Searching for the d* in photoreactions on transversely polarized deuterons

Dan Watts
Mikhail Baskanov, Michael Ostrick, ...
Overview

- Evidence from pn scattering
- EM properties – recent MAMI results
- \( d^* \) theory
- Potential added impact: Neutron stars, DM candidate
- Opportunities with nucleon polarisation observables
The $d^*(2380)$ in $pn$ scattering
Nucleon scattering with large acceptance

- $pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow d\pi\pi$

- $pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow NN\pi\pi$

![Diagram showing nucleon scattering processes](image)
d*(2380) signals

\[ pn \rightarrow d\pi^0\pi^0 \]

WASA data

DD

\[ \text{t-channel } \Delta\Delta \]

\[ \sqrt{s} \text{ [GeV]} \]

\[ \sigma \text{ [mb]} \]

\[ d\pi \text{ threshold} \]
\( p + n \rightarrow d^*(2380) \)

\( I(J^P) = 0(3^+) \)

\( \Delta\Delta \) decay \( \sim 90\% \)

\( pn \) decay \( \sim 10\% \)
d* decays to pn

- High partial waves in decay to a proton-neutron final state (J=3)

  90% of cases this is via the $^3D_3$ partial wave
  (L = 2, nucleon spins and L all aligned)

  10% of cases via the $^3G_3$ partial wave
  (L = 4, nucleon spins aligned, spin and L anti-aligned).
Deuterium photodisintegration ($\Sigma$)

- First detailed measurement in region of d*
- Good agreement with sparse existing data
- Almost complete acceptance – amenable to (truncated) PWA

Figure 2: (Color online) Beam-spin asymmetry ($\Sigma$) results from this experiment (red open circles) in comparison with previous results (black crosses) [30, 31, 32]. The corresponding systematic uncertainties are depicted as shaded bars on the bottom. Energy independent (energy dependent) $q_T^2$ fits are shown as solid red/dashed blue lines (see text).
**Σ decomposition**

\[
\frac{\sigma_1}{\sigma_{tot}} = \sum_{l=2}^{7} a_l P_i^2.
\]

Discrete gaussian sampling method
3 gaussians centroids 420,520,620 width 100 MeV

2 methods: Single energy & energy dependent (smooth functions for \(a_l\))

**Additional term:** BW, mass 2380 MeV, width=70 MeV, arbitrary strength

Pure M3 should manifest in \(a_6\) but not \(a_4\)

Pure E2 should manifest in \(a_4\) but not \(a_6\)

(E2 may contribute in \(a_6\) only with interference with higher multipoles E4 or higher)
Deuterium photodisintegration ($\Sigma$)

$$\Sigma \sim \sum_{l=2} a_l P_l^2 (\cos \Theta)$$

E2 transition $\Rightarrow$ small
M3 transition $\Rightarrow$ dominant

Consistent with $d^*(2380)$ as a compact object

H. Ikeda et al., NPB172, 509, (1980)

Bashkanov, Watts, Kay, CB@MAMI; PLB789 (2019) 7-12
Deuterium photodisintegration ($P_γ$)

- 1st measurement of final state neutron polarisation
  -> Both $p$ and $n$ highly polarised in region of $d^*$!

- $θ_{CM}$ dependence – consistent with spin 3

Bashkanov, DPW, Kay, CB@MAMI; PRL under review
Deuterium photodisintegration ($P_y$)

- 1st measurement of final state neutron polarization
- Both $p$ and $n$ highly polarized in region of $d^*$
- $\theta_{CM}$ dependence consistent with spin 3

$P_y$ vs $\theta_{CM} = 90^\circ$

$D(\gamma, pn) \rightarrow P^1_1 (\cos \Theta)$
C_x* for neutron final state

- Indications of strong polarisation transfer in region of d*
- Caveat: approx. (n,p) analyzing power used in analysis

Previous (proton) data

Combination of C_x* and P

-> real and imaginary parts of same amplitude combination

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<td>T</td>
<td>R_T(ImT_{11})</td>
<td>2Im \sum_{i=1}^{3} \sum_{j=0}^{1} \left[ F_{i+j+3}^+ + F_{i-j+3}^+ - F_{i+j-3}^- - F_{i-j-3}^- \right]</td>
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<td>\Sigma</td>
<td>R_{TT}</td>
<td>2Re \sum_{i=1}^{3} \left[ (-i)^i F_{i+3}^- + F_{i-3}^+ \right]</td>
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The $d^*(2380)$ in models

Any quark model with confinement and one gluon exchange *inevitably* predicts a 6-quark object with $(I)J^P=(0)3^+$.


\(d^*\) in pion cloud model

- EM properties determined in simple overlapping \(\Delta\) pion cloud model:
  - \(\Delta \Delta\)
  - \(N\Delta \pi\)
  - \(NN\pi\pi\)

  Spherical \rightarrow Donut \rightarrow Rugby ball

- EQM \(\rightarrow \Delta \Delta\) no contribution
  - \(N\Delta \pi\), \(NN\pi\pi\) \(\sim\) equal contribution but opposite sign \(\rightarrow\) cancellation

- MOM \(\rightarrow \Delta \Delta\) no contribution
  - \(N\Delta \pi\), \(NN\pi\pi\) \(\sim\) equal contribution but **same** sign

Bashkanov, Watts, Pastore; PRC 100 012201(R) 2019
The $d^*(2380)$ in neutron stars

- $d^*$ forms copiously above $2.5\rho_0$.
- $\sim20%$ $d^*$ at center of heavy stars.

- Star mass limit - around $2.1M_\odot$.
- $d^*$ in medium an important topic.
More $d^*(2380)$ in neutron stars

- Non-linear Walecka model to describe $d^*$- N interaction via $\sigma, \omega$
- $\rightarrow$ vary the couplings
- $d^*$ in medium (nuclei) crucial $\rightarrow$ Mihai’s thesis

A&A, under review
arxiv:2002.06571
The d*(2380) hexaquark and dark matter
Many body $d^*(2380)$ systems

- $d^*$ hexaquark - a new compact, **bosonic** and **isoscalar** form of light quark matter

- It’s a boson - can the $d^*$ form a Bose-Einstein condensate?
The Hoyle state – a condensate of alpha

- The Hoyle state of $^{12}$C (7.65 MeV) - crucial in nucleosynthesis

- $\alpha$ is also an isoscalar, bosonic object
  -> analogous to the d* (but much larger)

- The Hoyle state properties reproduced remarkably well assuming it is a dilute Bose-Einstein condensate of 3 alpha particles.

70% condensed state with 30% of time scattered out from interactions
The $d^*$ condensate?

- The Binding Energy of a condensate can be calculated as a function of $d^*$ multiplicity.
- Account for different scaling of binding and Coulomb terms (common wavefunction for all particles). Surface term not relevant for condensate – linear chain configuration.
- Vary volume coefficient (reflecting the $d^*\cdot d^*$ interaction potential) over physical ranges.

### Standard nuclei

$$B_{LD}/A = a_v - a_s \cdot \frac{1}{A^{1/3}} - a_c \cdot \frac{Z(Z-1)}{A^{4/3}}$$

### $d^*$ condensate

$$B/D = a'_v \cdot (D-1) - a'_c \cdot \frac{(D-1)}{D}; \quad a'_c [\text{MeV}] = 0.064 \cdot \frac{\rho}{\rho_0}$$

A new possibility for light-quark Dark matter

- The Independent, Daily Mail, Daily Express, Newsweek…. 40+ newspapers an journals all over the globe.
- 12k downloads a day, 15k+ downloads total.

The proposed programme with polarised deuteron targets
Possible beam-target D(\(\gamma, pn\)) observables

- **Longitudinal target polarisation**

\[
T_{10}^L(-E) \frac{d\sigma_0}{d\Omega_p} = \frac{1}{2} \sum_{s_{m_z}} |t_{s_{m_z}11}|^2 - |t_{s_{m_z}1-1}|^2
\]

\[
T_{10}^L(G) \frac{d\sigma_0}{d\Omega_p} = \Im m \sum_{s_{m_z}} (t_{s_{m_z}11}^* t_{s_{m_z}1-1})
\]

- **Circular \(\gamma\)-polarisation**

- **Linear \(\gamma\)-polarisation**

- **Transverse target polarisation**

\[
T_{11}^0(-T) \frac{d\sigma_0}{d\Omega_p} = \Im m \sum_{s_{m_z}} (t_{s_{m_z}1-1}^* t_{s_{m_z}10} + t_{s_{m_z}10}^* t_{s_{m_z}11})
\]

\[
T_{11}^c(-F) \frac{d\sigma_0}{d\Omega_p} = -\Re e \sum_{s_{m_z}} (t_{s_{m_z}1-1}^* t_{s_{m_z}10} + t_{s_{m_z}10}^* t_{s_{m_z}11})
\]

\[
T_{11}^l \frac{d\sigma_0}{d\Omega_p} = \Im m \sum_{s_{m_z}} (t_{s_{m_z}1-1}^* t_{s_{m_z}-10})
\]

\[
T_{1-1}^l \frac{d\sigma_0}{d\Omega_p} = -\Im m \sum_{s_{m_z}} (t_{s_{m_z}11}^* t_{s_{m_z}-10})
\]

- **Unpolarised**

- **Circular \(\gamma\)-polarisation**

- **Linear \(\gamma\)-polarisation**
Photodisintegration of polarized deuterons – measurement of angular distributions at $E_r = 450, 550$ and 650 MeV


Physikalisches Institut der Universität Bonn, Nussallee 12, D-5300 Bonn 1, Federal Republic of Germany

Received 14 February 1970

Taken as contribution of higher multipoles!

Significant improvement in data quality possible at MAMI
Expected sensitivity

Mainz MAID: $N^*(1680)\frac{5^+}{2} -$ same multipoles (E2,M3) as d*
Count rate estimate

- Measure all 4 transverse target asymmetries

- Stat accuracy $\delta A \sim 0.01$ for $\pm 15$ MeV bin in d* region, $P_T \sim 0.7$, $P_\gamma \sim 0.4$
  
  -> requires $\sim 100k$ events bin$^{-1}$ (good angular binning required)

Event rate = Beam intensity $\times$ tag eff $\times$ Number nuclei $\times$ efficiency $\times$ cross section

= $1 \text{ s}^{-1}$

Beam time $\sim 7$ weeks
Required beamtime

+ 1 week to setup/maintain the target
What will we learn?

- Clean separation of the d*(2380) from background channels
- Precise knowledge of the d* photo coupling
- d* can be excited in E2, M3 or E4 transitions
  - E2 ↔ Electric Quadrupole moment
  - M3 ↔ Magnetic Octupole moment
  - E4 ↔ Electric Hexadecapole moment

Size and structure of the d*
Summary

- MAMI can lead the way in providing key data to elucidate the d*(2380) with EM probes

- Important ramifications for hadron physics - potentially for astrophysics

- Campaign with polarized deuteron target would provide T and a trio of beam-target observables
Deuteron polarisation

 Tensor polarisation

 Vector polarisation
Extracted (approximate!) $d^*$ cross section from $\sigma$ and $\Sigma$

Coefficients: assuming M3 dominance!

\[
\begin{align*}
    a_2 &= 0.375|M3(3D_3)|^2 + 0.108|M3(3D_3)||M3(3G_3)| \cdot \cos(\delta_D - \delta_{G_3}) + 0.391|M3(3G_3)|^2 \\
    a_4 &= 0.014|M3(3D_3)|^2 + 0.021|M3(3D_3)||M3(3G_3)| \cdot \cos(\delta_D - \delta_{G_3}) + 0.017|M3(3G_3)|^2 \\
    a_6 &= 0.172|M3(3D_3)||M3(3G_3)| \cdot \cos(\delta_D - \delta_{G_3}) + 0.025|M3(3G_3)|^2
\end{align*}
\]

-> Use extracted even coefficients to estimate $d^*$ contribution

-> \textbf{4.6} \pm 1\%

Similar order as suggested by structure in $\gamma + D \rightarrow d\pi^0\pi^0$

($d^*$ coefficients only contribute to odd coefficients via interference with other partial waves -> therefore assumed small)
Primordial production at the quark hadron phase transition

- DM/matter ratio calculated in general terms assuming Boltzmann distribution in QGP

\[
\Omega_{DM}/\Omega_{\text{baryon}} = \frac{7}{4} M_N \left(1 - \frac{y_D}{M_N} \right)^{3/2} e^{-\frac{M_N y_D}{T}}
\]

\( y_D \) - \( d^* \) binding energy (units of nucleon mass)
\( T \) - temperature

At QGP phase transition (0.16 GeV) a BE\( \sim \)300 MeV would produce measured DM ratio.

Achievable with \( d^* \) condensate multiplicity \( \sim \)1000

Figure 2. The primordial production of \( d^* \) (2380)-BEC (expressed as a ratio to baryon matter) calculated as a function of binding energy and decoupling temperature. The red line shows the loci corresponding to the current experimental determination of the dark matter to matter ratio[33].
Signatures of d* condensates

- The (charged) chain condensates would attract electrons to become neutral objects (DFT calculations for linear chain configuration in progress)

- Breakup of a condensate “nucleus” would produce a characteristic decay spectrum

*Figure 3. The d*(2380)-BEC decay spectrum, presented as a flux per d*(2380), per MeV of kinetic energy. The flux is separated into the contributions from gamma(black), nucleons(green), deuterons(red) and charged pions(blue).*
Measurements of the $P_x$ component of neutron polarisation in the reaction $yd \rightarrow pn$ by linearly polarised photons in the energy range 0.3-0.5 GeV

To cite this article: F V Adamian et al 1988 J. Phys. G: Nucl. Phys. 14 831

- The target asymmetry $T$:

$$T = \frac{3}{2} \cdot \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_0 + \sigma_-} \quad \text{with} \quad -3/2 \leq T \leq 3/2. \quad (1)$$

- The tensor asymmetry $Z$:

$$Z = (-2) \cdot \frac{\sigma_+ + \sigma_- - 2\sigma_0}{\sigma_+ + \sigma_0 + \sigma_-} \quad \text{with} \quad -2 \leq Z \leq 4 \quad (2)$$

$\sigma_+$, $\sigma_0$ and $\sigma_-$ are the differential cross sections of the process with pure deuteron states. $\sigma_+$ for example is the cross section with all deuterons parallel to the polarization axis, in our case the $y$-axis. The latter is given by the $k \times q$-direction ($k$ photon- and $q$ pro-
Photoproduction of $d\pi\pi$ final state

- Photoproduction kinematics challenging $\rightarrow$ deuteron only detected at forward angles
- Active deuteron target prototype under construction

Conventional Background

See talk of B Krusche
Polarization observables - disintegration

For the differential cross section in the cm frame one obtains

\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \left[ 1 + P_1^7 \Sigma' \cos 2\Phi \right. \\
+ \sum_{l=1,2} P_l^7 \left( \sum_{M \geq 0} (T_{1M}(\Theta) \cos(M(\Phi_d - \Phi) - \delta_{1I1}\pi/2) \\
+ P_z^7 T_{1M}(\Theta) \sin(M(\Phi_d - \Phi) + \delta_{1I1}\pi/2))d_{M0}(\Theta_d) \right. \\
+ \left. \left. P_l^7 \sum_{M=-I} T_{1M}(\Theta) \cos(\Psi_M - \delta_{1I1}\pi/2) d_{M0}(\Theta_d) \right) \right]
\]

where

\[
\Psi_M = M(\Phi_d - \Phi) + 2\Phi.
\]

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<td>(T)</td>
<td>(R_T(1\text{mT}_{11}))</td>
<td>(2\text{Im} \sum_{i=1}^2 \sum_{j=0}^1 [F_{(i+j)}^* F_{(i+j+3)} - F_i F_{(i+j+3)}^*])</td>
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<td>(\Sigma)</td>
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<td>(T_1)</td>
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d*(2380) may have very significant effect on heavy neutron stars and the physics of mergers. (Vidal, Bashkanov, DPW, Pastore)
Figure 3: Induced polarization \( p_y \) in deuteron photodisintegration at \( \theta_{\text{cm}} = 90^\circ \). Only statistical uncertainties are shown. The curves are described in the text.

Figure 4: Polarization transfers \( C_x \) and \( C_z \) at \( \theta_{\text{cm}} = 90^\circ \). Only statistical uncertainties are shown. The curve is described in the text.
$d^*(2380)$ multipole expansion

\[
\frac{M_3}{E^2} \sim \frac{\langle \Omega \rangle_{d \rightarrow d^*}}{\langle Q \rangle_{d \rightarrow d^*}} \sim \frac{\langle Q \rangle_{d \rightarrow d^*} \mu_{d \rightarrow d^*}}{\langle Q \rangle_{d \rightarrow d^*}} \sim M_d \omega^2 \mu_{d \rightarrow d^*}
\]

If $\mu_{d \rightarrow d^*}$ is large the $d \rightarrow d^*$ M3 transition might be dominant

$\mu_{d^*} \sim 7.6\mu_N$

Neutron $A_y$ on Carbon

The graph shows the ratio $A_y^{nc}/A_y^{np}$ as a function of $E_{n}^{lab}$ [MeV]. The ratio decreases with increasing $E_{n}^{lab}$.
Measurements of the $P^x_n$ component of neutron polarisation in the reaction $yd \rightarrow pn$ by linearly polarised photons in the energy range 0.3-0.5 GeV.
Active deuteron target?

Detecting recoil deuteron in photoproduction of $d\pi\pi$ challenging
-> e.g stops in cryogenic target for much of phase space

Active target prototype developed at UoY

Scintillator pixels interleaved with CD2 target material

Tagging and separation of low energy Deuteron/spectator proton feasible
-> G4 simulation
\[ d^* (2380) \text{ SU}(3) \text{ multiplet} \]

\[ M_{d^*} - M_\Delta + M_{\Sigma^*} < M_{d_s^*} \leq M_\Delta + M_{\Sigma^*} \]

- \( \Delta \Delta \)
- \( \Delta \Sigma^* \)
- \( \Delta \Xi^* \)
- \( \Delta \Omega \)

\( d^* (2380) \)
\( d_s^* (2.53 - 2.60) \)
\( d_{ss}^* (2.68 - 2.76) \)
\( d_{sss}^* (2.82 - 2.90) \)
Strange Dibaryon decays

\[ pn \]
\[ \Delta \Delta \rightarrow NN\pi\pi \]
\[ d^*(2380) \]
\[ d_s^*(2530-2600) \]
\[ \Delta \Sigma^* \rightarrow (N\pi)(\Lambda\pi) \rightarrow NN\pi\pi\pi \]
E2 transition \((2^+)\)
M3 transition \((3^+)\)
E4 transition \((4^+)\)

\[ \gamma \rightarrow d^* \rightarrow p \quad d \quad n \]

\[ ^3D_3 \quad ^3G_3 \]

90\% \quad 10\%

\[ \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = P_\gamma \Sigma \cos 2\phi \]

![Diagram showing multipole strengths up to \(L = 4\) contributing to the total cross section with inclusion of MEC, IC, and IC for the Born n-space potential.](image)

Fig. 7.1.3: Multipole strengths up to \(L = 4\) contributing to the total cross section with inclusion of MEC, IC, and IC for the Born n-space potential.

H. Arenhoevel, M. Sanzone “Photodisintegration of the deuteron”
\[ \frac{\Sigma(\Theta)\sigma(\Theta)}{\sigma_0} \sim \sum_{j=2}^{P_f^2} (\cos \Theta) \]

\[ B_2 \sim c_1 |^3D_3(E2)|^2 + c_2 |^3D_3(M3)|^2 + c_3 |^3G_3(E2)|^2 + c_4 |^3G_3(M3)|^2 + \cdots \]

\[ B_6 \sim d_1 |^3G_3(M3)|^2 + \cdots + d_i |^3D_3(M3)|^3 |^3G_3(M3)| \cos \delta_i + \cdots + d_j |^3D_3(E2)|^{2S+1} L \geq 4_j(E4) \cos \delta_j + \cdots \]

\[ \gamma \rightarrow d^* \rightarrow p + n \]

Magnetic M3 transition might be sizable
Threshold

\[ p_n \]

\[ \Delta \Delta \]

\[ 2.2 \text{ MeV} \]

\[ \Delta \]

\[ 80 \text{ MeV} \]

\[ d^* \]

\[ I(J^p) = 0(1^+) \]

\[ I(J^p) = 0(3^+) \]

\[ r \sim 4 \text{fm} \]

\[ r \sim 1.2 \text{fm} \]

But width of \( d^* \) is 70 MeV – width(\( \Delta \Delta \))~240 MeV?

& strong decay open (NN\( \pi \pi \), N\( \Delta \pi \))?
**d* shape**

- Estimates made using simple pion cloud model.
- d* made from 2D spend part of time as nucleon plus pion – pure quark DD component, NNpp component and NDpi components
- Enables estimate M3/E2 ratios and ind. strengths
- Indicates d* is spherical (electrical quadropole deformation small)
- However magnetic octupole deformation may be large (don't cancel)
  - Octopole moment is quadropole x magnetic dipole
  - For 2 cases magnetic dipole moment of opposite sign (DDnp+ mag moment neut -2mu_b, p = 3mu_b
  - Ndpi + Dpipi like (but more compact deuteron) NN is like deuteron therefore magnetic moment +1Mu_b. The plot is a Y30 shape octupole
  - More polarization observables (long polarized target with transverse beam or transverse target circular beam), Ox, may help to experimentally determine these ratios M3/E2. This ratio is proportional to mag dipole moment of d* (cancellation)
- M3 prop octupole d* E2 quadropole d*
  - E2 photin spin up target L=1 in same direction 1+1, 1+ intrinsic spin 1- from angular gives 2+
  - 2+ from E2 plus 1 from deut must be aligned t give 3+
  - E4 L=1 in same direction gives 4+ E4 transition. 4+ and deuteron spin now in OPPOSite direction to get 3+
  - Even if d* is not compact the E2 is small because of cancellations. But in this model it is small. Radii of above similar in size to single delta

- Uadropole deformation of delta from pion cloud only, but on lattice shown comes from quarks and has similar size starting rom just quarks.
- doorway d* excited from d-wave of deuteron. Predictions give huge quadropole transition. Real cross section lot smaller. Therefore maybe not d-wave, maybe from 6q compinsnt. 3oo. If 6q get 0.15% so this might be it. 6q still deformed has cloud like nucleon and delta.