The Curious Incident of the Dog in the Night-Time: The Enigma of ^{8}B

Nicholas Keeley

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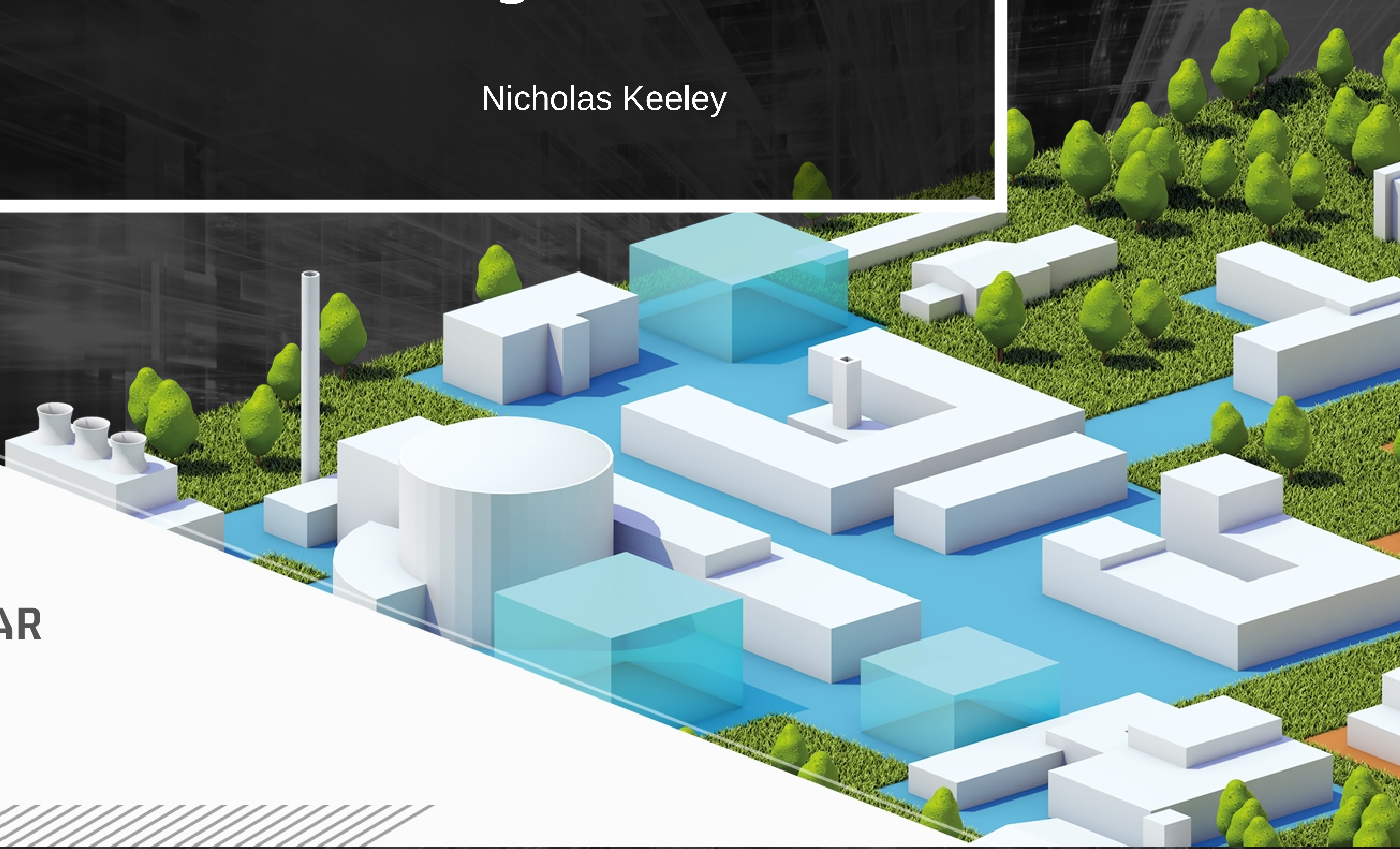
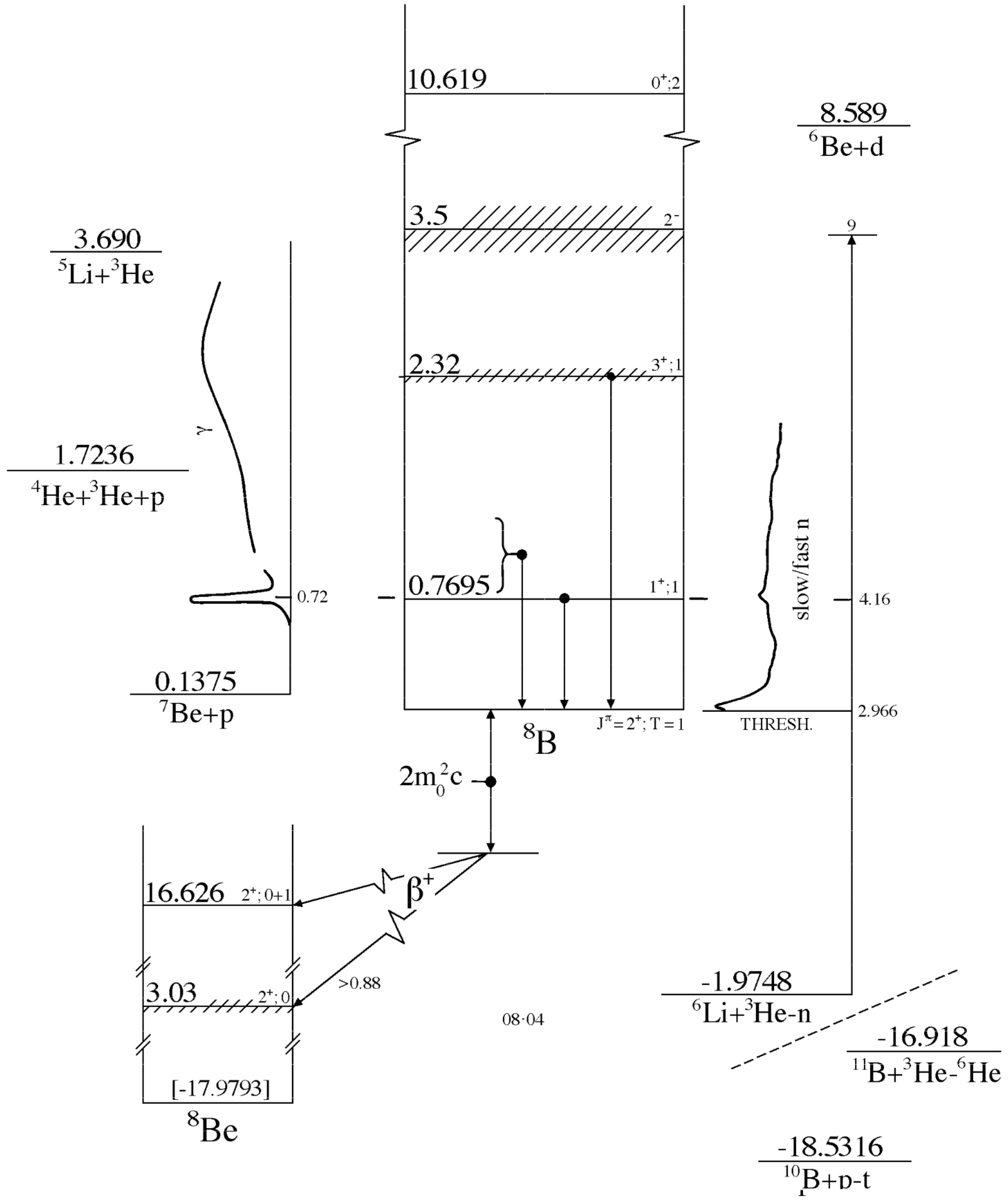


^{8}B is a weakly-bound, proton-rich radioactive nucleus, unstable to β^{+} decay ($T_{1/2}$ = 770 ± 3 msec) and a proton-halo candidate.

Its threshold against breakup into ^{7}Be + p of 137.5 keV is the lowest known, suggesting a ^{7}Be + p two-body cluster structure.

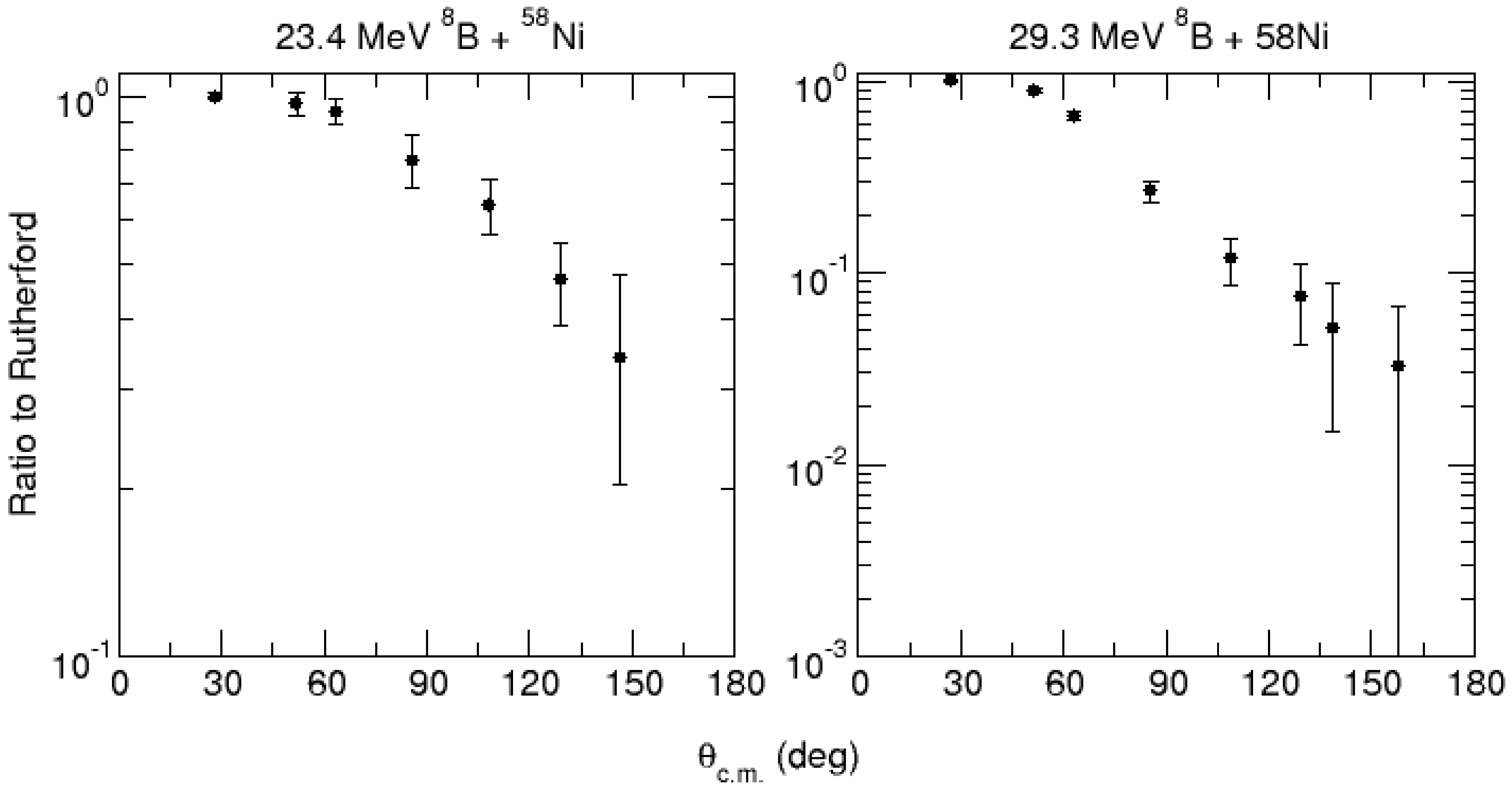
It also implies two other things: a (very) large breakup cross section and an important coupling effect on the elastic scattering.



Ideally, one would like to investigate these possibilities using beams of ^{8}B incident on heavy targets at energies close to the Coulomb barrier, since coupling effects are usually greatest under these circumstances.

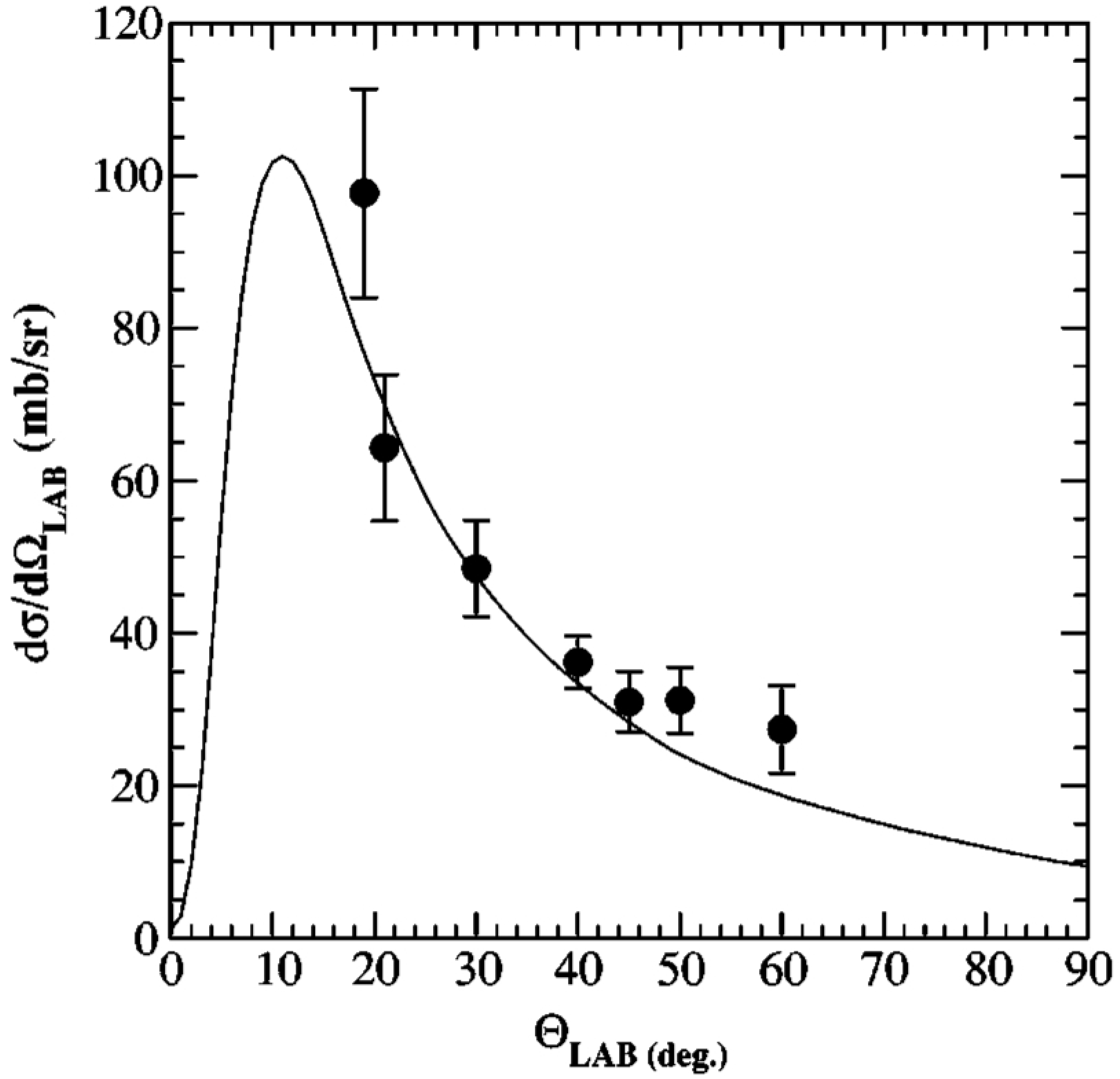
Unfortunately, a ^{8}B beam is difficult to produce at these energies. At facilities like TwinSol at the University of Notre Dame “cocktail” secondary beams of ^{8}B, ^{7}Be and ^{6}Li are produced by the interaction of a ^{6}Li primary beam with a ^{3}He gas target, yielding typical ^{8}B intensities of about 4×10^{4} pps at around 6% purity.

^{8}B beam spot size and divergence are also quite large, about 4 mm FWHM and ± 4° on target, making scattering angle definition difficult. This, combined with the poor statistics gives rather large experimental uncertainties:



Data from E. F. Aguilera *et al.*, Phys. Rev. C **79**, 021601(R) (2009)

Despite significant ^{7}Be contamination in the beam, measurements of the ^{7}Be yield from reactions are possible using Time-of-flight techniques:



Lab. Frame ^{7}Be angular distribution for 25.8 MeV ^{8}B incident on a ^{58}Ni target. The curve is a calculation of the ^{7}Be breakup angular distribution assuming a ^{7}Be + p cluster model of ^{8}B.

Taken from J. J. Kolata *et al.*, Phys. Rev. C **63**, 24616 (2001)

Thus, in spite of the challenges, the measurements we need are possible. How to interpret the data?

The obvious “first guess” is to model ^{8}B as a ^{7}Be + p two-body cluster. To first order we assume that the structure of the ^{7}Be core may be ignored and consider it to be inert (a rather extreme assumption …)

The ingredients for such a “cluster-folding” model are:
1) a p + ^{7}Be binding potential, 2) knowledge of the quantum numbers (n, ℓ, j) of the p relative to the ^{7}Be core, 3) p + target and ^{7}Be + target optical potentials at appropriate energies

We take the p + ^{7}Be binding potential from P. Navrátil, C. A. Bertulani and E. Caurier, Phys. Lett. B **634**, 191 (2006).

They also give spectroscopic factors for the $<{}^{8}\mathrm{B} \mid {}^{7}\mathrm{Be} + \mathrm{p}>$ overlaps: ^{7}Be(3/2^{-}) + 1$p_{3/2}$ proton = 0.96

^{7}Be(3/2^{-}) + 1$p_{1/2}$ proton = 0.09

^{7}Be(1/2^{-}) + 1$p_{3/2}$ proton = 0.28

We have already said that we will ignore the possible excitation of the ^{7}Be core, so on this basis we are also justified in assuming a pure 1$p_{3/2}$ configuration for the proton with respect to the core.

Finally, we need ^{7}Be + target and p + target optical potentials at the same MeV/nucleon as the ^{8}B projectile. These can be from fits to data (we get ^{7}Be scattering “for free” with the cocktail beam) or use global parameter sets (^{6}Li or ^{7}Li in lieu of ^{7}Be).

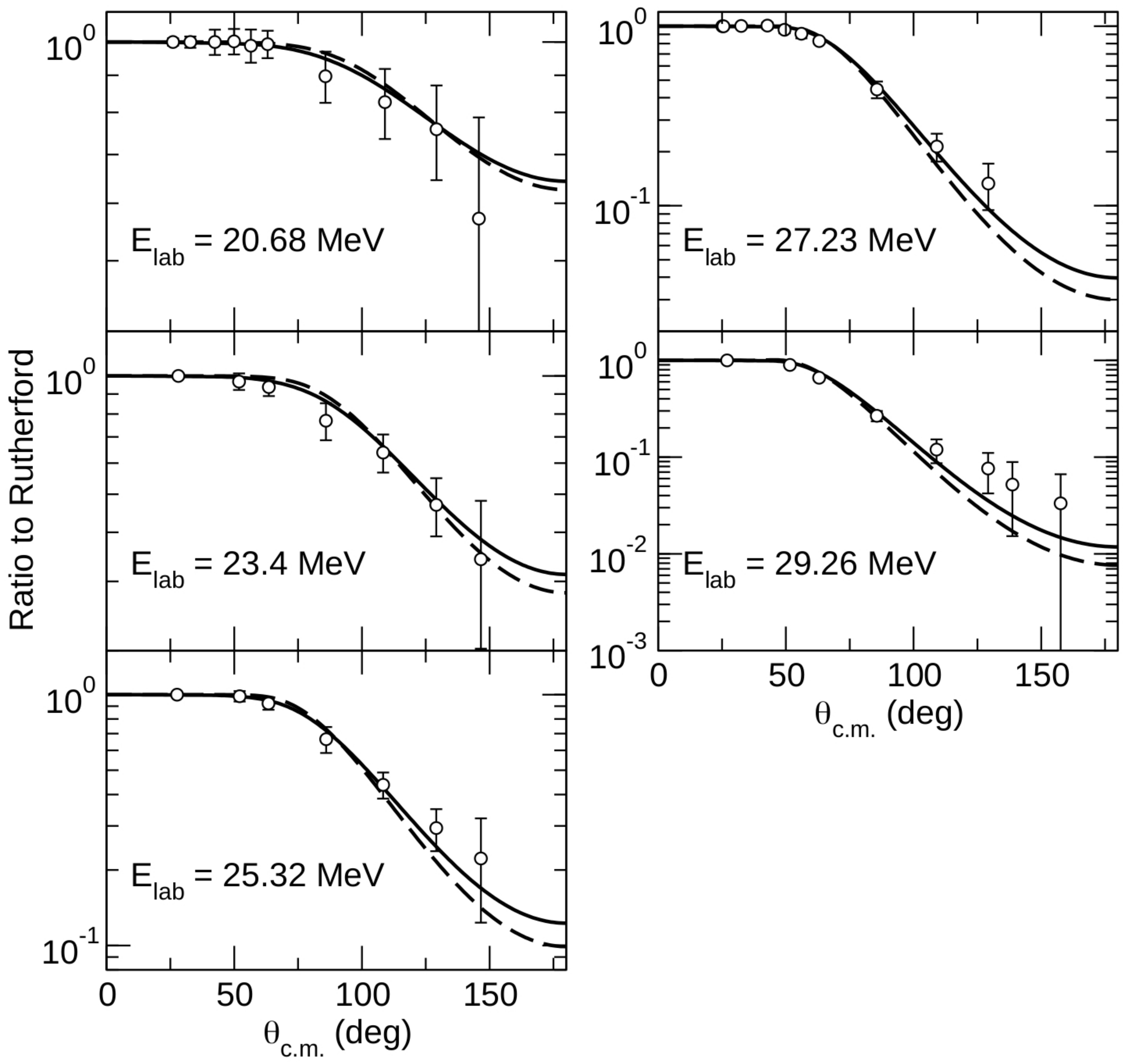
That takes care of ^{8}B in its ground state, but we also want to model the breakup and its influence on the elastic scattering. We do this using the continuum discretised coupled channels (CDCC) technique, staying within the general cluster-folding model.

CDCC is really just a fancy way of doing a coupled-channels calculation of inelastic scattering. It enables us to handle systems where the inelastic excitation is to the unbound continuum.

Very briefly, the continuum is discretised into bins in momentum (k) – essentialy excitation energy – and relative angular momentum (L) space and averaged wave functions calculated over the finite widths of these bins.

This leads to a lot of bins! We therefore also drop the non-zero spin of the ^{7}Be core from our calculations.

This has been done for the $^{8}B + ^{58}Ni$ data and we have already seen that it describes the ^{7}Be angular distribution well. How do the calculations compare to the elastic scattering?



The solid and dashed curves represent calculations with and without the inclusion of couplings to the $^{7}Be + p$ breakup. The effect is small in spite of large breakup cross sections (108 to 160 mb, c.f. σ_R = 262 to 1050 mb). However, the model seems to work well.

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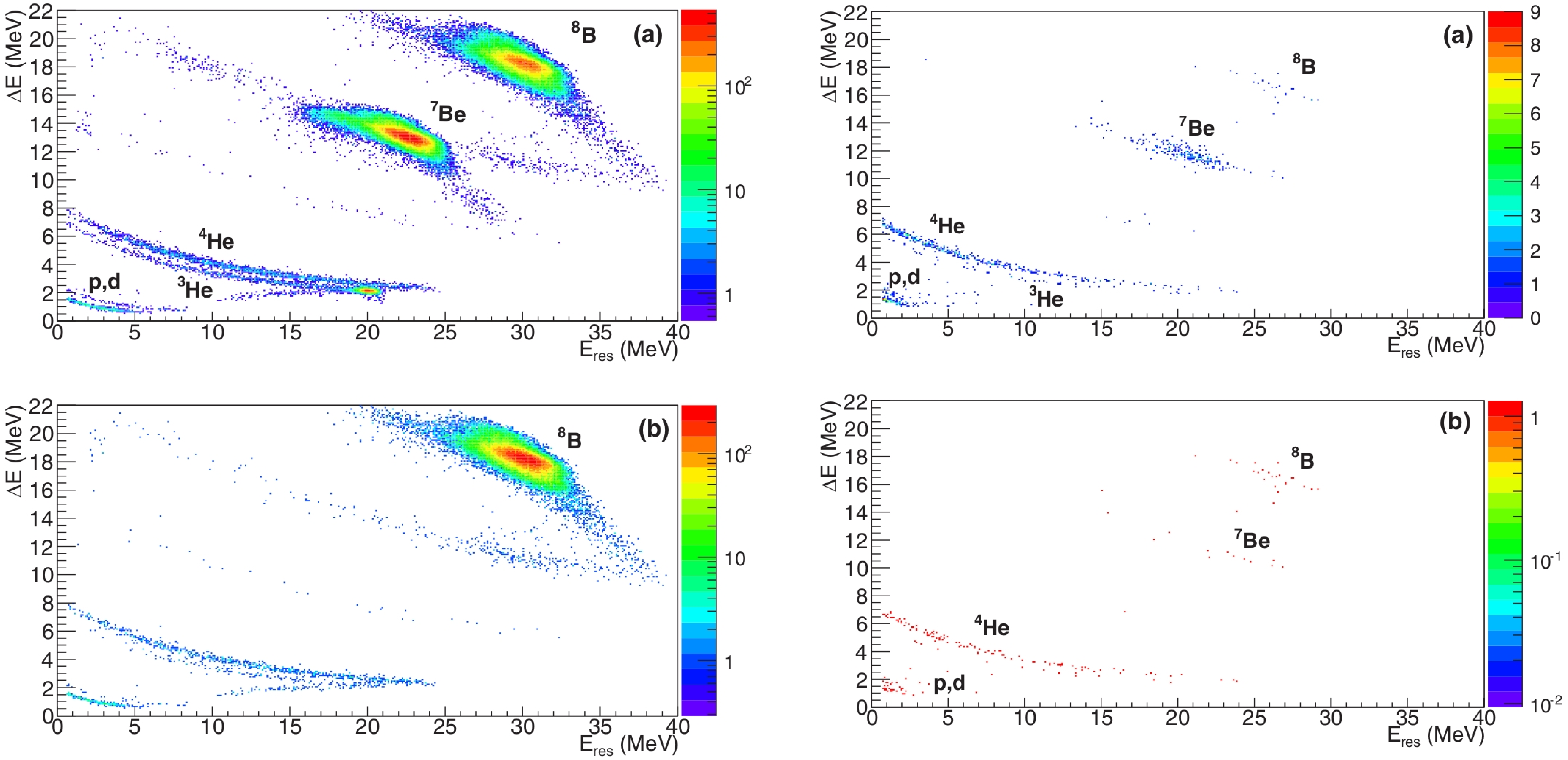
This is something of a paradox: why should a reaction process with such a large cross section apparently have such a small coupling influence on the elastic scattering?

To put it another way, why does the very weak binding of ^{8}B appear to manifest itself with regard to the elastic scattering as a “static” effect (increased size)?

We might expect any influence on the elastic scattering to be more pronounced for heavier targets. Calculations do not seem to bear this out, but new data are required to confirm this.

Recently, the elastic scattering of ^{8}B from a ^{208}Pb target was measured at an incident energy of 50 MeV at the CRIB facility, RIKEN, Japan. The same reaction as at TwinSol is used to produce the ^{8}B beam, resulting in significant ^{7}Be, ^{6}Li and ^{3}He contaminants.

About 10^{4} pps of ^{8}B (purity ≈ 20%) on target were obtained. The rejection capabilities of the CRIB facility ensured that very little of the ^{6}Li primary beam reached the final focal plane and most of the other contaminants could be eliminated by TOF software gates using the RF of the cyclotron accelerator:



Taken from M. Mazzocco *et al.*, Phys. Rev. C **100**, 024602 (2019)

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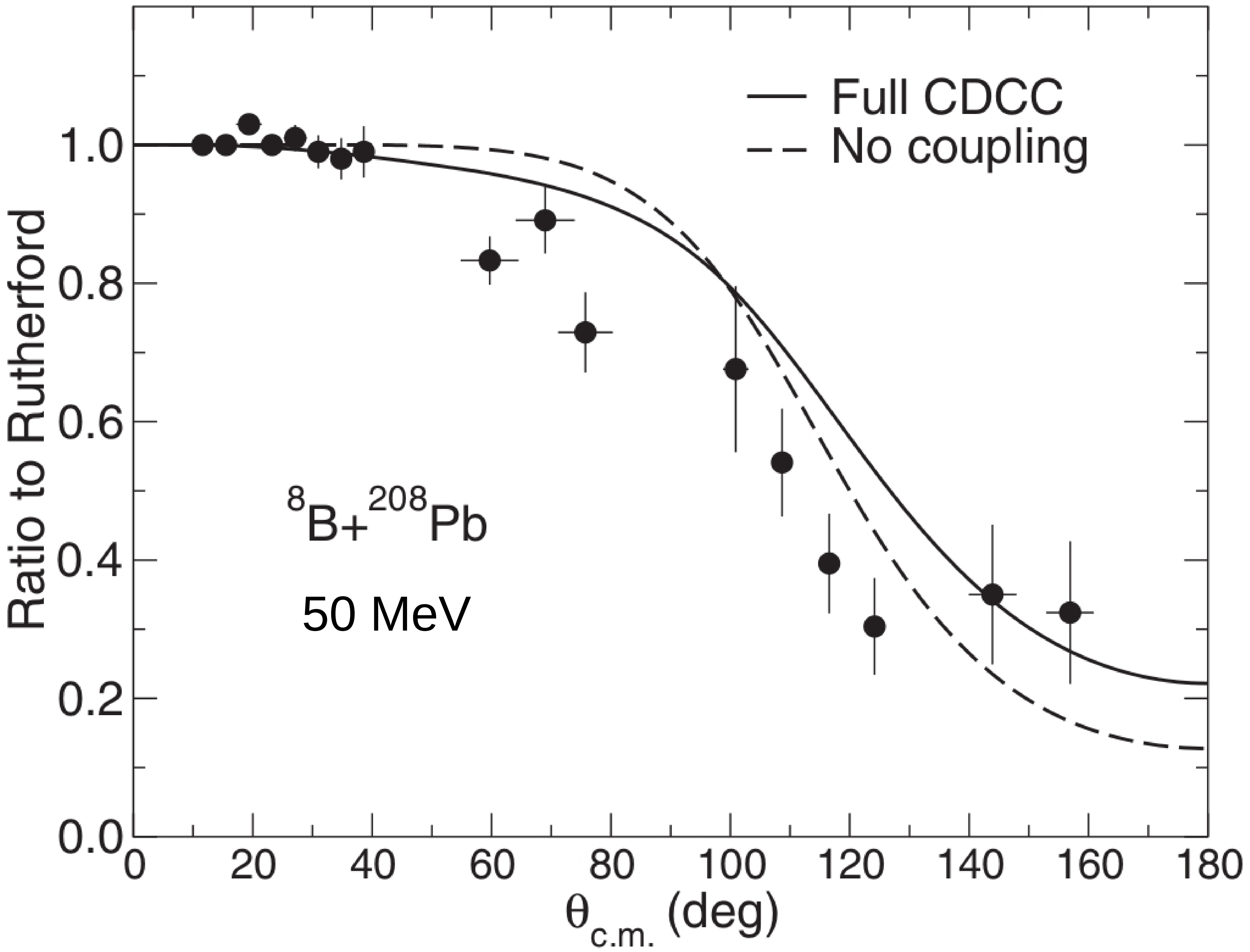
Data were obtained for the elastic scattering over a wide angular range, although the statistics were rather poor at the backward angles:



Taken from M. Mazzocco *et al.*, Phys. Rev. C **100**, 024602 (2019)

The curves denote calculations with (solid) and without (dashed) coupling to the ^{7}Be + p breakup.

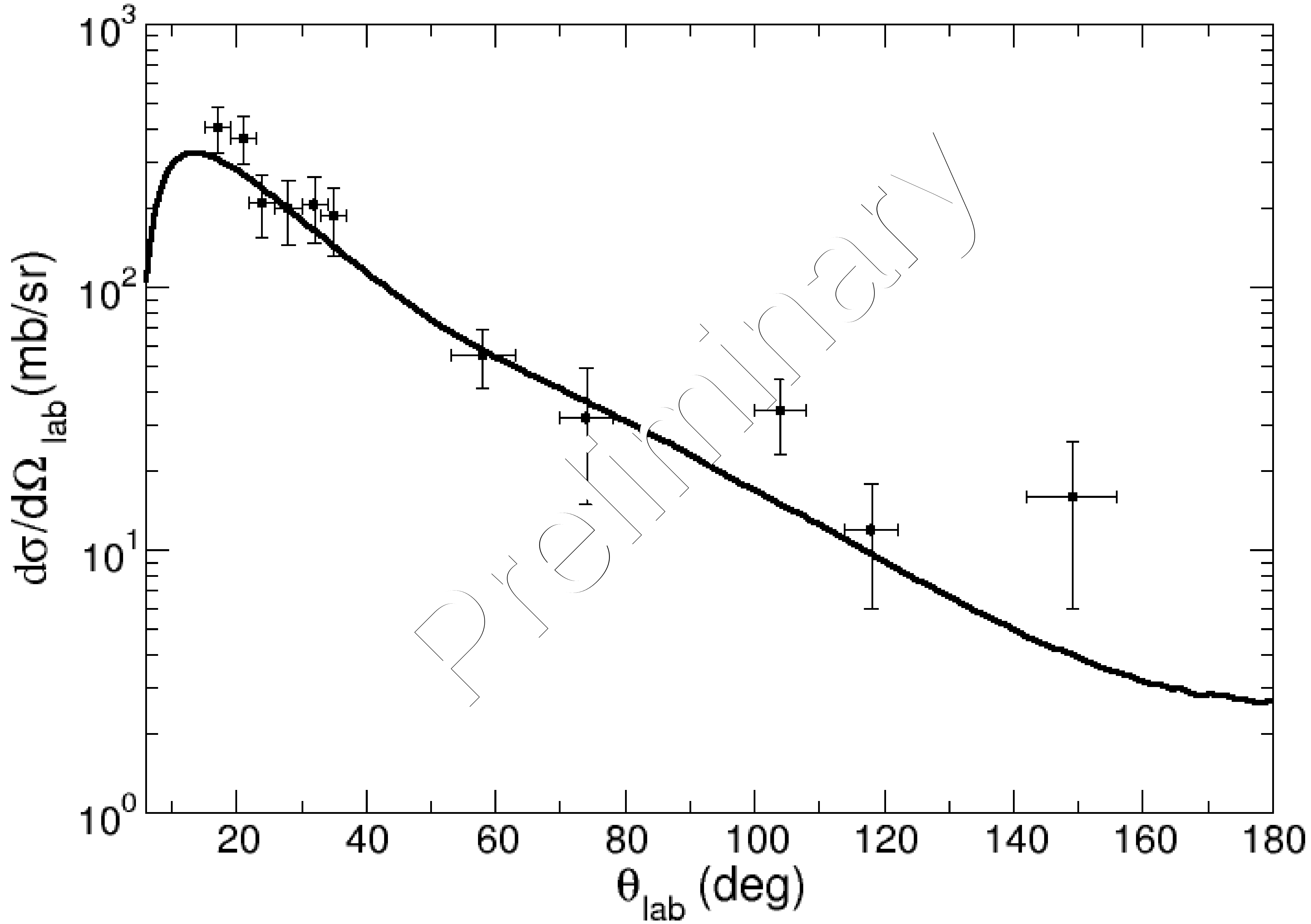
Similar small coupling effect as for ^{58}Ni target, but description is now not so good … The larger Coulomb field could exaggerate any deficiencies in the model?

Setting aside the discrepancy between data and calculations for the moment, what do the CDCC calculations predict for the breakup cross section?

The calculations yield σ_R = 1020 mb (c.f. 1112 mb from an OM fit) and σ_{BU} = 619 mb, around 60% of the calculated total! Of this, almost half comes from dipole (λ = 1) breakup.

This is striking: such a large part of the total reaction cross section yet the coupling effect is small; the increased Coulomb field compared to ^{58}Ni seems to have increased the breakup but not the coupling effect.

This is all very well, but is this large breakup cross section realistic? Using the RF signal of the cyclotron to impose TOF gates it was possible to extract a reliable angular distribution for ^{7}Be produced in reactions induced by the ^{8}B beam.



Curve is summed breakup from CDCC calculation, transformed to give lab. ^{7}Be angular distribution. Agreement very good, although indications that data are under-predicted at forward angles.

Data courtesy M. Mazzocco, INFN and University of Padua

Possible reasons for the discrepancy between data and model:

1) ^{7}Be + ^{208}Pb and/or p + ^{208}Pb OMPs are not realistic. ^{7}Be OMP obtained from fit to data, equivalent proton elastic scattering essentially Rutherford at all angles.

2) Breakup model space not converged. Tests show that it is.

3) Omission of resonances in ^{8}B. Tests show effect is negligible.

4) Missing couplings, i.e. transfer reactions. Tests suggest effects are negligible (in particular ^{208}Pb(^{8}B,^{7}Be)^{209}Bi, cross section negligible too).

5) Model of ^{8}B is too simplistic.

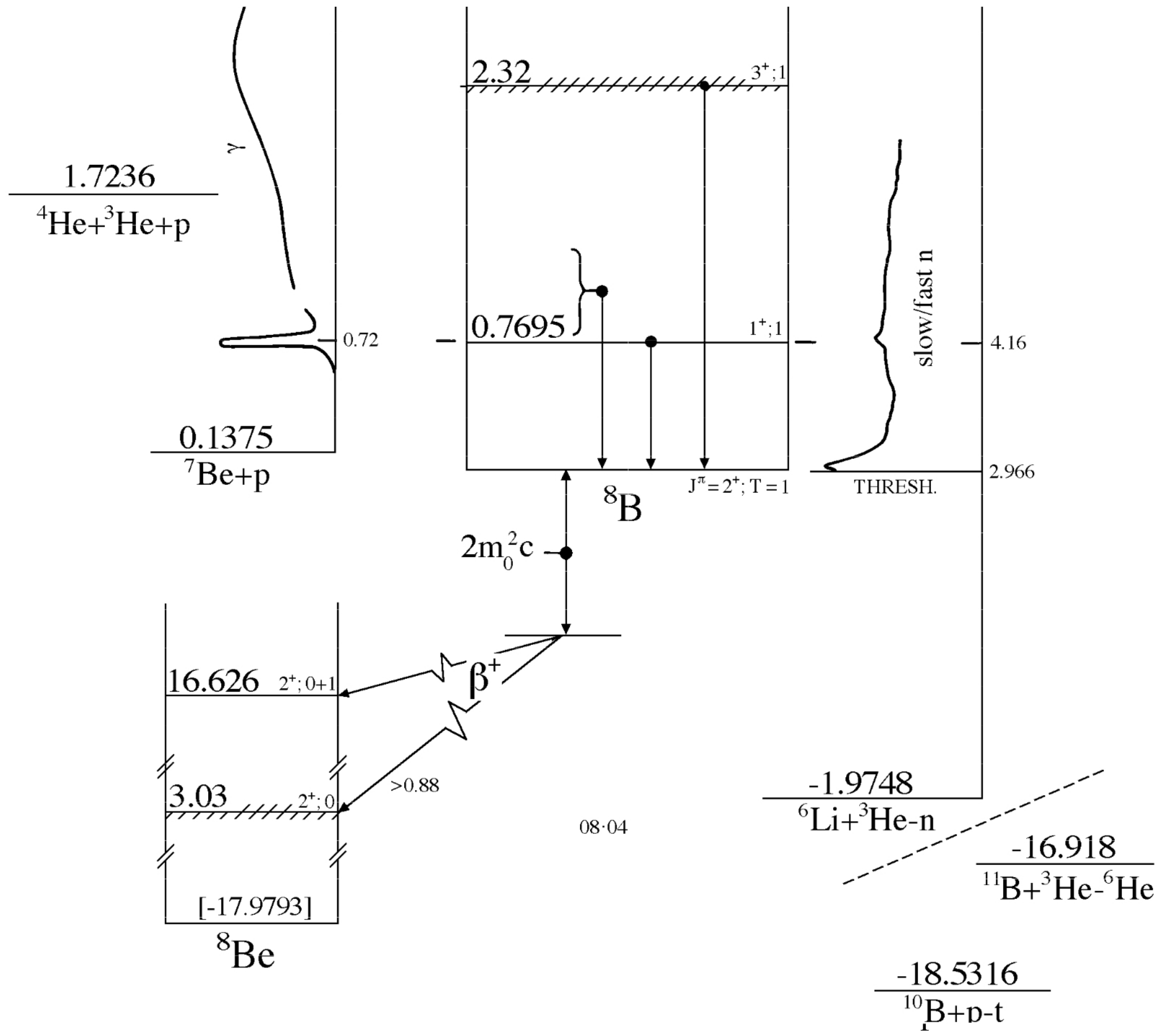
Taken together, the evidence points to the model of ^{8}B being too simplistic as the underlying cause. This is also the prime candidate in my mind for the apparent lack of breakup coupling effect on the elastic scattering.

We know that the ^{7}Be core is not inert: strong ground state reorientation coupling and coupling to 0.429 MeV $1/2^-$ state. Perhaps we need to take this into account? (recall SF of Navrátil for core in $1/2^-$ state).

Also, ^{7}Be is itself weakly-bound, unique (so far as I am aware) among “core” nuclei for halo systems. This may impact our model in two ways …

Firstly, empirical ^{7}Be OMPs contain effects due to the influence of the breakup of ^{7}Be into ^{4}He + ^{3}He. Usually seen as somewhat larger diffuseness (around 0.8 fm c.f. 0.65 fm). One can argue that these effects should not be present for the ^{7}Be “core” of ^{8}B.

Secondly, and more fundamentally, should we really consider ^{8}B as a three-body cluster, i.e. as ^{4}He + ^{3}He + p?



The first consideration is reasonably easy to check. One may assume a cluster-folding ^{4}He + ^{3}He model of ^{7}Be and use this to calculate a ^{7}Be OMP without breakup effects. If this is used in the ^{8}B CDCC calculation tests suggest it will give a larger breakup coupling effect but the description of the elastic scattering data is not significantly improved.

The other possibilities require the use of extended CDCC models to include core excitation or three-body projectile structure. This could be done but would be very time consuming.

Thus we are – or at least I am! - still in the situation of Inspector Gregory in “The Adventure of Silver Blaze.” The case is baffling to him, and he has the following exchange with Sherlock Holmes:

“Is there any point to which you would wish to draw my attention?”

“To the curious incident of the dog in the night-time.”

“The dog did nothing in the night-time.”

“That was the curious incident,” remarked Sherlock Holmes.

For me ^{8}B remains something of “a riddle, wrapped in a mystery, inside an enigma.”

Thank you for your attention

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