Probing nucleon-nucleon correlations via (p,pd) QFS Reactions

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Experimental and Theoretical Aspects of
Neutron-Proton Pairing and
Quartet Correlations in Atomic Nuclei

September 4-8th, 2023

ELSEVIER

Nuclear Physics A649 (1999) 45c

NUCLEAR PHYSICS A

Why are nuclei described by independent particle motion ?

B.R. Mottelson[a*]

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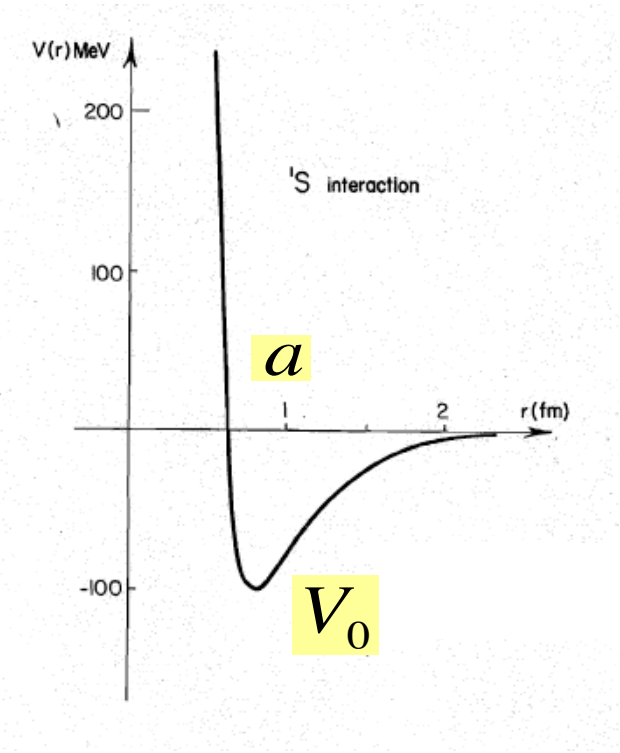
"Quantality Parameter"

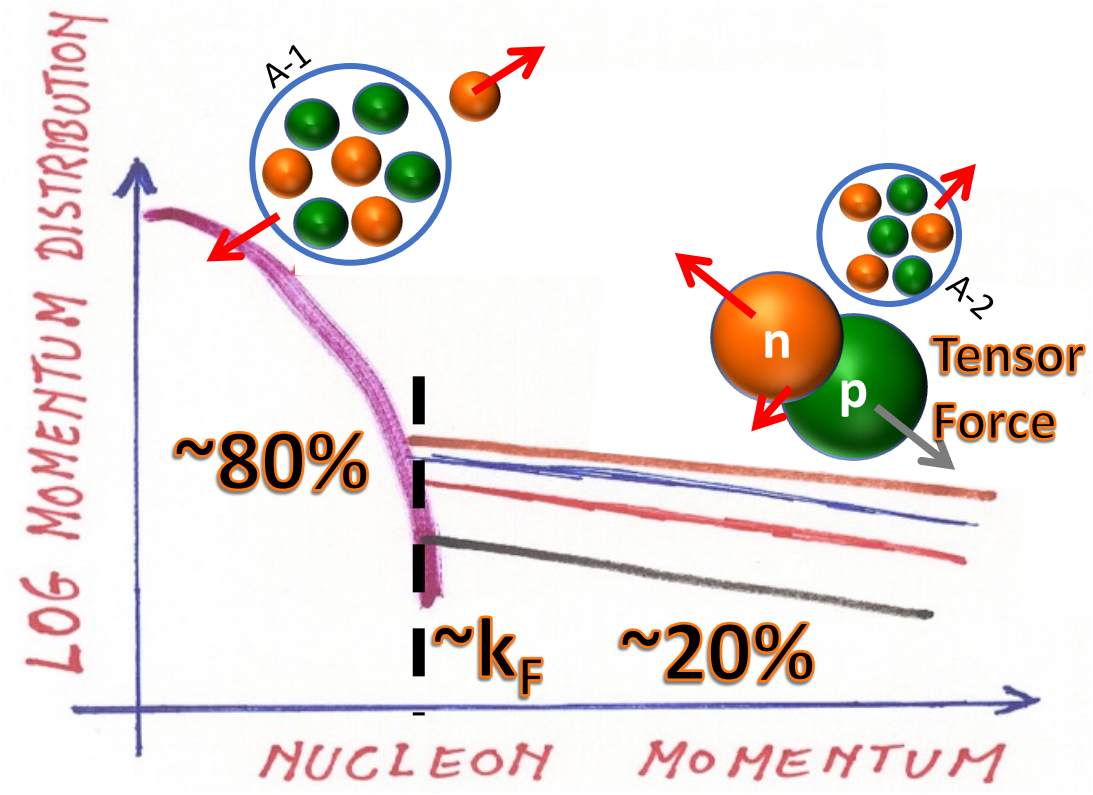
$$\Lambda = \frac{\hbar^2 / Ma^2}{V_0}$$

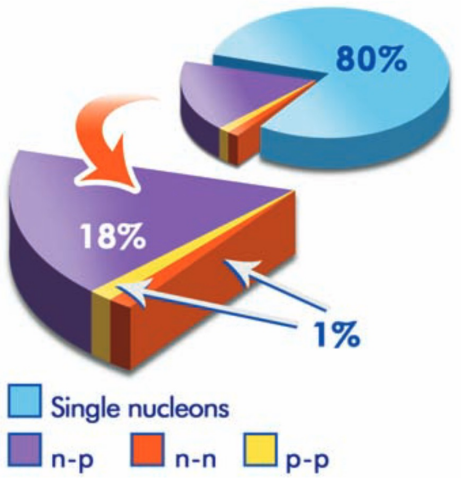
Constituents	M	V_0 [eV]	a [cm]	Λ	T=0 matter
^{3}He	3	$9{\cdot}10^{-4}$	$2.9{\cdot}10^{-8}$	0.21	liquid
^{4}He	4	$9{\cdot}10^{-4}$	$2.9{\cdot}10^{-8}$	0.16	liquid
H_2	2	$3{\cdot}10^{-3}$	$3.3{\cdot}10^{-8}$	0.07	solid
Ne	20	$3{\cdot}10^{-3}$	$3.1{\cdot}10^{-8}$	0.007	solid
nuclei	1	$1{\cdot}10^{8}$	$9{\cdot}10^{-14}$	0.4	liquid



Fermi Liquid → quasiparticles

Results from JLab on Short-Range Correlations (SRC)

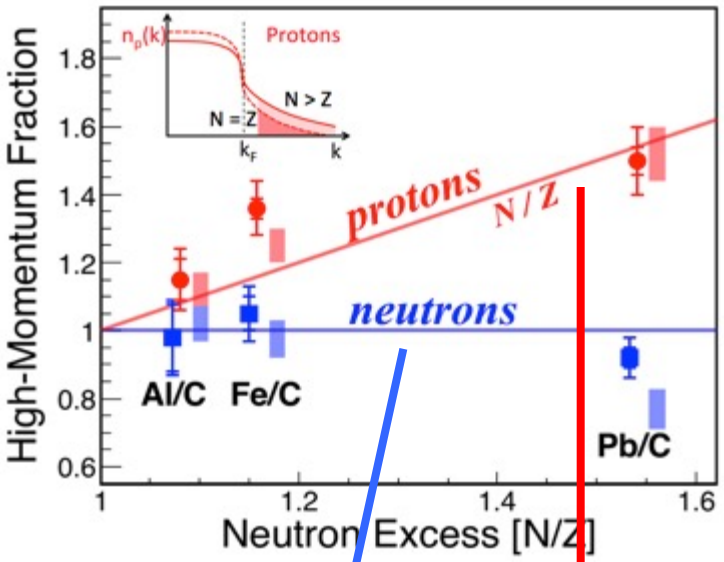


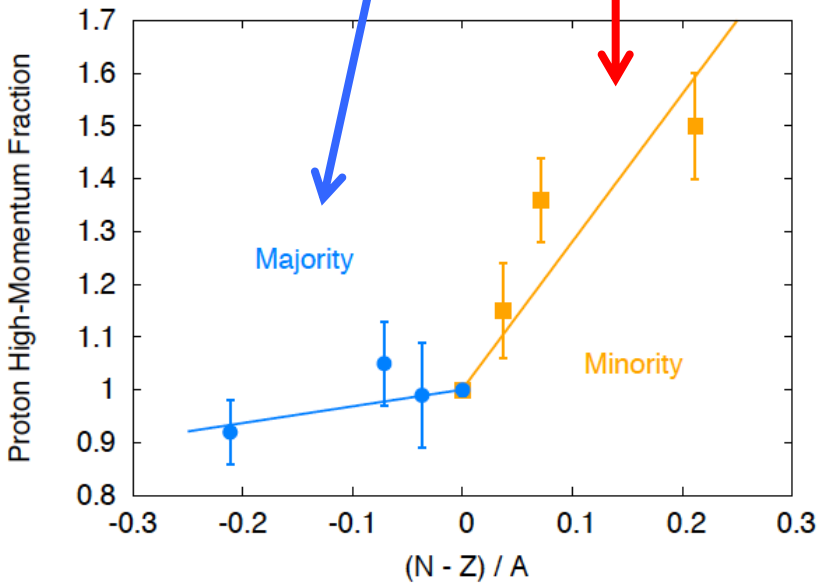


Manifestation of tensor part of the NN interaction which favours the S=1, T=0 (quasi-deuteron) channel

Duer, Nature (2018); Cohen, PRL (2018); Hen, RMP (2017); Hen, Science (2014); Hen, PLB (2013) Korover, PRL (2014); Fomin, PRL (2012); Subedi, Science (2008); Piasetzky, PRL (2007); Egiyan, PRL (2006)

SRC





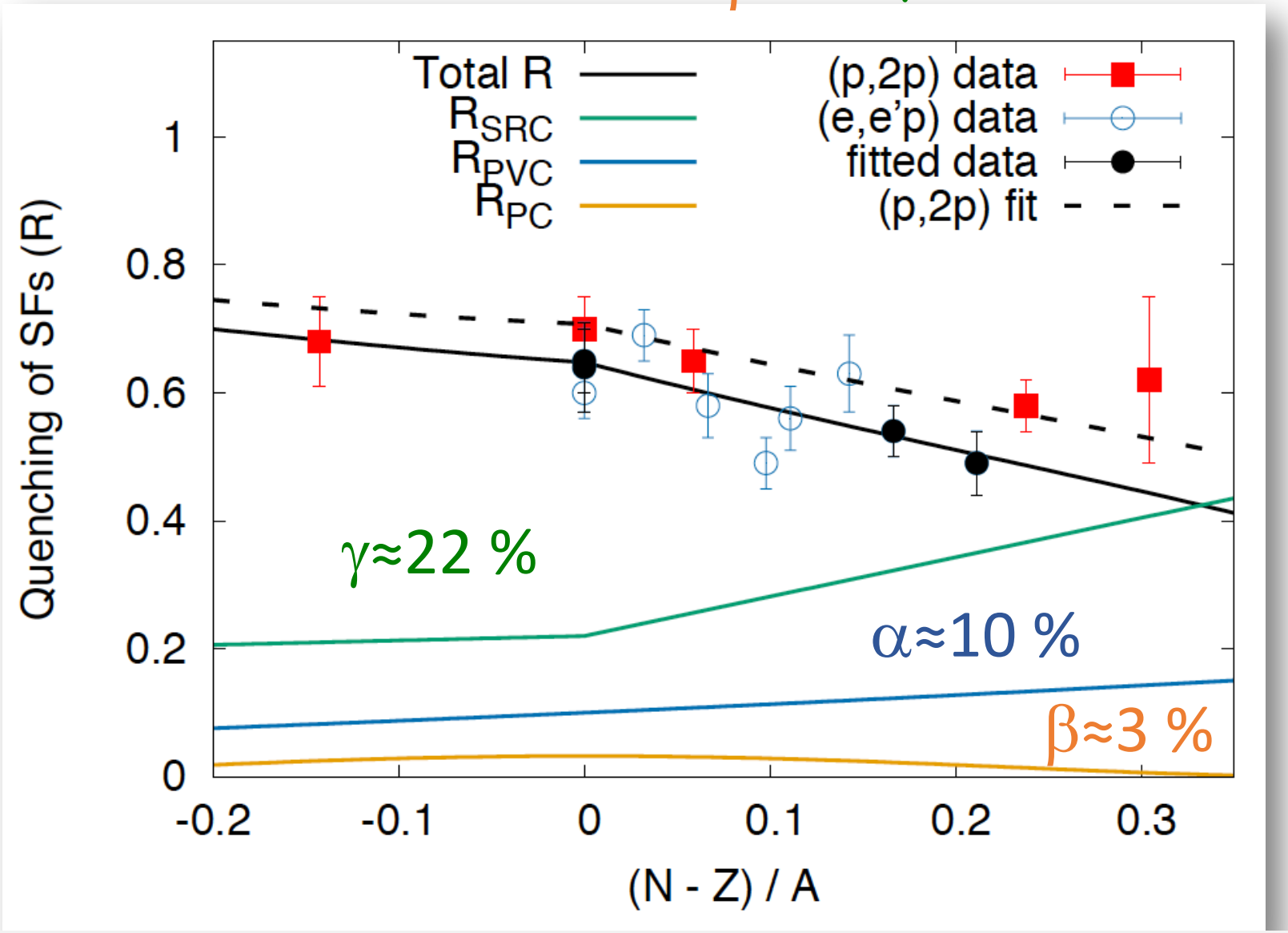
$$N > Z : R_{SRC} = \gamma\left(1 + SL^{p}_{SRC}\frac{N-Z}{A}\right),$$

$$N < Z : R_{SRC} = \gamma\left(1 + SL^{n}_{SRC}\frac{N-Z}{A}\right).$$

$$SL^{p}_{SRC} = 2.8 \pm 0.7$$

$$SL^{n}_{SRC} = 0.3 \pm 0.2$$

$$R = 1 - (R_{PVC} + R_{PC} + R_{SRC})$$
$$\alpha \qquad \beta \qquad \gamma$$



Kramer, et al., NPA **679** (2001) 267; Lee, et al., PRC **73** (2006) 044608; Atar et al., PRL 120 (2018) 052501

How do the IPM particles get dressed by the SRC?

We follow the seminal discussions of Brueckner,

"The evidence is that for relative distances less than roughly 10^{-13}cm, nucleon pairs in nuclei are correlated in the same way as they are in the deuteron or in free scattering processes"

[from K.A. Brueckner, Proceedings of the Rutherford Jubilee Int. Conf. Manchester 1961, Ed. J.B.Birks, London, **1961**]

Strong Interest in Theory

PHYSICAL REVIEW C **104**, 034311 (2021)

Short-range correlation physics at low renormalization group resolution

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PHYSICAL REVIEW C **106**, 024324 (2022)

Quasi-deuteron model at low renormalization group resolution

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"The nuclear wave function must include two-body short-range correlations (SRCs) with deuteron-like quantum numbers."

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https://doi.org/10.1140/epja/s10050-022-00765-z

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Theoretical Physics

Embedding short-range correlations in relativistic density functionals through quasi-deuterons

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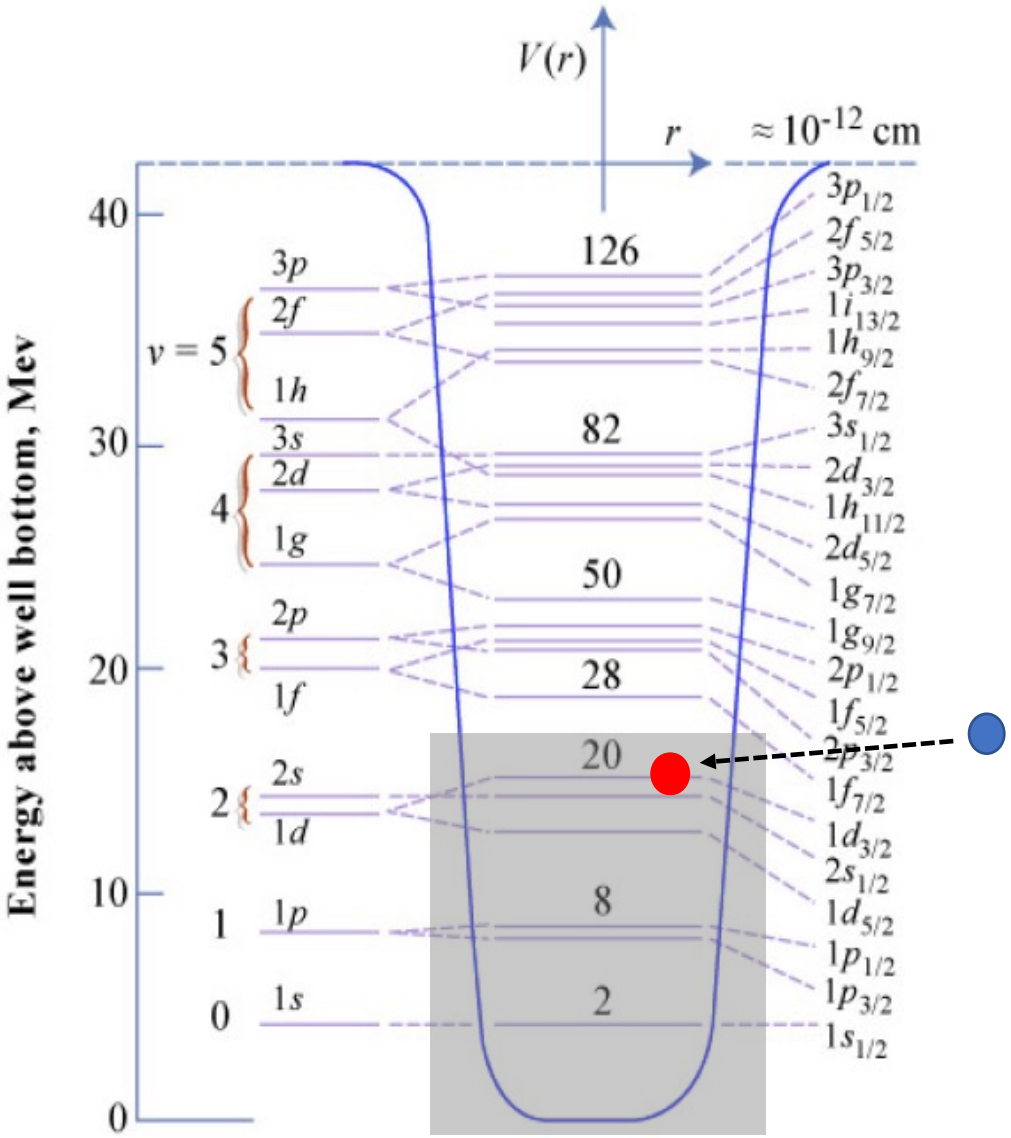
[2] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Theorie, Planckstraße 1, 64291 Darmstadt, Germany

Received: 1 April 2022 / Accepted: 12 June 2022 / Published online: 6 July 2022

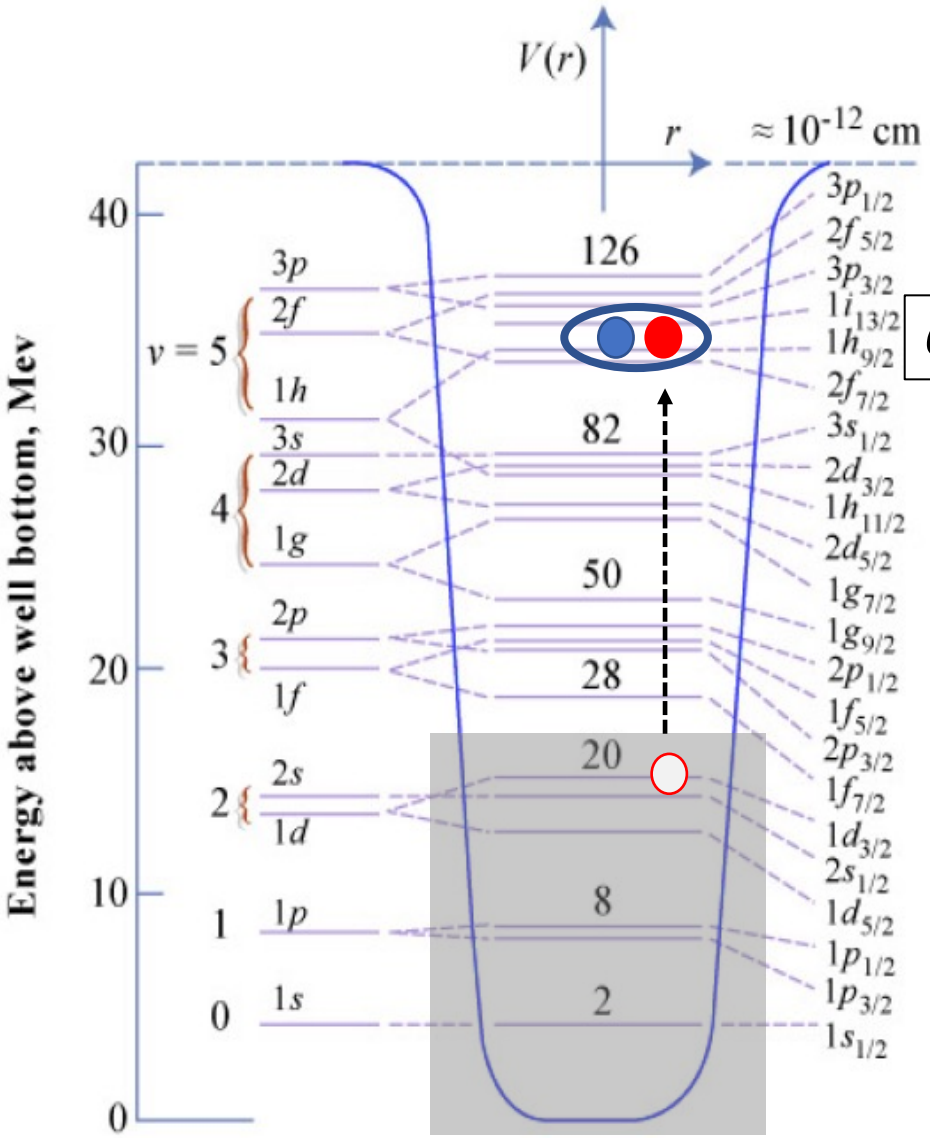
Communicated by Vittorio Somà

"The formation of clusters at sub-saturation densities, as a result of many-body correlations, constitutes an essential feature for a reliable modelization of the nuclear matter equation of state (EoS)."

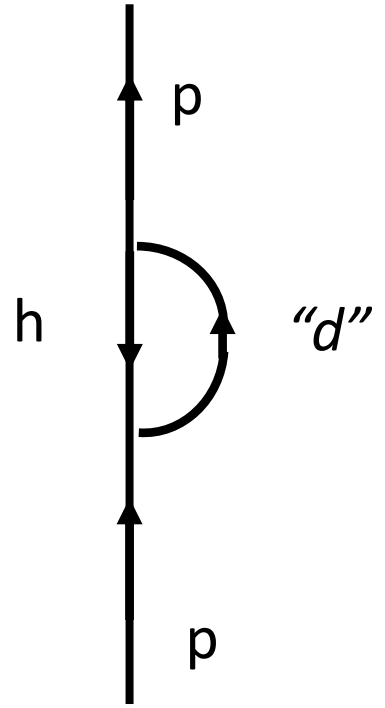
How do the IPM particles get dressed by the SRC?



How do the IPM particles get dressed by the SRC?

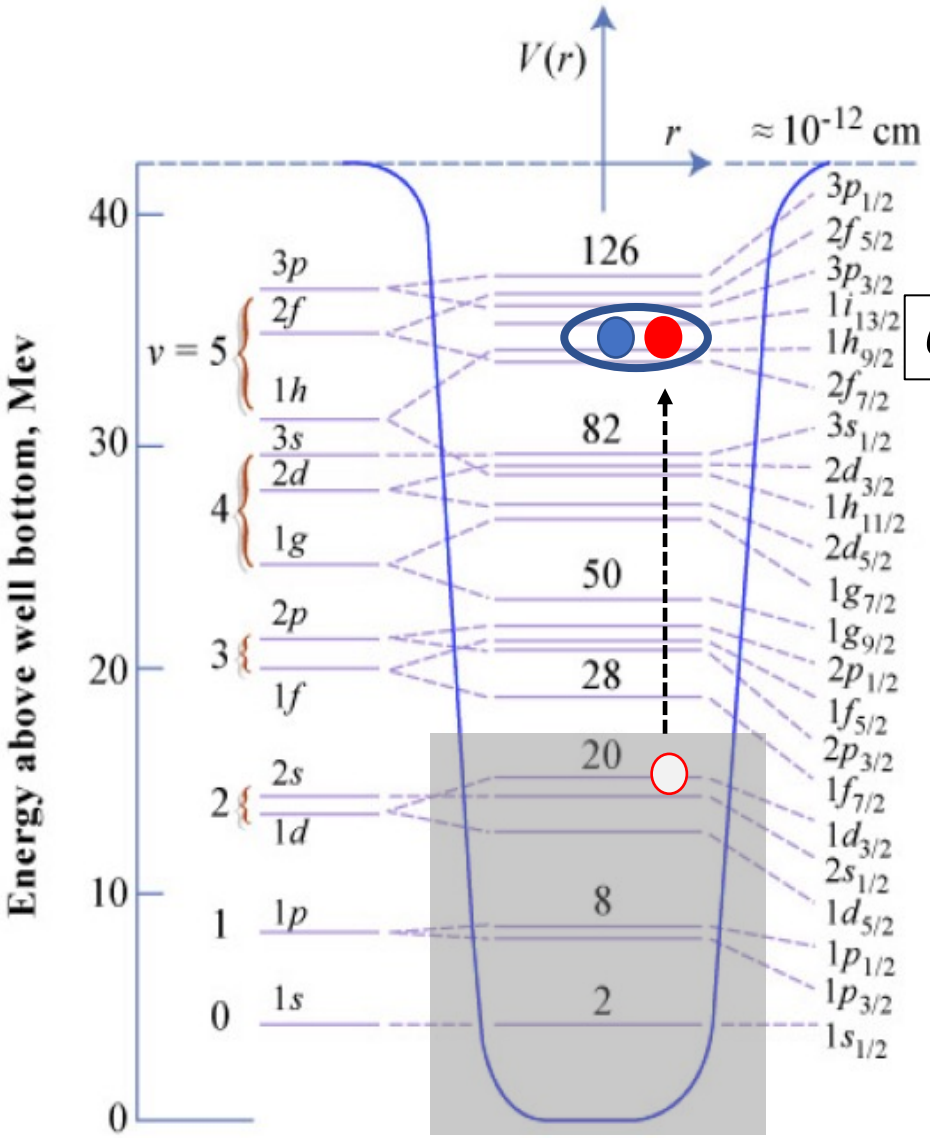


Quasi-deuteron



$|qp\rangle \sim 80\% |p\rangle + 20\% |h\rangle \times |qd\rangle$????

How do the IPM particles get dressed by the SRC?

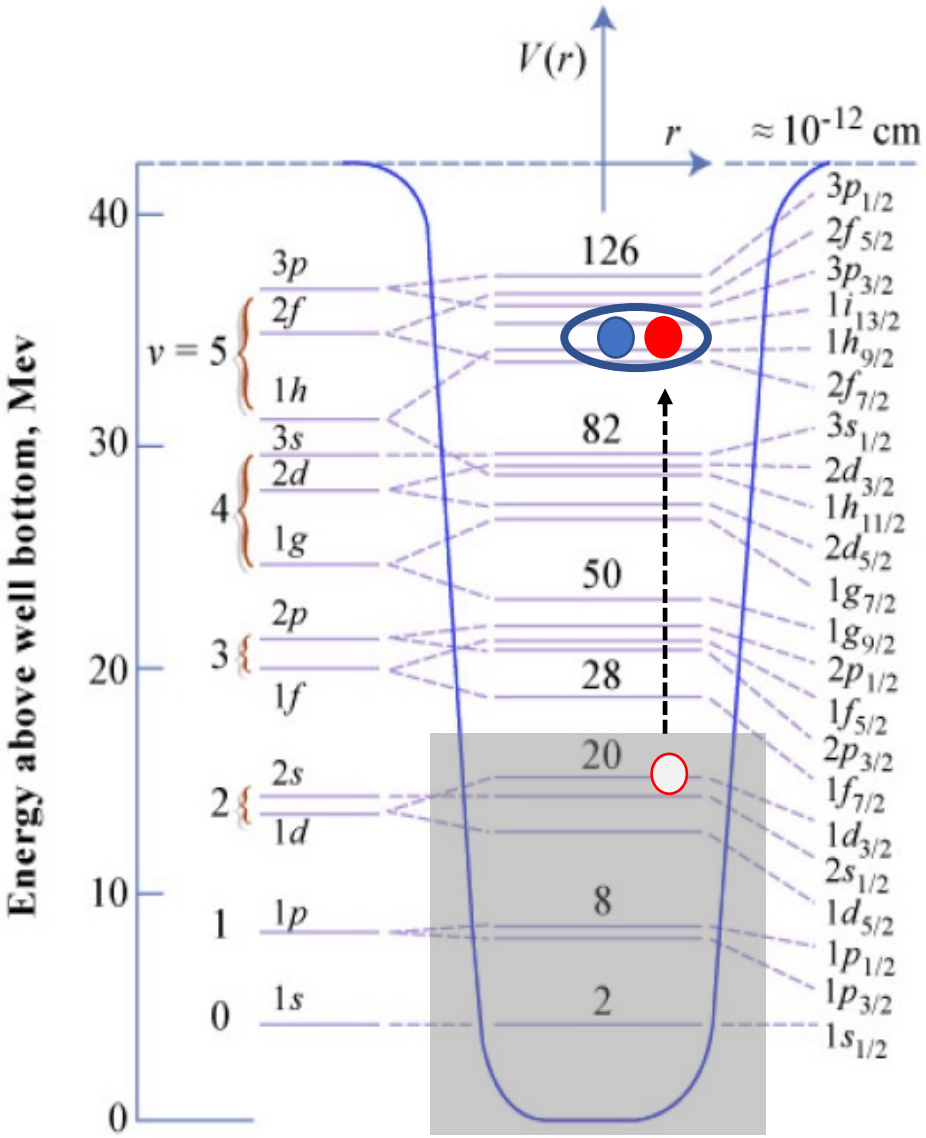


Quasi-deuteron

Maria Patsyuk
BM@N

|qp > ~ 80% |p> + 20% |h > x |*qd* > ????

How do the IPM particles get dressed by the SRC?



Quasi-deuteron

Isao Tanihata - RCNP

(p,pd) reaction studies
R3B @ GSI

$|qp\rangle \sim 80\% |p\rangle + 20\% |h\rangle \times |qd\rangle$????

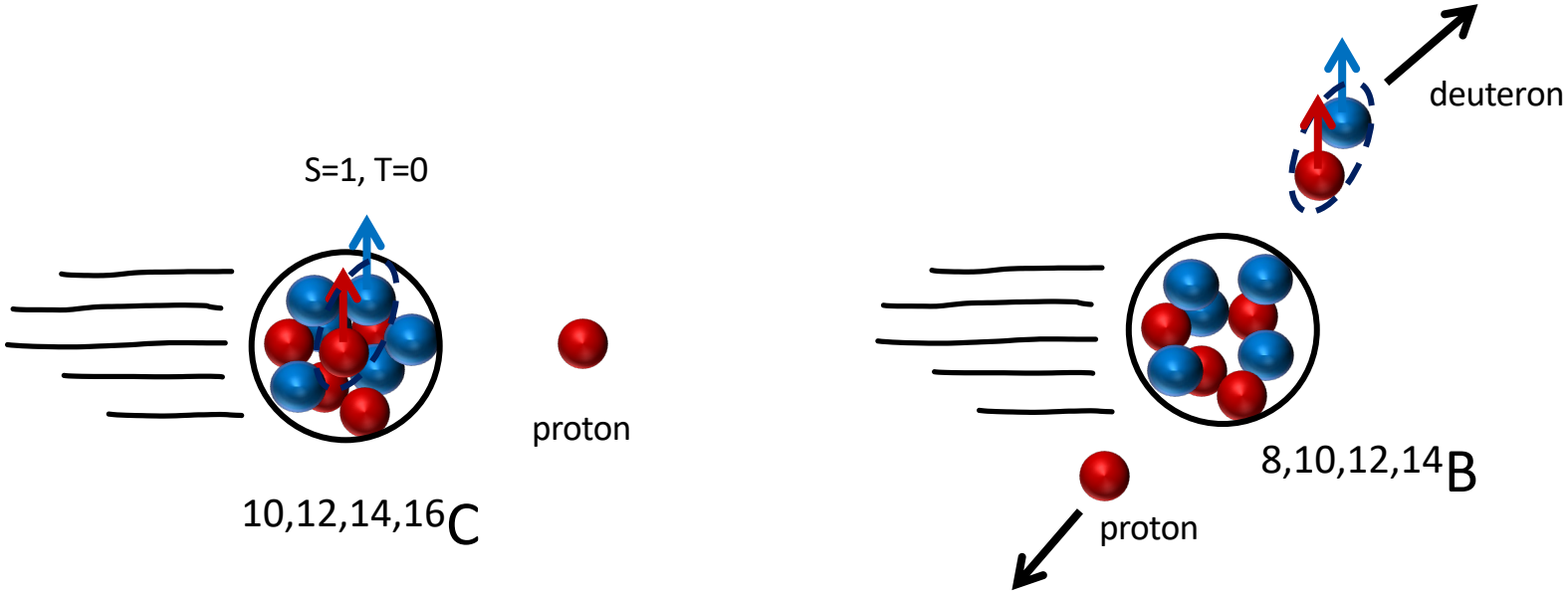
Probing nucleon-nucleon correlations in atomic nuclei via (p,pd) QFS Reactions

Experiment G-22-00091 (approved by the GSI PAC)

M. Petri[1], S. Paschalis[1], A. O. Macchiavelli[2]
for the R^{3}B Collaboration

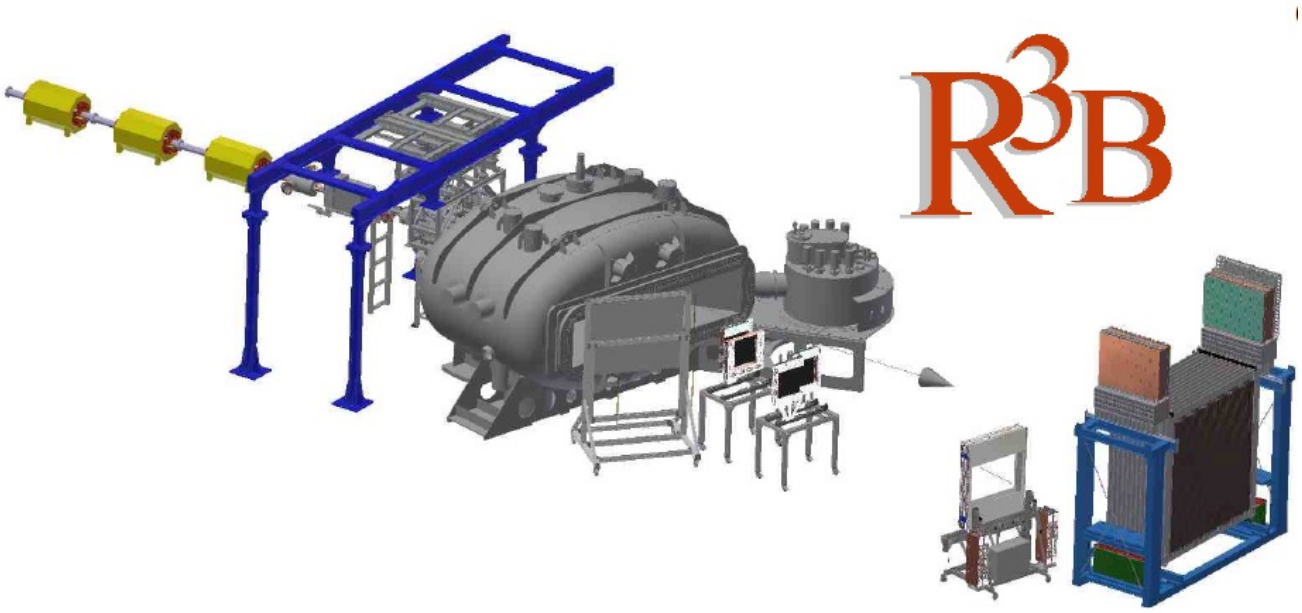
[1] Department of Physics, University of York, UK
[2] Physics Division, Oak Ridge National Laboratory, USA

(p,pd) QFS reactions



- Quasi-elastically knocking out deuterons along the C isotopic chain to probe the number of quasi-deuterons in a nucleus and their isospin dependence

(p,pd) QFS reactions

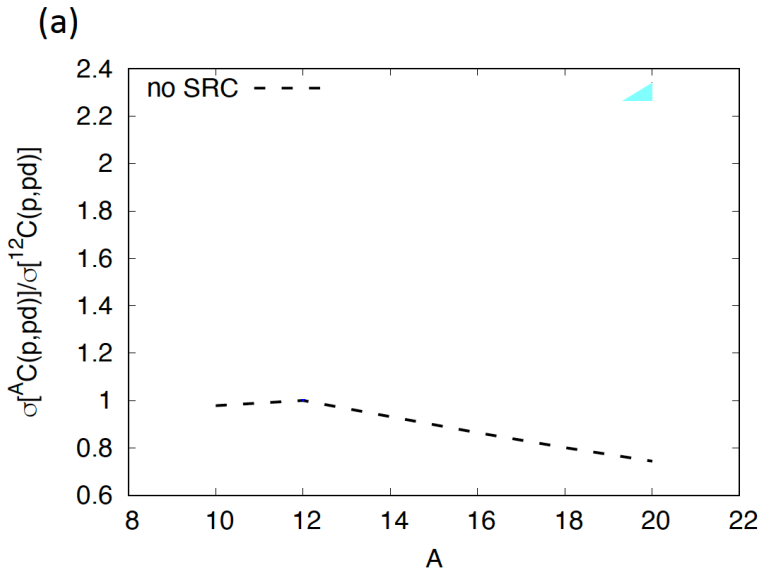


- Kinematically complete measurements at R^3B using high purity beams from FRS at high energy (justifying the Quasi-elastic assumption)

(p,pd) QFS reactions

In a non-interacting system, the ^{A}C(p,pd) cross section should scale with the number of 1^{+} *T=0* n-p pairs that can be formed in the given ^{A}C system. The number of T=0 n-p pairs in a system of A nucleons with isospin *T* is given as $A^2/8 + A/4 - T(T+1)/2$, which naturally decreases in more asymmetric systems. Specifically for the C isotopes, we estimate that about 50% of these pairs have the 1^{+} spin/parity assignment that corresponds to the deuteron ground state.

Furthermore, we estimate a 50% overlap between the 1+, T=0 shell-model $p^2_{3/2,1/2}$ n-p pairs and the detected $^3S_1$ deuteron. Scaling the number of deuterons to the one in ^{12}C, we should expect an A dependency of the cross section



SRC and quasi-deuterons

Due to short range correlations single particle excitations of ΔE ~ 50 MeV will occur with the probability discussed above.

$$\Delta p \sim \frac{\hbar}{\Delta x}$$

This corresponds to changes in the principal oscillator quantum number

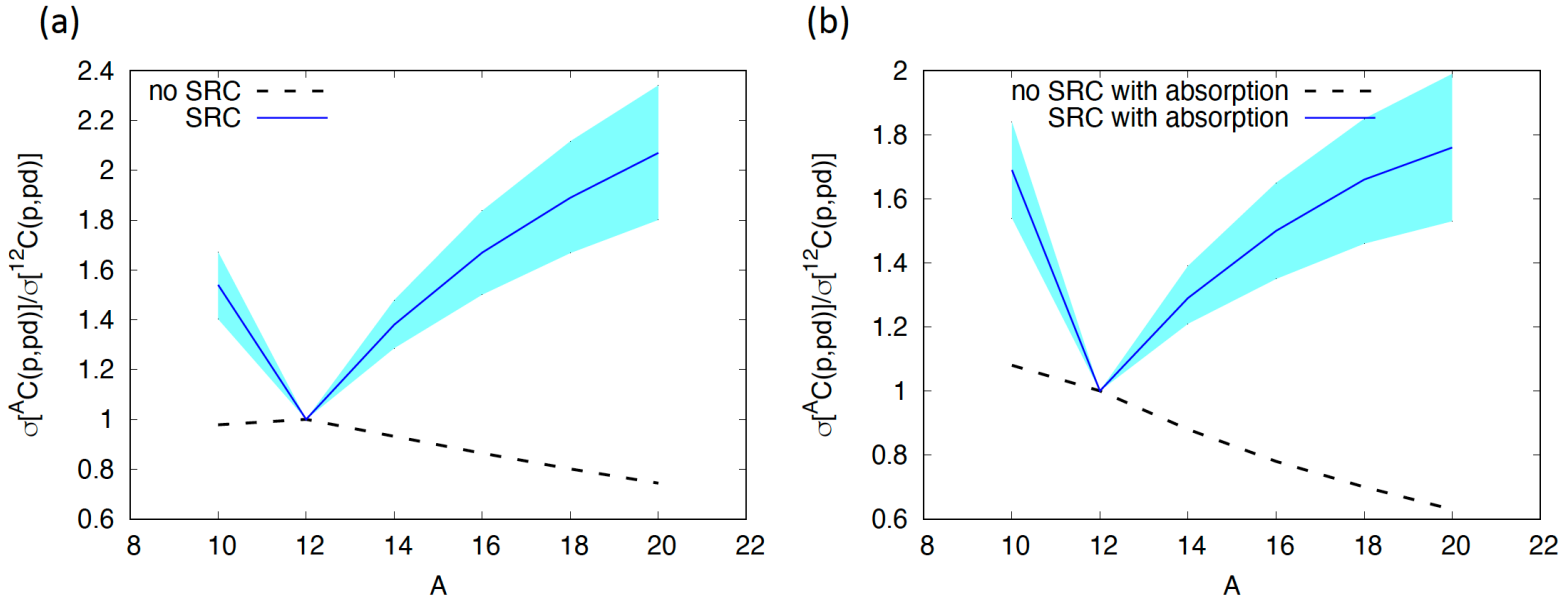
$$\Delta N \sim \Delta E / \hbar\omega_0$$

|qp > ~ 80% |p> + 20% |h > x |*qd* > ????

$$|qd\rangle \approx \frac{\sum_j (2j+1)\,|j^2\rangle^{1^+}}{\sum_j (2j+1)}$$

project the $^3S_1$ amplitude that becomes smaller the larger the j

(p,pd) QFS reactions



Cross-sections estimate

ISSN 1063-7788, Physics of Atomic Nuclei, 2017, Vol. 80, No. 6, pp. 1061–1072. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © A.A. Terekhin, V.P. Ladygin, Yu.V. Gurchin, A.Yu. Isupov, A.K. Kurilkin, P.K. Kurilkin, N.B. Ladygina, S.M. Piyadin, S.G. Reznikov, A.N. Khrenov, 2017, published in Yadernaya Fizika, 2017, Vol. 80, No. 6, pp. 594–604.

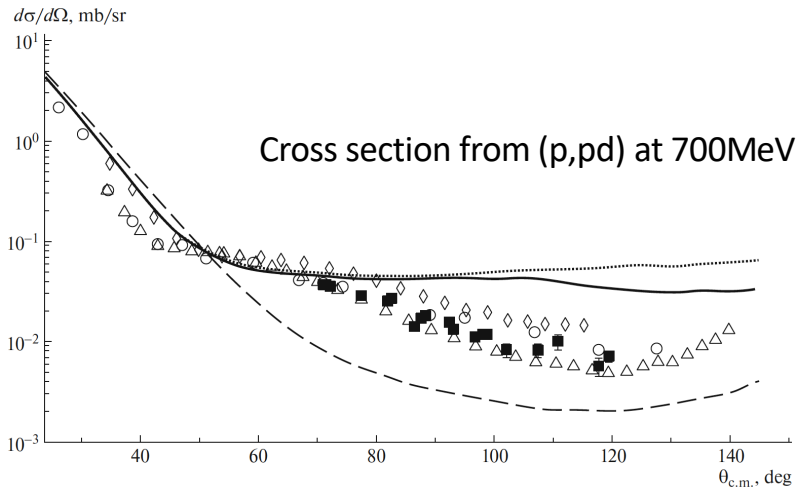
NUCLEI
Experiment

Differential Cross Section for Elastic Deuteron–Proton Scattering at the Energy of 700 MeV per Nucleon

A. A. Terekhin*, V. P. Ladygin, Yu. V. Gurchin, A. Yu. Isupov, A. K. Kurilkin, P. K. Kurilkin, N. B. Ladygina, S. M. Piyadin, S. G. Reznikov, and A. N. Khrenov

Joint Institute for Nuclear Research, ul. Joliot-Curie 6, Dubna, Moscow oblast, 141980 Russia

Received May 22, 2017



Cross section from (p,pd) at 700MeV about 1-2mb

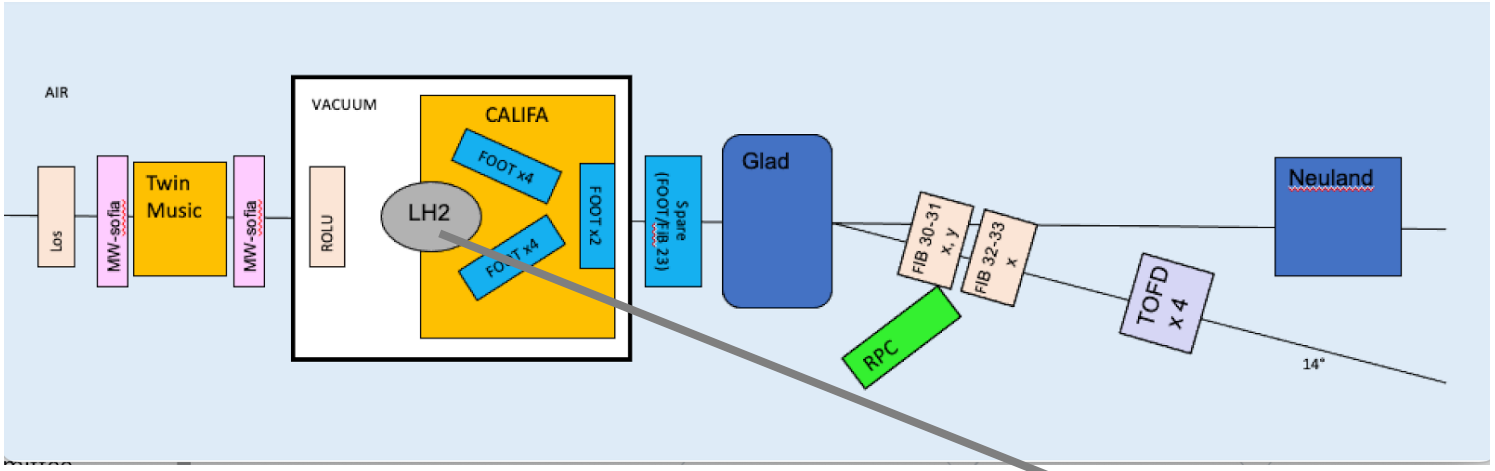
Fig. 8. Differential cross section for elastic deuteron–proton scattering at the energy of 700 MeV per nucleon: (closed boxes) results of measurements at the nuclotron; (open diamonds, circles, and triangles) experimental data at the energies of, respectively, 641.3, 792.7 [34], and 800 MeV/nucleon [35]; and (dotted, dashed, and solid curves) results of, respectively, ONE + SS, ONE + SS + DS, and ONE + SS + DS +Δ calculations performed within the relativistic multiple-scattering model [30–32, 44] at the energy of 700 MeV per nucleon.

Table 3. Differential cross section for elastic deuteron–proton scattering at the energy of 700 MeV per nucleon

$\theta_{c.m.}$, deg	$d\sigma/d\Omega$, μb/sr	$\Delta\sigma_{stat}$, μb/sr	$\Delta\sigma_{syst}$, μb/sr
71.2	36.33	1.20	5.07
71.6	35.91	1.28	5.14
72.3	35.01	1.79	7.05
77.5	28.36	1.12	4.93
82.1	25.12	1.16	4.12
82.8	26.38	1.85	6.29
86.7	13.78	0.91	2.11
87.7	16.61	1.13	2.70
88.4	17.29	1.16	4.21
92.6	15.06	0.79	2.61
93.3	12.98	0.76	2.08
96.8	10.98	0.61	1.72
98.2	11.43	0.67	1.92
98.9	11.62	0.64	2.03
102.0	8.15	1.26	2.13
107.6	7.98	1.21	2.33
110.8	9.77	1.58	2.86
117.8	5.56	1.16	1.56
119.5	7.12	0.83	1.47

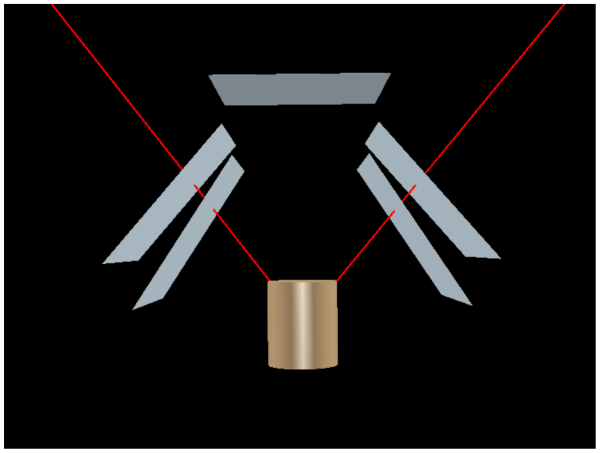
Consistent with experiment S296
S. Panin *et al.* who estimated 1-2 mb for ^{12}C(p,pd) at 400MeV/u in the same kinematic region of large momentum transfer

Setup



The R^{3}B setup Protons and deuterons emitted from the (p,pd) reactions of interest will be detected using the FOOT Si tracking detectors and the CALIFA calorimeter.

- FOOT covers 20-60 degrees
- In the angular range considered here, we estimate an integrated cross section of about 1mb for the (p,pd) QFS reactions. Geometric and detection efficiencies of the detectors for measuring (p,pd) at these angles: 20%.
- 5cm LH2 target

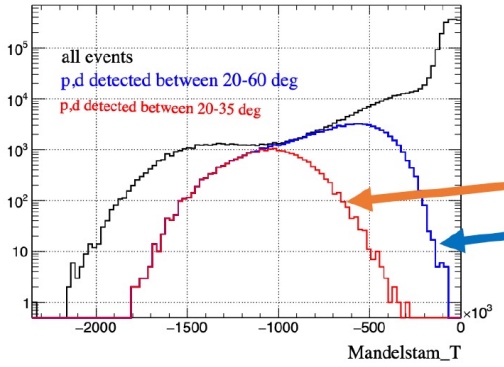


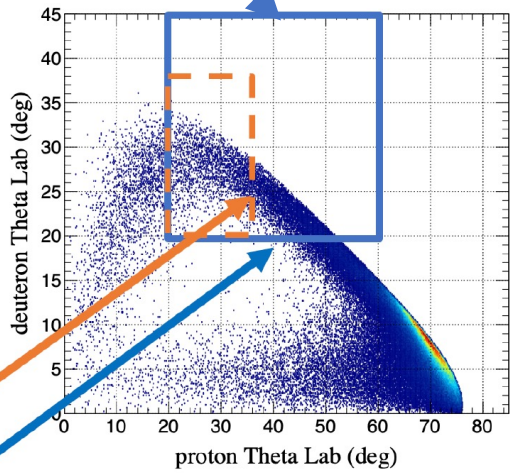
5cm LH2 target (R3BRoot simulations from A. Revel)

Kinematics of the ^{A}C(p,pd) reaction at 480 MeV/u.

Angular coverage of the Si tracker and CALIFA (20-60 degrees), which includes the majority of the high-momentum transfer events

Kinematics for (p,pd) at
480 MeV/nucleon





High momentum transfer

Rate estimates

- Assuming a 1 mb cross section, and $5x10^4$ pps for each incoming isotope of interest

	^{10}C	^{12}C	^{14}C	^{16}C
Primary target (mg/cm^2)	16076	16076	16076	16076
Particles/$5x10^{10}$ beam/spill	2.29E+05	5.45E+06	7.60E+06	1.13E+06
Total rate	2.34E+05	5.45E+06	7.65E+06	1.13E+06
Purity	9.79E+01	9.97E+01	9.95E+01	9.96E+01
Spill length (s)	1	1	1	1
Final rate (pps)	**5.73E+04**	**1.36E+06**	**1.90E+06**	**2.81E+05**

24 h per target will reach a statistical uncertainty better than 5% in the cross-section measurements,

Rate estimates

- Assuming a 1 mb cross section, and $5x10^4$ pps for each incoming isotope of interest

	^{10}C			
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24 h per target will reach a statistical uncertainty better than 5% in the cross-section measurements,

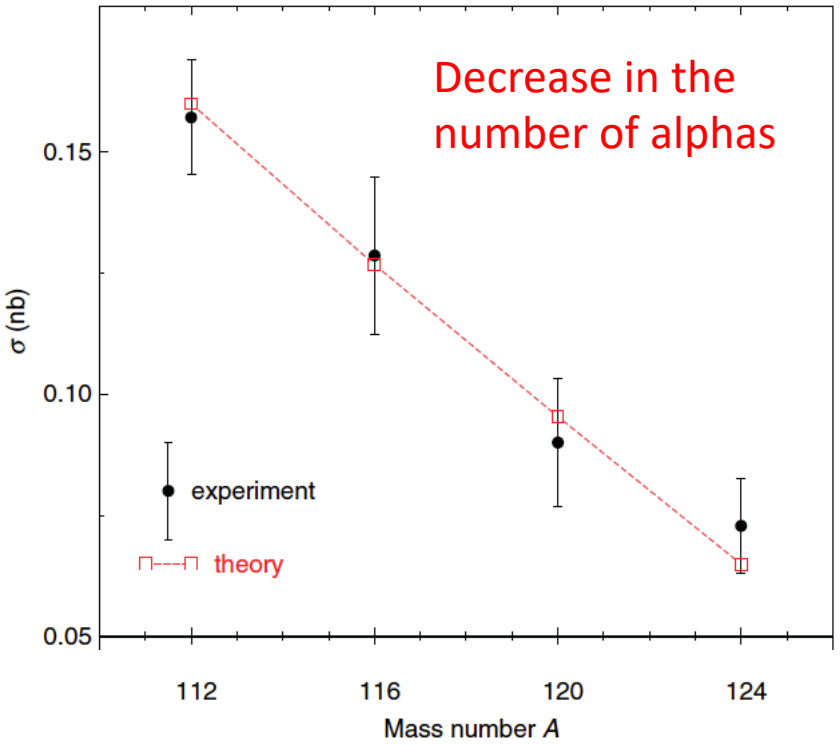
A somewhat related question

Science

Formation of α clusters in dilute neutron-rich matter

Junki Tanaka, Zaihong Yang, Stefan Typel, Satoshi Adachi, Shiwei Bai, Patrik van Beek, Didier Beaumel, Yuki Fujikawa, Jiaxing Han, Sebastian Heil, Siwei Huang, Azusa Inoue, Ying Jiang, Marco Knösel, Nobuyuki Kobayashi, Yuki Kubota, Wei Liu, Jianling Lou, Yukie Maeda, Yohei Matsuda, Kenjiro Miki, Shoken Nakamura, Kazuyuki Ogata, Valerii Panin, Heiko Scheit, Fabia Schindler, Philipp Schrock, Dmytro Symochko, Atsushi Tamii, Tomohiro Uesaka, Vadim Wagner, Kazuki Yoshida, Juzo Zenihiro and Thomas Aumann

Science **371** (6526), 260-264.
DOI: 10.1126/science.abe4688



Do SRCs have anything to say?

Piet's Shell Model Analysis provides a much needed reference !

Acknowledgments

* This work is based on the research supported in by the Director, Office of Science, Office of Nuclear Physics, of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

Acknowledgments

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Merci !