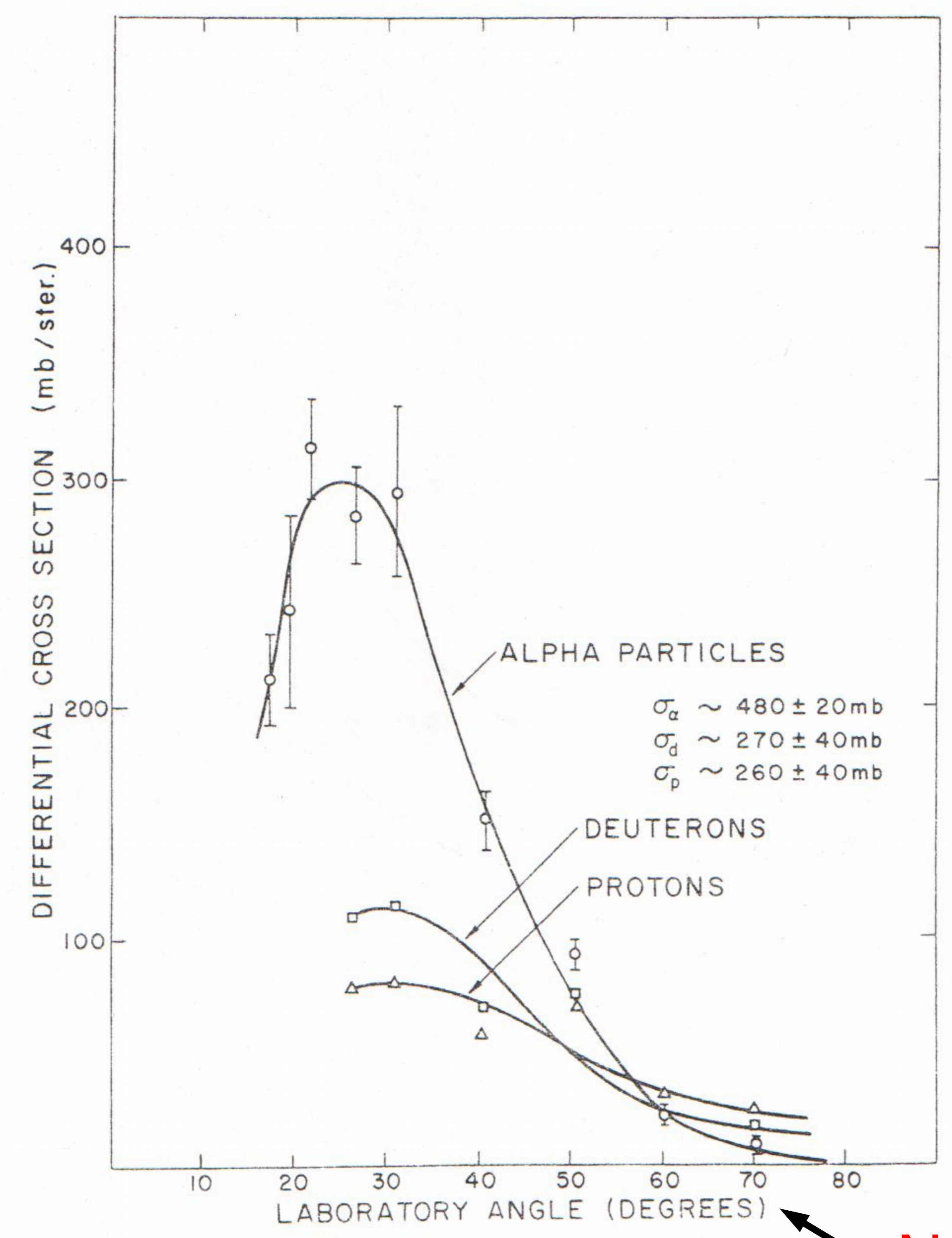
Reactions induced by light weakly-bound nuclei produce large numbers of light charged particles (d, t, α, etc.) with atomic number less than that of the projectile.

This phenomenon was first observed almost sixty years ago—cf. C. E. Anderson, *Proc. 2nd Conf. on reactions between complex nuclei*, Gatlinburg, 1960, ed. A. Zucker, E. C. Halbert and F. J. Howard (Wiley, N.Y., 1960)—and is still an active topic of research today, e.g. J. Lei and A. M. Moro, Phys. Rev. C **95**, 044605 (2017).

Why this continuing interest? Surely “every one knows” that these particles come from breakup of the weakly-bound projectile?

However, the production mechanism must be more complex than this since, at least for nuclei with alpha-clustering structures, many more α particles are observed than d, t ^{3}He etc.

This observation dates back to the initial (inclusive) measurements of Andersen …



Data are for 60.6 MeV ^{6}Li incident on gold.

$\sigma_\alpha \approx 2 \times \sigma_d$

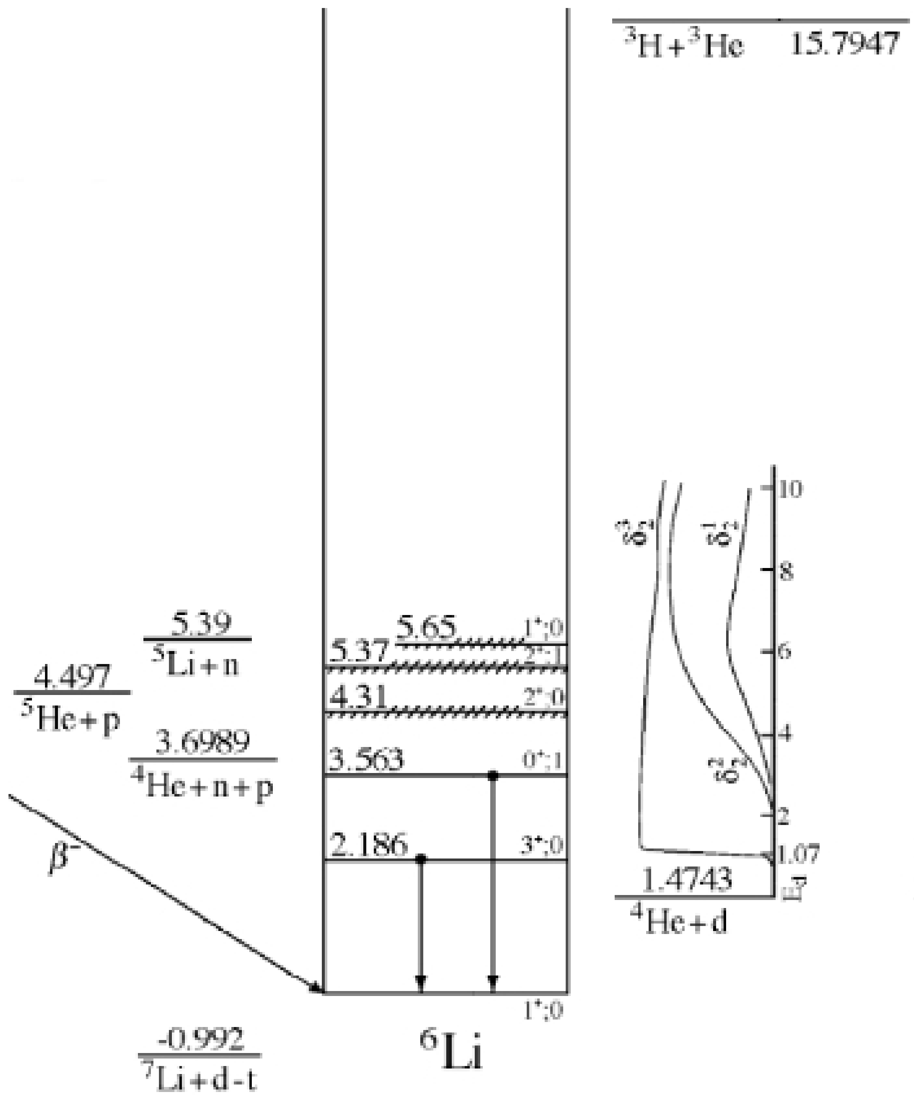
but:

$\sigma_\alpha \approx \sigma_d + \sigma_p$

First thought was that α particles came from $^6\text{Li} \rightarrow \alpha + d$ breakup and that some of the deuterons then broke up in their turn.

Note: *laboratory* angle

However, while this explanation is plausible it is untenable. Examine the level scheme for

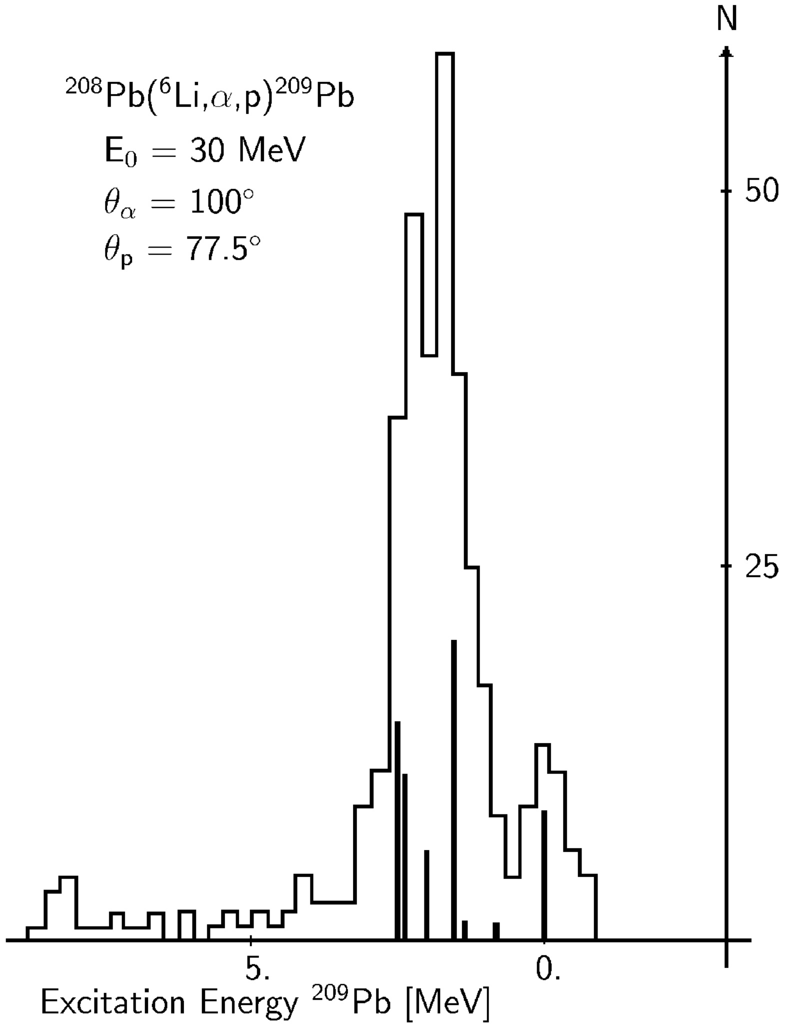


^{6}Li. Threshold for direct 3-body breakup (^{6}Li → α + n + p) is 3.7 MeV, above 2.19 MeV 3^+ resonance. Lifetime of this resonance is 2.7×10^{-20} s, so on average it can only decay into α + d at distances too far away for breakup of d.

Why is the 3^+ resonance important? We can also have "direct" breakup to the α + d continuum → shorter "life time".

Exclusive measurements by Ost *et al*., Z. Phys. **266** (1974) 369 for ^{6}Li + ^{208}Pb system found α + d coincidences enhanced for sequential breakup via ^{6}Li 3^+.

They also saw α + p and α + α coincidences. Evidence for ^{208}Pb(^{6}Li,^{5}Li)^{209}Pb and ^{208}Pb(^{6}Li,^{8}Be)^{206}Tl stripping and pickup …

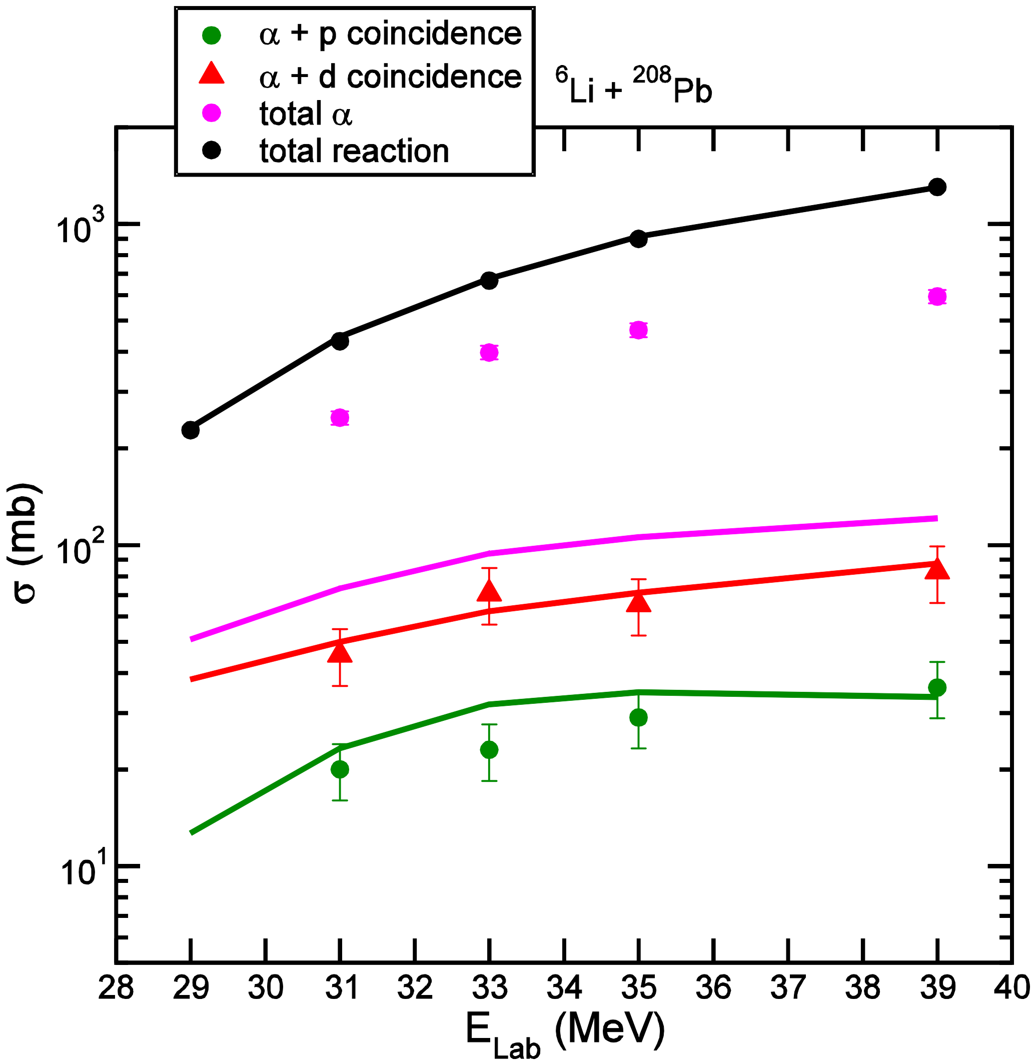


Projection of α + p coincidences shows that they indeed come from the 1n stripping reaction, mostly via g.s. of ^{5}Li.

Conclusion was that the 1n stripping and d pickup reactions could account for the observed excess of α particles over d.

Qualitatively satisfying, but does this explanation hold up *quantitatively*?

Signorini *et al*., Phys. Rev. C **67** (2003) 044607: ^{6}Li + ^{208}Pb inclusive *and* exclusive measurements …



Firstly, note that data bear out quantitatively conclusions of Ost *et al.*, breakup makes small contribution to total α cross section.

Calculations compared with data of Signorini *et al.*, CDCC for breakup plus standard CRC for 1n stripping.

Description is good, but we are still a long way from describing the total α cross section (cf. magenta points with curve) but have shown α + p coincidences consistent with stripping mechanism.

Quantitative estimate of ^{208}Pb(^{6}Li,^{8}Be)^{206}Tl not possible, too many unknowns: exit channel OMP, spectroscopic factors for <^{208}Pb|^{206}Tl + d> overlaps, which states in ^{206}Tl populated?

However, “kinematics” is at least consistent with observation of α + α coincidences: *Q* value of d pickup is +9.65 MeV, estimate of optimum *Q* is +12.0 MeV, roughly calculated assuming:

$$Q_{\text{opt}} = \left[\frac{Z_{\text{b}} Z_{\text{B}}}{Z_{\text{a}} Z_{\text{A}}} - 1 \right] E_{\text{cm}}$$

favours population of low-lying states of ^{206}Tl

We thus see that the predominance of α particles over d for ^{6}Li incident on heavy targets can, at least qualitatively (and to some extent quantitatively) be explained if the majority of α particles are produced by transfer reactions rather than breakup.

Pursuing this hypothesis, let us compare the various transfer reactions that could lead to α particles or d:

(^{6}Li,^{5}Li) → ^{4}He + p

(^{6}Li,^{5}He) → ^{4}He + n

(^{6}Li,^{8}Be) → ^{4}He + ^{4}He

(^{6}Li,^{7}Li*) → ^{4}He + ^{3}H

(^{6}Li,^{6}Be) → ^{4}He + p + p

(^{6}Li,^{6}He*) → ^{4}He + n + n

(^{6}Li,^{4}He) (i.e. deuteron stripping)

(^{6}Li,^{7}Be*) → ^{4}He + ^{3}He

Admittedly, many of these are unlikely to occur with any probability

By contrast, the only transfer process that I can think of that could produce deuterons is the (^{6}Li,d) α stripping

Of course, the relative importance of these reactions will depend very much on the target: *Q* and *L* matching will be critical to giving a significant cross section (as of course will the availability of suitable target-like states with large spectroscopic factors).

The relative contribution of breakup will also depend to some extent on the target (higher Z implies more Coulomb breakup, thus a bigger breakup cross section).

Finally, for lighter targets there is the possibility of fusion-evaporation of α particles and deuterons, added complication

Further support for the transfer hypothesis comes from the fact that for ^{7}Li we also see many more α particles than tritons in inclusive measurements; breakup of the t after ^{7}Li → α + t breakup is unlikely.

E.g.: J. L. Québert *et al.*, Phys. Rev. Lett. **32**, 1136 (1974) singles yields as follows (^{7}Li + ^{197}Au):

σ_{tot} (mb)	Particle
11 ± 3	p
9 ± 2	d
19 ± 3	t
220 ± 10	α
9 ± 3	^{6}He

Also see significant α + d coincidences from (^{7}Li,^{6}Li*)

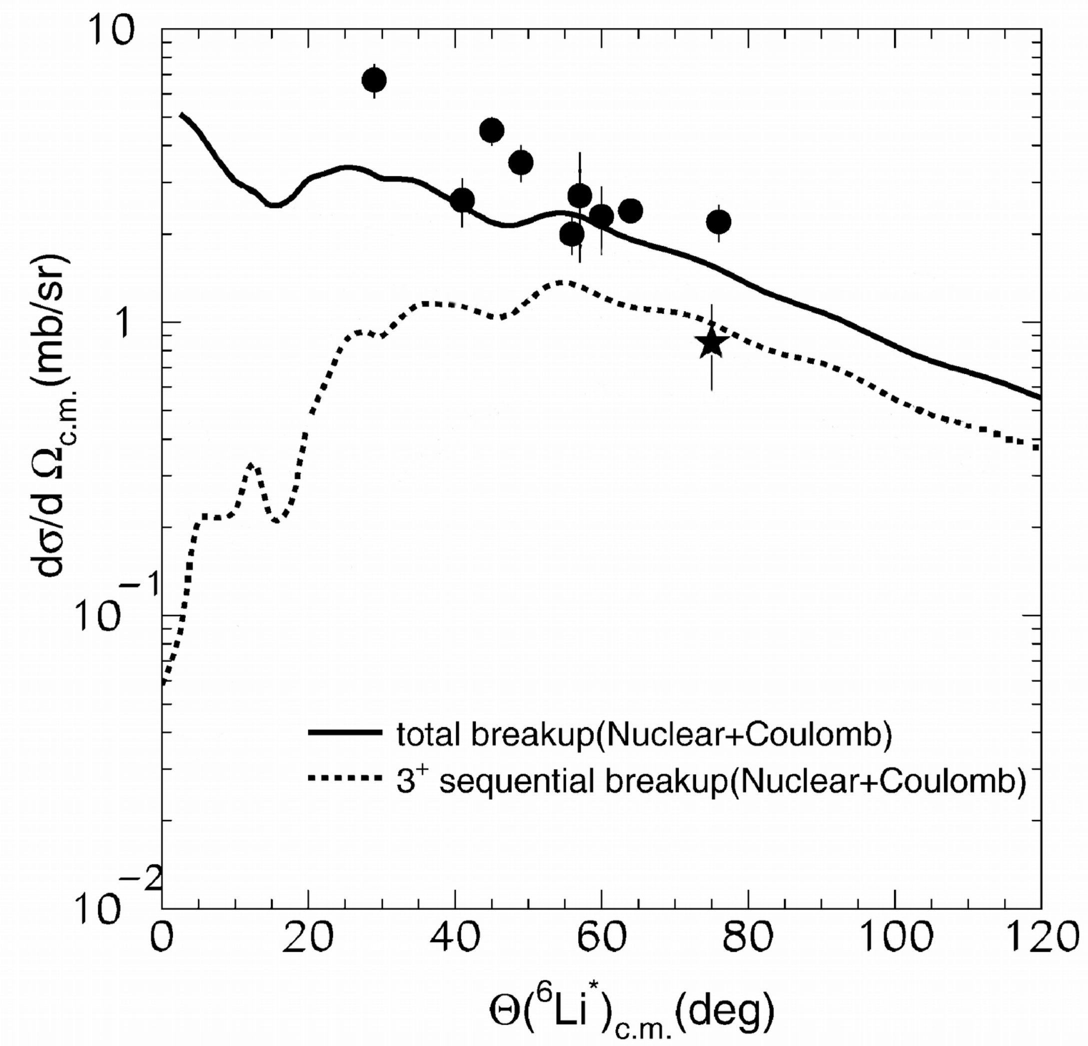
What further experimental support is there for the importance of transfer process in α particle production for ^{6}Li and ^{7}Li induced reactions?

Extensive study of ^{6}Li + ^{28}Si system:

A. Pakou *et al.*, Phys. Rev. Lett. **90**, 202701 (2003),
A. Pakou *et al.*, J. Phys. G **31**, S1723 (2005),
A. Pakou *et al.*, Phys. Lett. B **633**, 691 (2006),
A. Pakou *et al.*, Phys. Rev. C **76**, 054601 (2007).

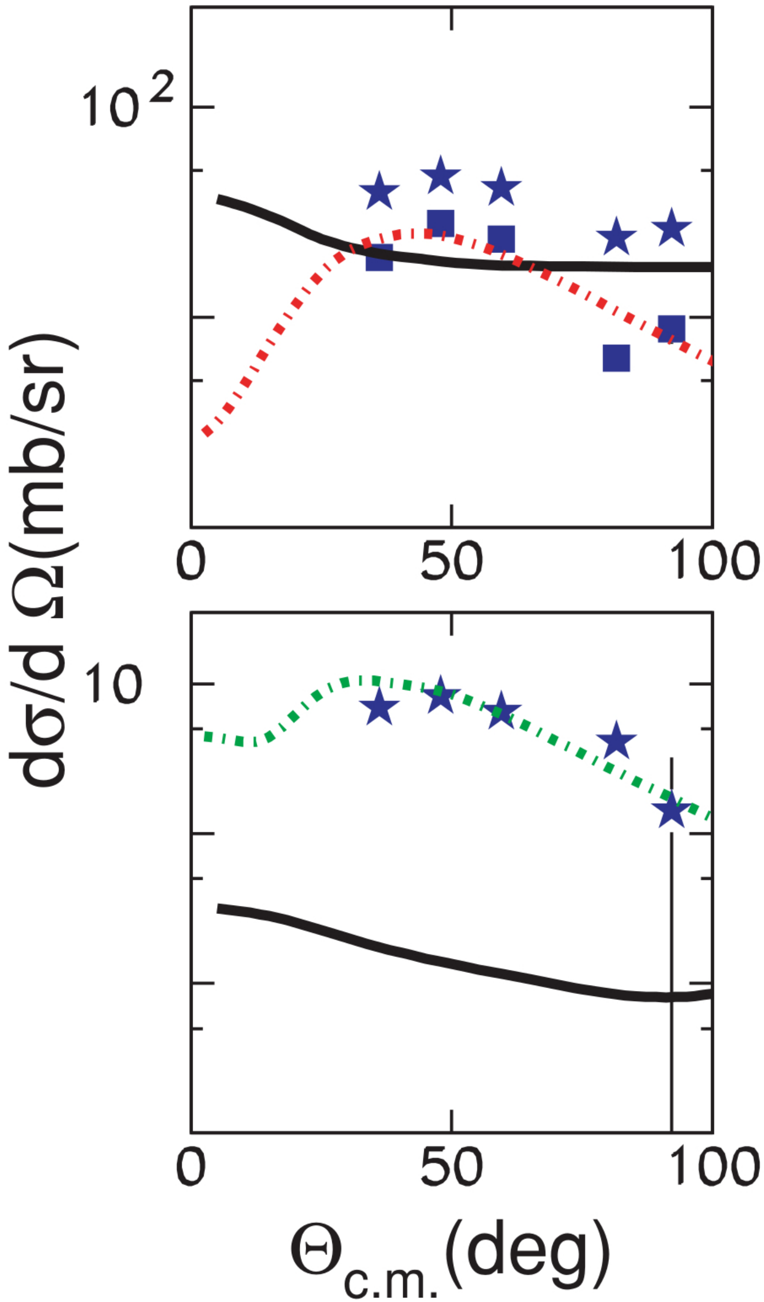
Exclusive (coincidence) data show importance of transfer processes …

13 MeV ^{6}Li + ^{28}Si



α + d coincidences (breakup) well described by CDCC

Note importance of sequential breakup via 3^+



13 MeV ^{6}Li + ^{28}Si α-γ coincidences

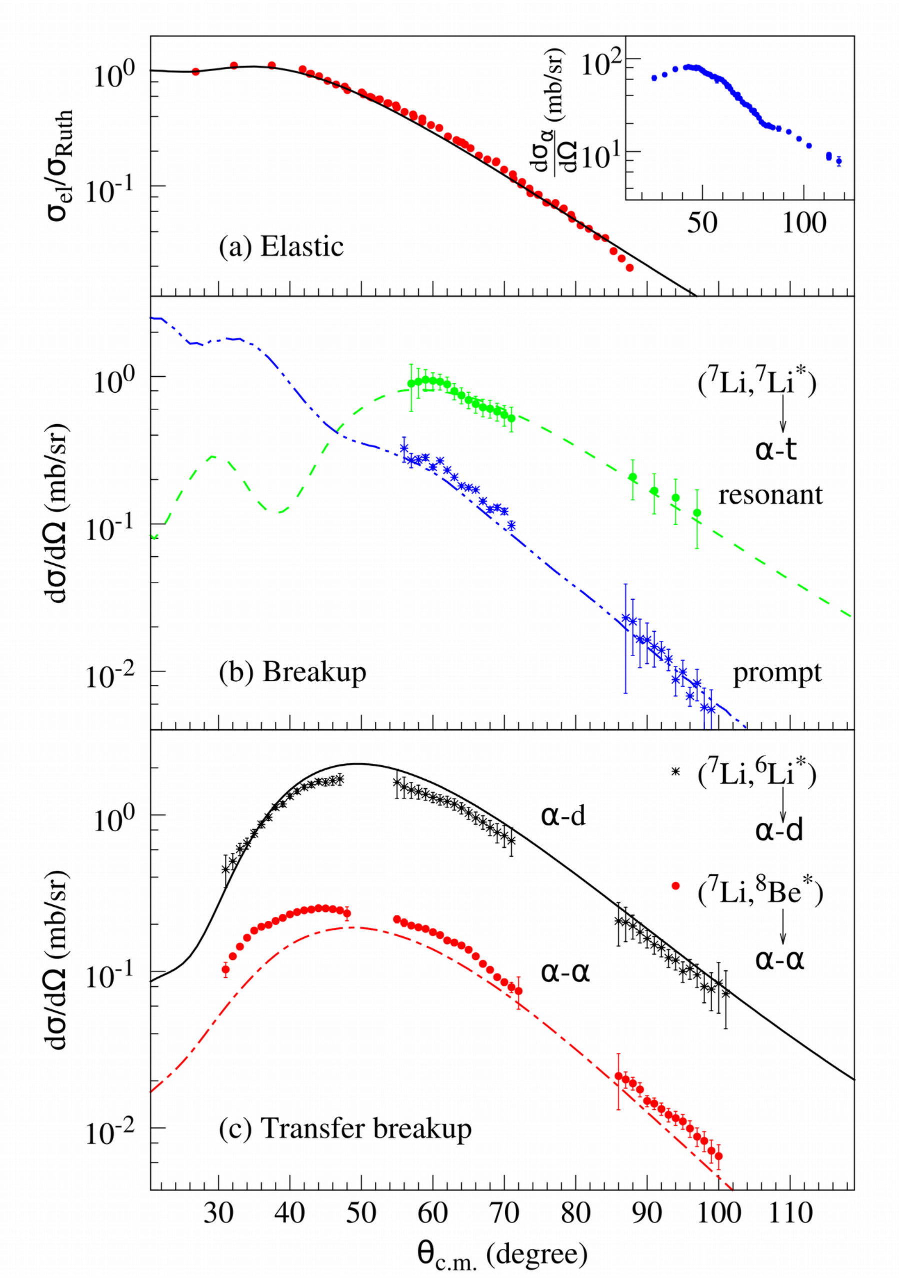
Upper: ^{29}Si + α + p

Lower: ^{29}P + α + n

For this light target there can be significant contributions from compound nucleus processes, shown on plots as solid lines.

Stars are “raw” data, squares are “direct” data (compound subtracted) Dot-dashed curves are DWBA for 1n and 1p stripping respectively (x3.5 and x2.2 to match data).

Similar study also performed for the ^{7}Li + ^{28}Si system.



A recent study of the ^{7}Li + ^{93}Nb system, S. K. Pandit *et al.*, Phys. Rev. C **93**, 061602(R) (2016) also provides quantitative confirmation of conclusions of Québert *et al.*

Plots at left are for incident ^{7}Li energy of 28 MeV.

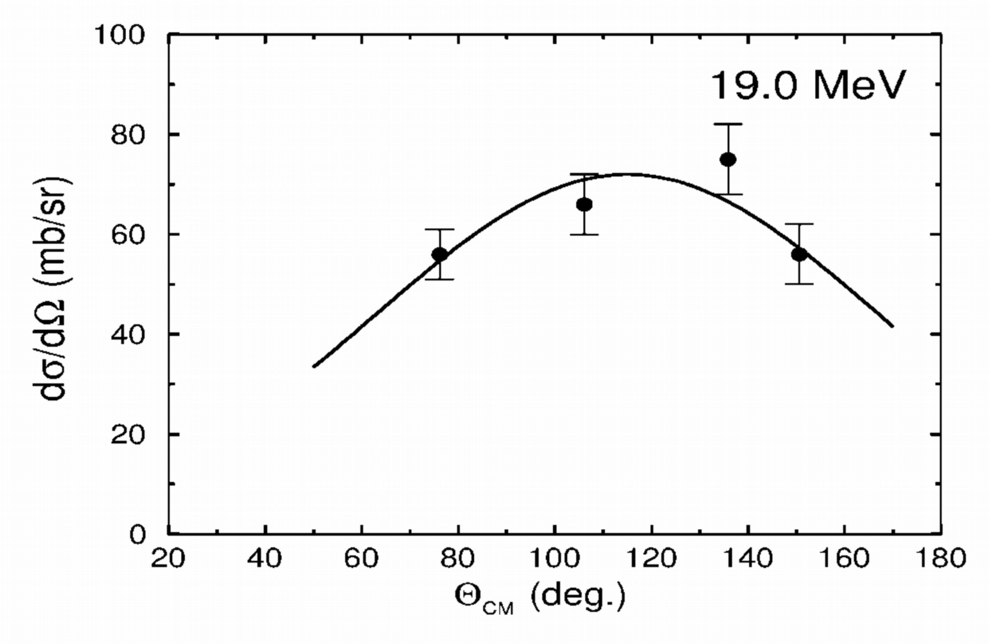
We will now look at some selected weakly-bound radioactive beams

Probably the most studied of these nuclei is ^{6}He (most intense beam)

Most complete data set for the $^{6}He + {}^{209}Bi$ system, measured at the TwinSol system of the University of Notre Dame

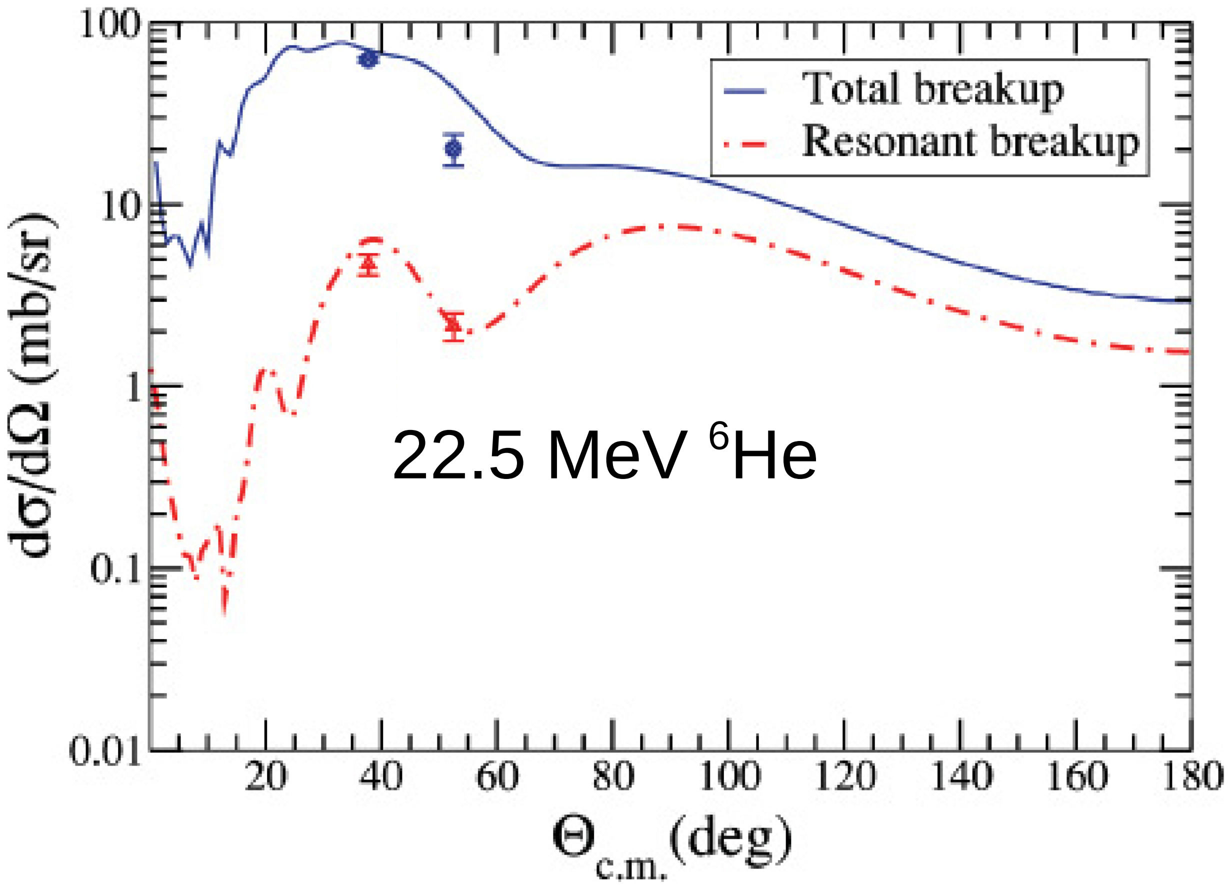
Measured inclusive α yield at several near-barrier energies and later on α-neutron coincidences.

Very large α yield, much larger than measured fusion cross section. Angular distributions suggested direct process(es):



E. F. Aguilera *et al.*, Phys. Rev. Lett. **84**, 5058 (2000).

Cross section holds up at energies well below the Coulomb barrier, implies that it is not dominated by breakup …



Adapted from J. J. Kolata *et al.*, Phys. Rev. C **75**, 031302(R) (2007)

α + n (+ n) coincidence measures. A series of experiments established that ≈ 75 % of the total α particle yield comes from (^{6}He,^{5}He) and (^{6}He,^{4}He) 1n and 2n transfer, the rest is breakup

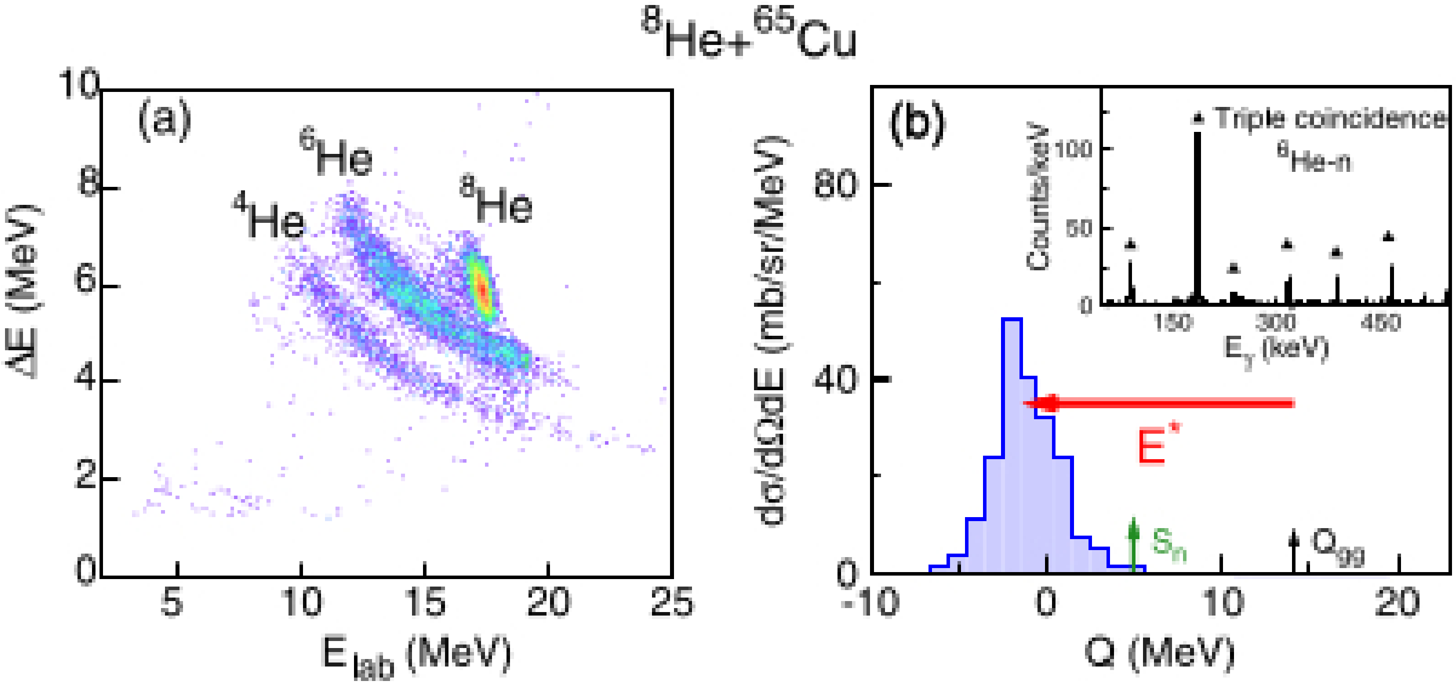
Channel	$\sigma_{c.m.}$ (mb)	σ_α (mb)	σ (Refs. [1,2]) (mb)
Fusion	310 ± 45		
1n transfer	155 ± 25		
2n transfer	410 ± 122	770 ± 140	773 ± 31
Breakup	205 ± 65		
σ_{reac}	1080 ± 148		1170 ± 150

It is something of a paradox that the total α particle production cross section is understood for the radioactive beam ^{6}He but still not completely so for the stable ^{6}Li and ^{7}Li (although we do have plenty of clues).

The situation for ^{8}He is somewhat similar, but a little more complicated. Not only are the available beam intensities two orders of magnitude lower than for ^{6}He but we have substantial ^{6}He as well as ^{4}He production.

Nevertheless, particle-γ coincidences have been measured and we can make some inferences …

Experiments were possible at GANIL-SPIRAL where ^{6}He - γ – n coincidences were measured in an experiment with a ^{65}Cu target: A. Lemasson *et al.*, Phys. Lett. B **697** (2011) 454.



^{4}He mostly from fusion-evaporation. *Q*-distribution in (b) is from ^{6}He-γ coincidences: consistent with *Q*-matching conditions for transfers. Don't see any ^{67}Cu from 2n stripping since it would populate states that decay by single neutron emission …

From measurements of the in-beam characteristic γ rays of the residues the total 1n + 2n transfer cross section can be estimated, after correction for fusion-evaporation contributions.

Resulting cross sections are: 782 ± 78 mb at 19.9 MeV and
759 ± 114 mb at 30.6 MeV

Individual cross sections for 1n and 2n could not be obtained since the beam intensity was too low to enable the required triple coincidences, plus decay of unbound excited states of ^{6}He to ^{4}He further complicates things.

However, these are large cross sections: corrections from fusion-evaporation amounted to 13% and 21% at 19.9 and 30.6 MeV respectively. Transfer even more important for ^{8}He than for ^{6}He.

How do things stand with other weakly-bound radioactive beams?

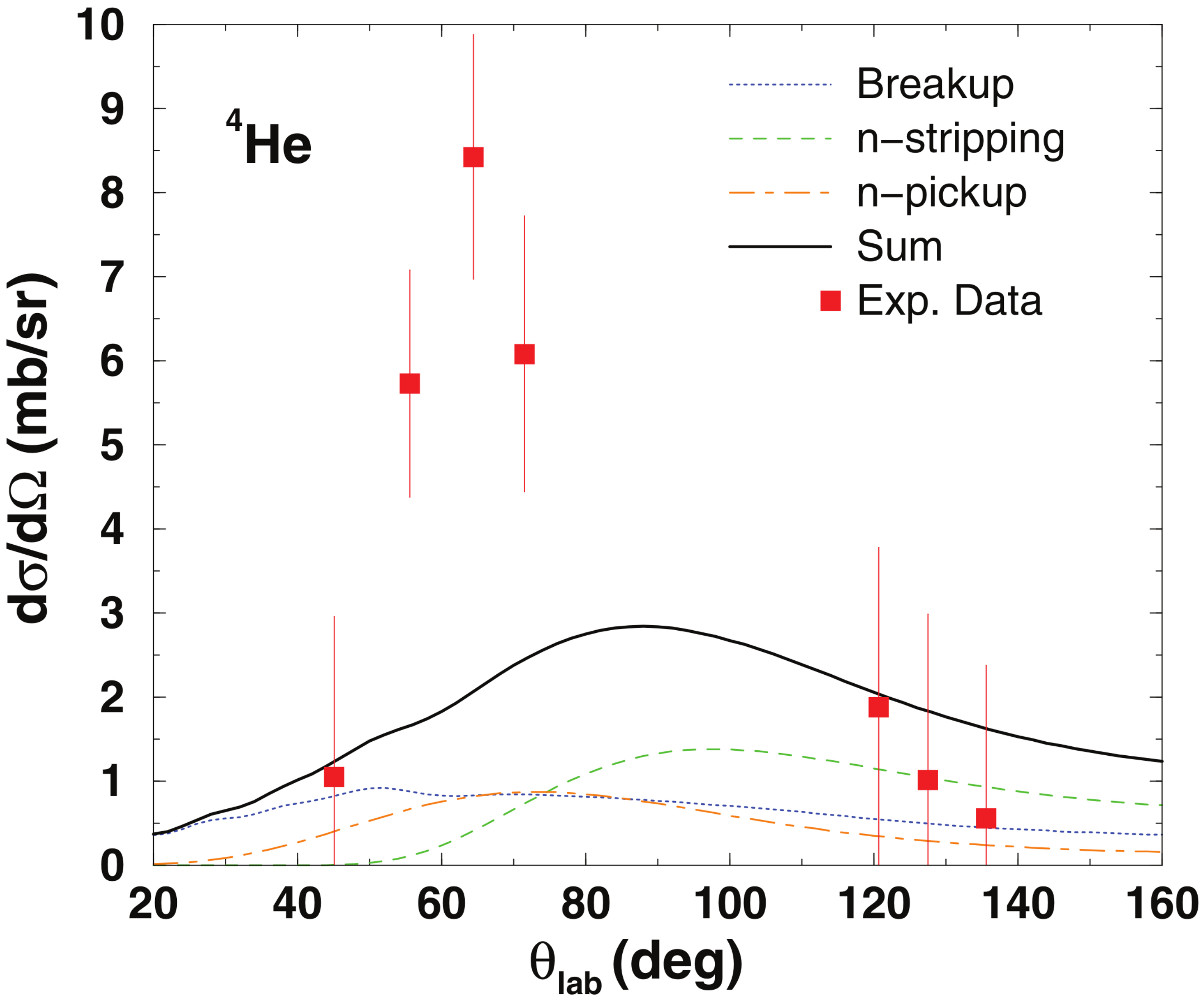
^{7}Be similar to ^{6}Li and ^{7}Li: more α than ^{3}He but we still cannot be absolutely sure of all the production mechanisms:

M. Mazzocco *et al.*, Phys. Rev. C **92**, 024615 (2015), 22 MeV ^{7}Be + ^{58}Ni: ^{4}He mainly from fusion evaporation in this system, ^{3}He production seems to be dominated by ^{4}He stripping.

^{3}He can only be formed by ^{7}Be → ^{4}He + ^{3}He breakup or ^{58}Ni(^{7}Be,^{3}He)^{62}Zn

^{4}He production more complicated: ^{7}Be → ^{4}He + ^{3}He breakup, ^{58}Ni(^{7}Be,^{8}Be)^{57}Ni 1n pickup, ^{58}Ni(^{7}Be,^{6}Be)^{59}Ni 1n stripping, ^{58}Ni(^{7}Be,^{4}He)^{61}Zn ^{3}He stripping and fusion-evaporation.

Fusion-evaporation most important, the direct processes seem to contribute about equally …



Data have (calculated) fusion-evaporation component already subtracted.

Other weakly-bound radioactive beams may be different.

Breakup may be dominant source of light charged particles in systems involving ^{11}Be and ^{11}Li beams, for example.

For ^{8}B and ^{17}F it is fairly certain that the inclusive ^{7}Be and ^{16}O cross sections are dominated by breakup.

For ^{15}C the honours may be equal for the ^{14}C production

Of course, to some extent the exact trade-off between breakup and transfer will depend on the target and the incident energy.

There are still unanswered questions in this field:

Is ^{4}He (and d, t or ^{3}He) stripping really important for light particle production in reaction induced by ^{6}Li, ^{7}Li and ^{7}Be? Or is the mechanism something else like “incomplete fusion” or “capture breakup”? All have problems, and is it even meaningful to talk about different mechanisms here?

It is something of a paradox that the weakly-bound radioactive nuclei are easier to understand in this context, since the number of different mechanisms involved is much less than for ^{6}Li and ^{7}Li

e.g. ^{14}C production in reaction induced by ^{15}C – only need consider $^{15}C \rightarrow {}^{14}C + n$ breakup and (^{15}C,^{14}C) stripping

More exclusive (coincidence) data needed to help unravel these problems

Dziękuję za uwagę!